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CONTROL APPOARCHES OF THE CARBONATION COLUMN FOR SODA MANUFACTORING

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ABSTRACT. The paper presents the design of decentralized control systems for the carbonation column of the ammonia-soda production process. The proposed control structures are tested on the basis of an experimentally identified multiple-input-multiple-output dynamic model, capable of describing the behavior of the main carbonation column variables. Two new control structures are investigated. The first one proposes a new pairing of the manipulated to the controlled variables, based on the Relative Gain Array Matrix. The second one implements ratio control aimed to ensure the desired relationship between the inlet ammoniacal-brine and CO_2 flows. Behavior of the designed control structures are tested in the presence of setpoint changes and action of typical disturbances. Results are compared to the traditional decentralized control system configuration in order to reveal both the incentives and the limitations of the proposed control structures.

Keywords: *carbonation column, decentralized control, flowrate ratio control.*

INTRODUCTION

Sodium carbonate (Na_2CO_3), also denoted as soda ash, is a very important chemical compound as it is a main raw material for several other products obtained in different commodity manufacturing fields, such as glass, paper, steel, detergent and chemical industries or for water treatment and flue gases purification. Nowadays, about three quarters of the world sodium carbonate production (exceeding since 2005 the value of 6 kg per each Earth's inhabitant) is synthetically manufactured, while the rest is obtained from naturally formed sodium (bi)carbonate (such as trona minerals or nahcolite) [1]. The sodium hydrogen carbonate ($NaHCO_3$), from which soda

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ash is subsequently obtained by calcination, uses brine solution (NaCl), lime stone (for CO_2 and $Ca(OH)_2$), ammonia and water as raw materials. They are processed according to the ammonia-soda process, also called Solvay process due to the contribution Belgian chemist had to its development during the 1860s. In an overall, but very simplified form, the reactions of the Solvay process for bicarbonate production may be represented by:

$$Na^{+}_{(aq)} + CO_{2\,(g)} + NH_{3\,(g)} + H_2O_{\,(l)} \rightarrow NaHCO_{3\,(s)} + NH_4{}^{+}_{(aq)} \qquad (1)$$

Even today, the Solvay process may be considered as a very good lesson of chemical engineering process design, wisely integrating heat and mass flows.

The core of the synthetically manufactured sodium bicarbonate is the carbonation column. It is the unit where very complex physical and chemical three-phases heterogeneous processes are taking place in order to obtain sodium bicarbonate crystals. The operation of the carbonation tower for obtaining the quantitative and qualitative specifications of the product, associated to low energy costs and while satisfying the environment regulations, is a very challenging task. Therefore, it asks for an appropriate control system.

The present paper presents two decentralized control system configurations aimed to provide smooth and efficient functioning of the carbonation column. The first one emerges from an alternative to the traditional controlled-manipulated variables pairing, while the second one proposes a control structure which correlates the ammoniacal-brine and CO_2 flows. Performance of both control structures have been tested in the presence of disturbances and setpoint changes.

RESULTS AND DISCUSSION

The ammoniacal brine, entering at the top of the carbonation column, is contacted in countercurrent with two carbon dioxide flows. One is the low CO_2 concentration (38%) flow, which is issued by the limestone decomposition in the lime kiln and is introduced at the middle of the carbonation tower. The second one is the high CO_2 concentration (70%) flow, supplied by the recycled carbon dioxide from the sodium bicarbonate calcination, and is introduced at the bottom of the carbonation column. CO_2 is gradually absorbed by the ammoniacal brine and sodium bicarbonate is formed increasing its concentration as it descends the column, until it precipitates. Formation of the sodium bicarbonate crystals is assisted by the water based cooling section situated at the lower part of the of the carbonation tower.

The schematic representation of the carbonation column and its associated traditional decentralized control system structure is presented in Figure 1 [2]. The significance of the presented flows is: 1 – cooling water inlet flow, 2 – outlet flow of sodium bicarbonate, 3 – feed flow of ammoniacal-brine, 4 – feed of 38% CO_2 flow, 5 – feed of 70% CO_2 flow, 6 – gases (CO_2 and ammonia) leaving the column and 7 – cooling water outlet flow. The controlled variables considered in this work are: temperature of the sodium bicarbonate outlet flow (y1), column's sodium bicarbonate outlet flowrate (y2), level of the ammoniacal-brine at the top of the carbonation column (y3), flowrate of the 38% CO_2 entering the column (y4) and flowrate of the 70% CO_2 entering the carbonation tower (y5). The available manipulated variables are the valve openings of the control valves situated on the following flows: cooling water inlet flow (u1), ammoniacal-brine inlet flow (u2), sodium bicarbonate outlet flow (u3), 38% CO_2 inlet flow (u4) and 70% CO_2 inlet flow (u5) [2, 4].

The traditional decentralized control system structure consists in the following control loops: I – temperature control of the sodium bicarbonate leaving the column, II – flow control of sodium bicarbonate extracted from the column, III – level control at the top of the column, IV – flow control of the 38% CO_2 fed at the middle of the column and V – flow control of the 70% CO_2 entering at the bottom of the column [2, 5]. They are also shown in Figure 1.

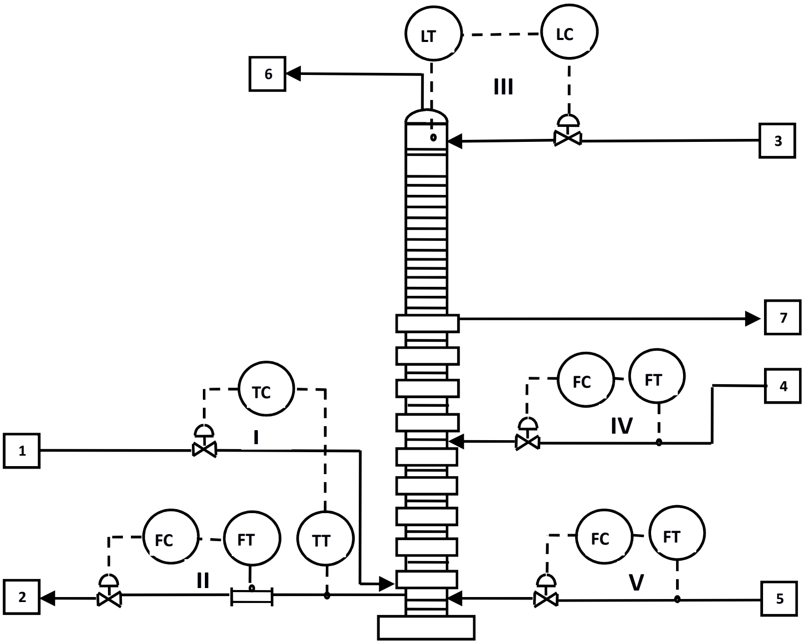

Figure 1. Layout of the carbonation tower, its associated flows and the traditional structure of the control loops [2, 4].

The carbonation column is a multivariable (MIMO) system and the pairing of the manipulated to the controlled variables, for the decentralized control system design, may be performed on the basis of the steady state Relative Gain Array (RGA) matrix [3]. As the experimentally identified model under the form of the MIMO transfer function matrix was available [4], the RGA was computed and presented in Table 1. The new manipulated to the controlled variables pairing was suggested by RGA matrix and it is carried out according to the diagonal elements of the matrix shown in Table 1. Their associated values show the suggested pairing importance for making the suitable tradeoff aimed to reduce control loops interactions.

Table 1. Relative Gain Array Matrix

	u1	**u2**	**u3**	**u4**	**u5**
y1	**1.000**	0	0	0	0
y2	0	**0.4761**	0.4891	0.0348	0
y3	0	0.4691	**0.5303**	0.0001	0.0004
y4	0	0.0545	-0.0195	**0.9650**	0
y5	0	0.0002	0.0001	0	**0.9996**

This RGA proposed decentralized control structure is shown in Figure 2.

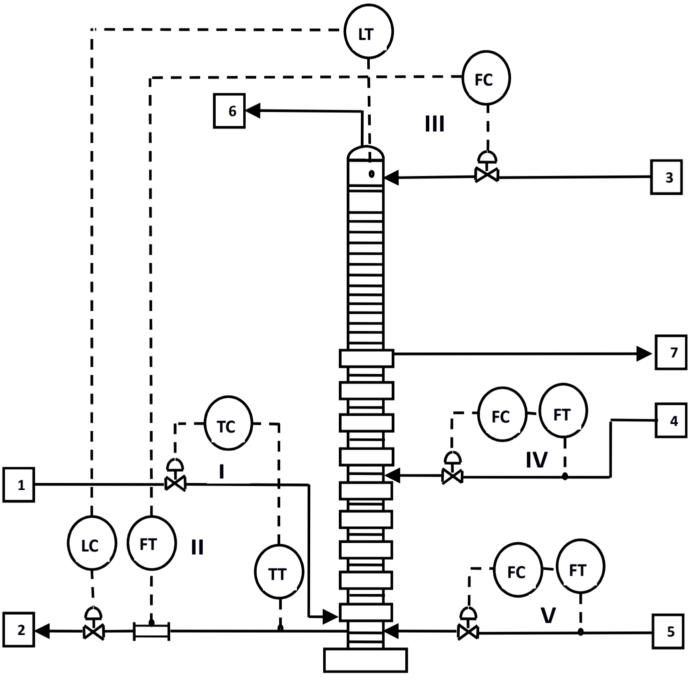

Figure 2. Layout of the RGA proposed structure of the control loops.

The new pairing of the manipulated-controlled variables, generating the proposed control loops structure, has been tested in order to the assess its setpoint tracking and disturbance rejection capability. Simulation results of the control system for the step sodium bicarbonate outlet setpoint change from 26 to 32 m^3/h, introduced at the time moment of 2000s, are presented in Figure 3. Figure 3 also presents the control performance of the traditional control pairing.

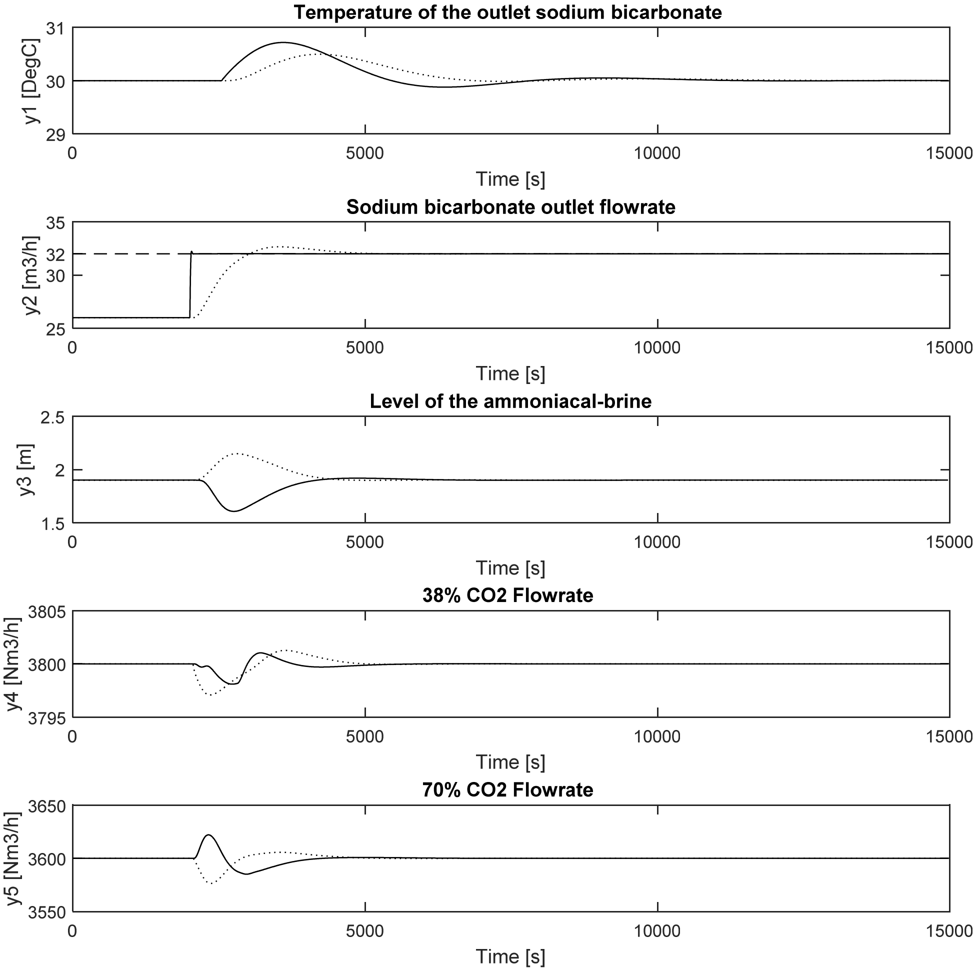

Figure 3. Comparative setpoint tracking performance of the traditional (plain line) and proposed (dotted line) control systems, for the case of the sodium bicarbonate step outlet setpoint change from 26 to 32 m^3/h, introduced at the time of 2000s.

The steady state RGA analysis promises a slightly better pairing, compared to the traditional control approach. The dynamic simulation results partially confirm this expectation. For the proposed pairing control of the temperature (y1), level (y3) and 70% CO_2 flowrate (y5) show improved control performance, while sodium bicarbonate flowrate (y2) reveals an increased setpoint tracking time. Both control structures provide zero steady state offset and the proposed one enhances stability.

One of the most desired requirements for the carbonation column operation is to keep the ratio between the input ammoniacal-brine flowrate and the input CO_2 flowrates, as close as possible to desired values.

Achieving this goal ensures the optimal (off-line computed or experimentally obtained) reactants ratio entering the carbonation reactor, during both steady state and dynamic periods. Neither the traditional control structure, nor the previously proposed one is aimed to fulfill this objective. The second proposed control system structure proposed in this work is designed to accomplish this goal. The layout of this decentralized control system is presented in Figure 4.

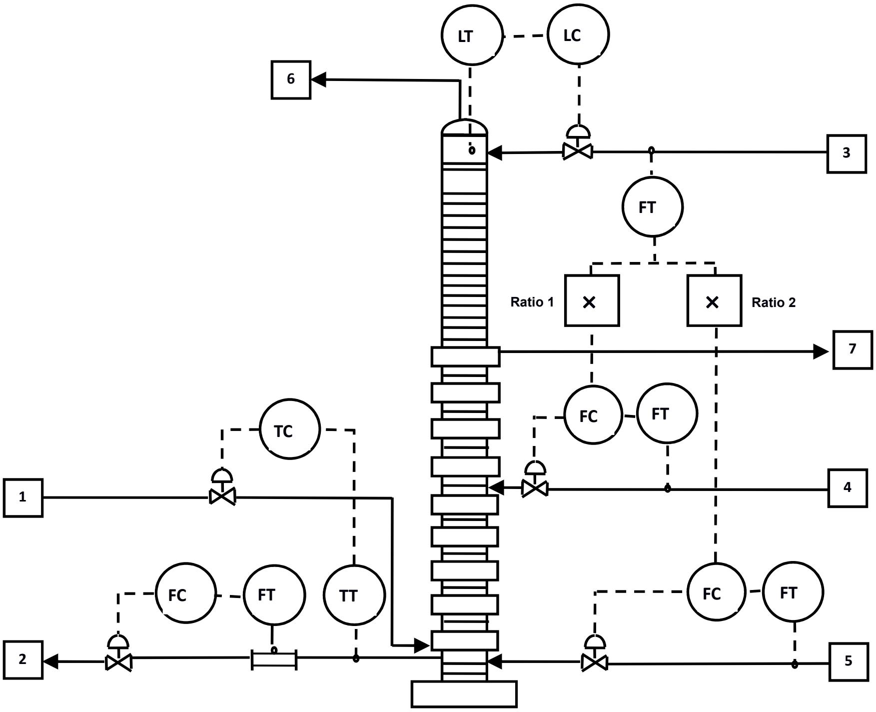

Figure 4. Layout of the flow proposed ratio control loops structure.

As implied by the ratio control system structure, the changes in the ammonia-brine input flow are automatically followed by the necessary changes of both input CO_2 flowrates. The desired ratios are: Ratio1=146.15 [Nm^3/h 38% CO2 / m^3/h ammoniacal-brine] and Ratio2=128.46 [Nm^3/h 70% CO2 / m^3/h ammoniacal-brine].

In order to demonstrate the capability of the ratio control system to keep the desired flowrates ratio, dynamic simulation results of two disturbance rejection tests are presented in Figure 5. The first test considers the typical ammoniacal-brine inlet flowrate disturbance, acting according to the scenario presented in the top graph of Figure 5. It consists of the ammoniacal-brine inlet flowrate step increase of 1.85 m^3/h disturbance, introduced at moment t=1000s, followed by a flowrate ramp decrease of 2.5 [m^3/h / h] starting at moment t=12000s, down to the flowrate initial value of 24 [m^3/h]. The second test considers another typical disturbance consisting in a flowrate step decrease of the outlet flow of sodium bicarbonate of 11 m^3/h, introduced at time t=30000s (not shown in Figure 5).

Results presented in Figure 5 show the ability of the ratio control system to tightly keep the CO_2 controlled flowrates at the desired ratios and the other controlled variables at their setpoint/nominal values when influent ammoniacal brine flowrate changes. The ratio-control scheme discloses the same favourable control performance as it efficiently rejects the sodium bicarbonate flowrate disturbance.

CONCLUSIONS

Efficient and smooth operation of the carbonation column is essential for soda production. As three phase complex chemical heterogeneous processes compete for achieving the desired throughput and product specifications, appropriate control system is asked to meet the operation challenges. Two decentralized control system structures are proposed and tested. The first one, based on RGA matrix, recommends a new 5×5 manipulated to controlled variables pairing. The dynamic simulation results reveal advantages of the new control structure, compared to the traditional one, for the majority of the controlled variables and with slower response for sodium bicarbonate flowrate, but increased stability. The second control structure is designed to maintain the desired ratios between the inlet ammoniacal-brine flowrate and the inlet CO_2 flowrates. Tested in the presence of typical inlet ammoniacal-brine and extracted sodium bicarbonate flowrate disturbances, the proposed control structure demonstrates its success in promptly rejecting their undesired effects, while preserving the required flowrate ratios. The obtained results propose the investigated control structures as potential control system solutions for the industrial implementation.

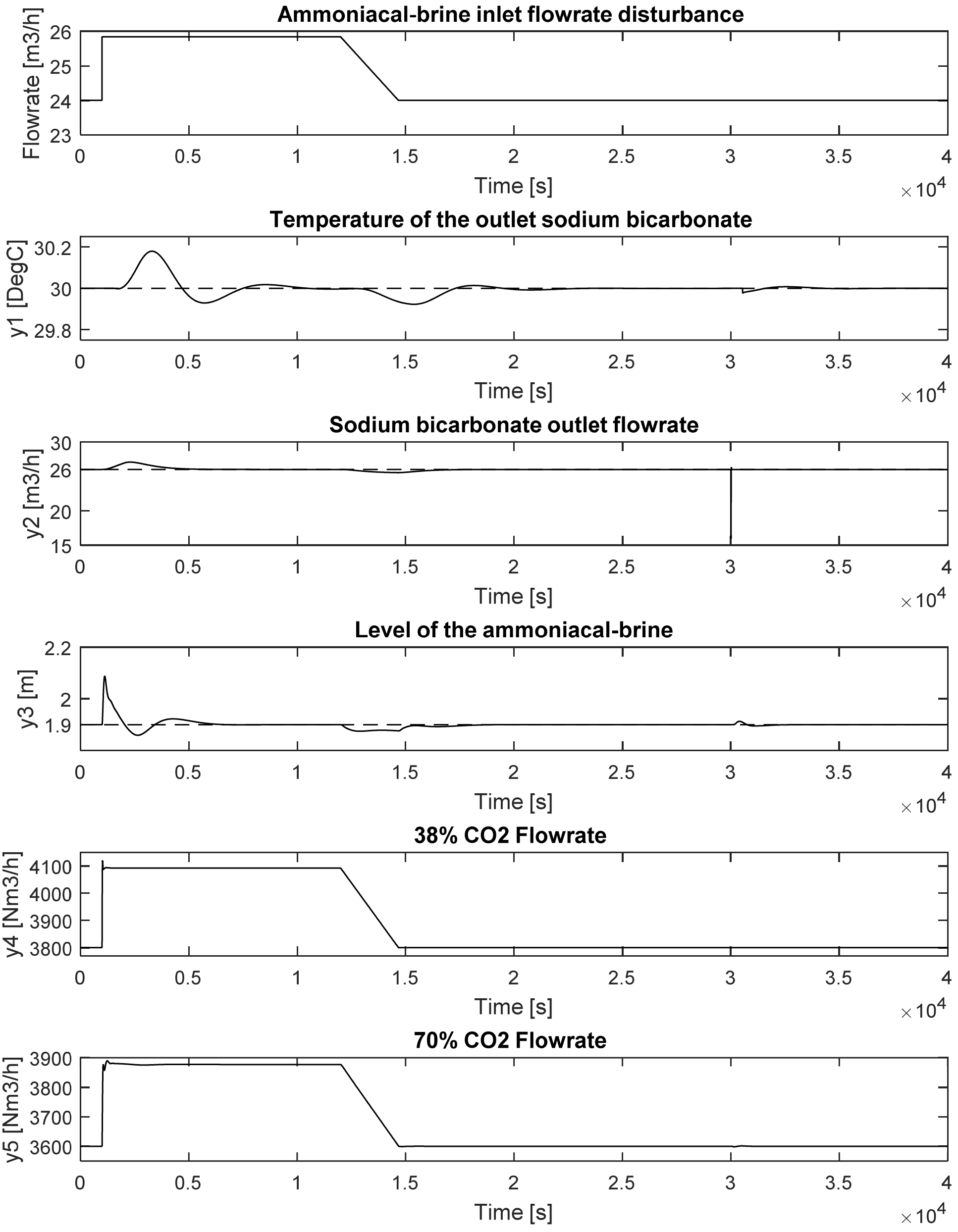

Figure 5. Disturbance rejection performance results of the ratio control system as response to the ammoniacal-brine flowrate increasing-step decreasing-ramp disturbance and to the sodium bicarbonate flowrate step-decreasing disturbance (plain line); setpoint/nominal values of the control loops (dashed line).

EXPERIMENTAL SECTION

The carbonation column dynamic model used in the present work has the transfer matrix form and was identified experimentally in [2, 4]. The PID/PI controllers have a parallel form and have been tuned by making a good balance between performance and robustness. Dynamic simulations were carried out in Matlab and Simulink® software environment.

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