

Modeling and Output Feedback Distributed Control for an Absorption Packed Column

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Abstract

This work consists of modeling, simulation and multiple models control of an industrial absorption packed column designated to remove CO₂, from natural gas. The multiple models approach is an elegant way of turning nonlinear problems into linear ones. In this paper, we used the output feedback distributed control (ODC) coupled with local linearization of the model of the absorption packed column. We compared the results with those obtained with the traditional PID control and the results were satisfactory.

Index terms— multiple models, PDC control, methyldiethanolamine (MDEA) absorption packed column, LMI, lyapunov function.

1 Introduction

he absorption packed column is a physicochemical separation unit largely used in the chemistry industry. It consists of a tube where we send gas mixtures in order to separate one or more compounds from the principal mixture. It is largely used for the separation of acid gases (CO₂, H₂S) from natural gas.

The model presented in this paper is a dynamic model of the absorption packed column and consists of a set of non linear partial differential equations; it is elaborated starting from considerations on CO₂ and MDEA mass balance in gas and liquid phases and considers also the energy balance [2]. We finally obtain a non linear distributed parameters system.

Few studies were carried out on modelling and controlling the absorption column. Crosby and Durbin [3] studied the performance of a state controller. Roffel [4] developed a sub-optimal output controller with state inequality constraint. Darwish and Fantin [5] used a decentralized control with pole placement. Petrovsky [6] developed a multivariable PI regulator. Najim [7] developed a self-adjusting regulator in the case of CO₂ absorption by a diethanolamine solution and also multilevel learning control [8]. It took again the problem later on with predictive control [9].

Few studies have also been published concerning the modelling and simulation of CO₂ absorption by aqueous solutions of MEA or MDEA on pilot and industrial columns [10][11][12].

For the model developed in our study, it seemed interesting for us to use the multiple models approach for the control of the absorption packed column because it enables us to obtain good performances for complex dynamics processes. We develop in first stage the PID regulation to compare the performances of the classical techniques with the performances of the Takagi-Sugeno multiple model approach.

2 II.

Modeling and Open Loop Simulation of the Industrial Absorption Packed Column

The absorption packed column presented here is located at Khrechba and is part of the In Salah Gaz project [17], it removes CO₂ from natural gas by using an aqueous solution of methyldiethanolamine (MDEA) as a washing liquid, It is a packed type column measuring 8 meter height and 4 meter in diameter with Pall rings to improve the surface of contact between phases. For a better elimination of CO₂ from the natural gas, the liquid

5 PID REGULATION OF THE INDUSTRIAL ABSORPTION PACKED COLUMN

flow (water+ MDEA) is counter-current with gas flow. The working pressure and temperature are respectively 71.5 bar at 55°C [2].

At contact between liquid and gas phase occurs on the surface of the Pall rings, CO₂ passes from the gas phase to the liquid phase; this diffusion is accelerated by chemical reaction of CO₂ with the MDEA in the liquid phase. The liquid flow (water+ MDEA) and the CO₂ concentration in the gas mixture are respectively selected as control variable and output variable. In order to simplify the model, the following assumptions are done [2,13]:

- ? There is no resistance in gas phase
 - ? The reaction between CO₂ and MDEA is fast ($Ha > 5$)
 - ? Axial dispersion is negligible in the gas phase and the liquid phase
 - ? The MDEA does not pass in gas phase
- The mass balance on an elementary section dz of the column for CO₂ in the gas phase is written [2,13,14]:
- Quantity of aqueous solution at input Z = quantity of aqueous solution at the output $(z+dz)$ + quantity of aqueous solution transferred from the liquid phase to the gas phase + accumulation.

3 Which gives:

$$dz \frac{dC_S}{dt} = G \frac{dC_G}{dz} - C_A \frac{dC_G}{dz} + r_A \quad (1)$$

Where G (m³/s) is the volumetric gas flow, r_A the CO₂ flow transferred from the gas phase to the liquid phase, S the section of the column and C_A (mol/m³) the CO₂ concentration in the gas phase. Given $U = G/S$ (m/s) the gas flow velocity, we obtain then: $dt \frac{dC}{dz} = U \frac{dC}{dz} - C_A \frac{dC}{dz} + r_A \quad (2)$

The chemical reaction between CO₂ and the MDEA is [10][11][12]: $CO_2 + MDEA \rightleftharpoons HCO_3^- + MDEA^+ \quad (3)$

The reaction rate r_A has the following form [14,15]: $r_A = k_f C_A C_B - k_r C_C \quad (4)$

Where k is the constant for reaction rate [14,15]: $k_f = 2,9610 \cdot 10^5 \exp(-5332.8/T) \quad (5)$

C_A is the CO₂ concentration in the liquid phase and C_B the MDEA concentration in the liquid phase. The mass balance for CO₂ in the liquid phase gives finally: $U \frac{dC}{dz} = C_A \frac{dC}{dz} - k_f C_A C_B + k_r C_C \quad (6)$

Which means that the totality of CO₂ transferred to the liquid phase reacts with the MDEA.

The mass balance for the MDEA in the liquid phase gives: $dz \frac{dC_S}{dt} = S \frac{dC_S}{dz} - C_C \frac{dC_S}{dz} + C_L \frac{dC_S}{dz} - C_B \frac{dC_S}{dz} + r_B \quad (7)$

Where L is the volumetric liquid flow. By taking account of (5) and noting by $U_L = L/S$ (m/s) the mean liquid flow velocity, we obtain: $dt \frac{dC_S}{dz} = U_L \frac{dC_S}{dz} - C_C \frac{dC_S}{dz} + C_L \frac{dC_S}{dz} - C_B \frac{dC_S}{dz} + r_B \quad (8)$

Our absorption packed column is finally described by the following set of partial derivative equations: $\frac{dC_G}{dz} = U \frac{dC_G}{dz} - C_A \frac{dC_G}{dz} + r_A$ and $\frac{dC_S}{dz} = U_L \frac{dC_S}{dz} - C_C \frac{dC_S}{dz} + C_L \frac{dC_S}{dz} - C_B \frac{dC_S}{dz} + r_B \quad (9)$

The procedure to compute flow Q is given in [2] according to [14][15][16].

We have finally to consider the boundary conditions which for gas phase are the CO₂ concentration at the column bottom or input concentration C_{AGe} and for liquid phase the MDEA concentration at the column top or input concentration C_{BLe} . $C_{AGe} = C_{AGi}$ and $C_{BLe} = C_{BLe}$ (10)

Chemical reactions within the industrial column induces a strong heat emission and the appearance of a temperature gradient throughout the column; the temperature variation is approximately 5°C between the input and the output of the column, which leads us to establish an energy balance in order to describe the temperature changes which affects the various concentrations along the column [16]: $\frac{dT}{dz} = \frac{Q}{G C_p} \frac{dC_G}{dz} - \frac{Q}{L C_p} \frac{dC_S}{dz} + \frac{r_A \hat{H}}{G C_p} \quad (11)$

With: C_{ig} : concentration in gas phase at the interface (mol/m³) C_{il} : concentration in liquid phase at the interface (mol/m³) $c_{p,ig}$:

Specific heat in the gas phase at the interface (J/mol.K) $h_{g/l}$: coefficient of heat transfer (convection) (J/m².K.s) T_l : Liquid temperature (K) T_g : Gas temperature (K) \hat{H} : enthalpy of the reaction (J/mol) $c_{p,il}$: specific heat in the liquid phase at the interface (J/mol.K)

We finally take into account the boundary conditions for the temperature which are the temperatures for gas and the liquid at the column input. $T_{gz} = T_{gz}$ and $T_{lz} = T_{lz}$ (12) b) Model validation

A test was carried out on our industrial absorption column to compare the output CO₂ concentration given by the model with the real one and this for a step input variation of 10 t/h. the data were collected on a horizon of 6800 seconds. The results are grouped in figure 2 where we represent respectively, the flows of MDEA and gas at the output and then the concentrations of CO₂ at the column output either experimental or given by the model [2]. Simulations show that the system is stable. It presents a dead time in response to a step input disturbance on the CO₂ concentration due to the gas propagation along the absorption column.

4 III.

5 Pid Regulation of the Industrial Absorption Packed Column

We apply a PID regulation to the dynamic model of our absorption packed column. We choose a sampled control with a sampling period of 10 seconds. The reference for the input CO₂ concentration is 0.25mole %, which corresponds to a concentration of The simulation results are satisfactory; the PID regulator cancels

103 the permanent error and ensures a quick response due to the derivative action. The regulation shows a net
 104 asymmetrical behaviour between responses to positive and negative step input disturbances due to the strong
 105 non linearity of the relationship between the input and the output IV.

106 6 Multiple Models Control of the Industrial Absorption Packed 107 Column a) Introduction

108 The multiple models is a non linear modeling technique which allows to achieve a good compromise between
 109 precision and model complexity. In the light of the numerous work related to it in recent years [18], [19], [20],
 110 it arises a great interest, especially in applications dealing with simulation and control. It can also be seen as
 111 a particular fuzzy modeling technique [21], [22], corresponding to a Takagi Sugeno (TS) approach [23]. A TS
 112 model is a composed of a finite number of linear models connected with non linear functions called membership
 113 functions and verifying the convex mapping property (i.e. they are non negative and their sum is equal to 1).
 114 It allows us to solve various problems of control, observation and diagnosis for non linear systems with linear
 115 techniques.

116 The approach associated with multiple models in control is known as the Parallel Distributed Compensation
 117 (PDC) [24]. This method is based on a set of linear controllers designed for each linear model, and stability of
 118 the overall closed loop is guaranteed via a Lyapunov function common to all the linear models.

119 In this paper, we identify the absorption packed column as a multiple model of the TS type and proposes a
 120 control based on Output feedback Distributed Control (ODC).

121 7 b) Problem formulation i. The Multiple model approach

122 The multiple models have three basic structures: Coupled states (TS), uncoupled states [25] and hierarchical
 123 structure. The coupled states Structure (TS) is the most popular in the analysis and synthesis of the multiple
 124 models. It is written in the following form: $\dot{x}(t) = A(x) x(t) + B(x) u(t)$ $y(t) = C(x) x(t)$

125 $A(x) = \sum_{i=1}^r \mu_i(x) A_i$ $B(x) = \sum_{i=1}^r \mu_i(x) B_i$ $C(x) = \sum_{i=1}^r \mu_i(x) C_i$ $\mu_i(x) \geq 0$ $\sum_{i=1}^r \mu_i(x) = 1$ (13)
 126 $x(t)$ being the state vector, $u(t)$ the input vector, $y(t)$ the output vector
 127 R is the decision variable or premises and the matrices A_i B_i C_i $\times \mu_i$, μ_i $\times \mu_i$, $\mu_i \times \mu_i$, $\mu_i \times \mu_i$
 128 $\mu_i \times \mu_i$ $\mu_i = 1$, μ_i . . . , μ_i are constant and supposed to be known.

129 The activation function or membership function $\mu_i(x)$ determines the degree of activation of the i
 130 th local model. It allows a progressive passage from this model to the other close local models. These functions
 131 can depend of the measurable variables of the system (the input and output signals) or of the non measurable
 132 variables of the system (the states). They can be of triangular or Gaussian form and satisfy the properties of
 133 convex mapping: $\mu_i(x) = \sum_{j=1}^r \mu_j(x) \mu_i(x) = 1$ $(\mu_i(x) + \mu_j(x)) \mu_i(x) = \mu_i(x) \mu_j(x)$
 134 $\mu_i(x) = 1$ $\mu_i(x) \mu_j(x)$ (14)

135 The multiple models can be viewed as universal approximators since any nonlinear system can be approximated
 136 by a multiple models representation with sufficient accuracy and this simply by increasing the number of sub-
 137 models. In practice, a reduced number of sub-models can be sufficient to obtain a satisfactory approximation,
 138 and we can use the tools of linear systems analysis to achieve this goal.

139 There are three approaches largely used in the literature allowing us to obtain a TS model: Identification,
 140 transformation by nonlinear sectors [26], or linearization. This last one is used in this work (figure ??).

141 Figure ?? : PDC control for TS multiple models Using convex analysis for regulator synthesis, the multiple
 142 models allows us to obtain control laws by the simultaneous resolution of a finite number of Linear Matrix
 143 Inequalities (LMI). In this case, the number of LMI inequalities is polynomial with respect to the number of local
 144 models. Thus, it is advisable to minimize the number of local models to limit the conservatism of the method.

145 In the case of TS multiple models, this technique of regulator synthesis corresponds to the PDC method,
 146 It supposes that all the linear sub-models are at least stabilizable. Subsequently, they will also be supposed
 147 controlled.

148 Given the TS model given by equation (13), a control law resulting from PDC synthesis will thus be the
 149 combination of linear control laws for each sub-model, given by: $u(t) = \sum_{i=1}^r \mu_i(x) u_i(t)$ $\mu_i(x) \geq 0$ $\sum_{i=1}^r \mu_i(x) = 1$ (14) Applying this control law to the TS multiple model, we obtain in closed loop: $\dot{x}(t) = \sum_{i=1}^r \mu_i(x) (A_i x(t) + B_i u_i(t))$
 150 $\mu_i(x) \geq 0$ $\sum_{i=1}^r \mu_i(x) = 1$ (15)

151 Or, in a more explicit way: $\dot{x}(t) = \sum_{i=1}^r \mu_i(x) (A_i x(t) + B_i u_i(t))$ $\mu_i(x) \geq 0$ $\sum_{i=1}^r \mu_i(x) = 1$ (16) The stability conditions for the closed loop system amounts
 152 to find a control gain F_j such that the derivative of the candidate Lyapunov function associated with the system
 153 is negative. Stabilizing the system thus amounts to solve the following problem: Find a positive definite matrix
 154 P and F_i matrices, $i=1, \dots, M$ such that:

155 $(A_i + B_i F_i) P + P (A_i + B_i F_i)^T < 0$ (17) We notice that this inequality is non
 156 linear with respect to P and F_i . By using the congruence of the symmetrical full row matrix: $\mu_i(x) = 1$ (18)

157 We get: $\mu_i(x) (A_i + B_i F_i) P + P (A_i + B_i F_i)^T \mu_i(x) < 0$ (19)

158 By using the bijective variable change $X = \mu_i(x) x(t)$, $\mu_i(x) = 1$, $\mu_i(x)$, (20)

159 The problem becomes LMI in variables X and M_i . $\mu_i(x) (A_i + B_i F_i) P + P (A_i + B_i F_i)^T \mu_i(x) < 0$ (21)

163 We finally get: $\sum_{i=1}^M \mu_i(x) = 1$ (22)

164 And we can express the following result:

165 Theorem 4.1 [24] Given a continuous TS model, the PDC control law (14) and the μ_{ij} , if it exists a positive

166 definite matrix X and M_i matrices, such that (21) is satisfied for all $i, j=1, \dots, M$, then the closed loop is overall

167 asymptotically stable. Moreover, if the problem has a solution, the gains of the PDC control are given by: $K_i = -X^{-1} M_i^{-1} B_i^{-1} A_i$ (23)

168 = $X^{-1} M_i^{-1} B_i^{-1} A_i$ (23)

169 And the PDC control is: $u = -\sum_{i=1}^M \mu_i(x) K_i x$ (24)

170 If $\mu_i(x) = 1$, $\mu_j(x) = 0$, then we define a linear control law. In practice, to determine the matrix P and

171 the control gain F_i , we have to solve (21) for all $i, j=1, \dots, M$. In the particular case where the multiple models

172 verify the positive co linearity of the input matrices, this: $\sum_{i=1}^M \mu_i(x) B_i = B$ (25)

173 The closed loop multiple models system of (26) is rewritten without the crossing terms $B_i F_j$: $\dot{x} = \sum_{i=1}^M \mu_i(x) (A_i - B_i F_i) x$ (26)

174 $\dot{x} = \sum_{i=1}^M \mu_i(x) (A_i - B_i F_i) x$ (26)

175 The stability conditions of theorem 4.1 reduce then to the stability of the dominant models: $P > 0, (P A_i - B_i F_i)^T + (P A_i - B_i F_i) < 0, \mu_i(x) = 1, \mu_j(x) = 0$ (27)

176 $\dot{x} = \sum_{i=1}^M \mu_i(x) (A_i - B_i F_i) x$ (27)

177 Substituting B_i by B , the control law leads to similar conditions. Year 2014 c) Multiple models identification

178 The structural identification of a multiple models representation consists in the determination of the local

179 models structures and the operation zones (or validity zones) for each local model [25]. The local models can be

180 of various structures but in general we use simple structures, such as linear models.

181 The identification leads to a family of functions parameterized by the parameters vector θ_i defining the

182 structure of the i th local model, and the parameters vector ϕ_i characterizing the zone of validity of this local

183 model. The parametric estimate consists in determining for each local model i the parameters vector: θ_i, ϕ_i

184 θ_i, ϕ_i

185 The parametric estimation (also called training) is done on the basis of minimization of a functional binding

186 the inputs and outputs system to the characteristics parameters of the model: $J = \sum_{k=1}^N (y_k - \hat{y}_k)^2$ (28)

187 $J = \sum_{k=1}^N (y_k - \hat{y}_k)^2$ (28)

188 $J = \sum_{k=1}^N (y_k - \hat{y}_k)^2$ (28)

189 In order to simplify the model, we choose linear sub-models of ARX type (auto regressive with exogenous

190 inputs) with 3 inputs (system MISO): Liquid Flow U_l [ton/h] ? Gaz flow U_g [ton/h] ? Input CO_2 concentration

191 C_{ge} [mol%]

192 The chosen local models are second order ones, they are written in the following form: The decision variable

193 $z(t)$ is in our case the state vector $x(t)$ output gas concentration of the industrial column C_{gs} , $\dot{z}(t) = A z(t) + B u(t)$ (29)

194 $\dot{z}(t) = A z(t) + B u(t)$ (29)

195 A multiple models with four sub-models can easily be obtained

196 in the form: $\dot{z}(t) = \sum_{i=1}^4 \mu_i(x) (A_i z(t) + B_i u(t))$ (29)

197 $\dot{z}(t) = \sum_{i=1}^4 \mu_i(x) (A_i z(t) + B_i u(t))$ (29)

198 With the memberships functions $\mu_i(x(t))$ either triangular or Gaussian. The parameters of the four models

199 are: $\mu_i(x) = 1$ if x is in the zone of validity of the i th model, otherwise $\mu_i(x) = 0$.

200 8 Discussions

201 The oscillations of the output CO_2 concentration for the industrial column are mainly due to fuzzy control, but

202 the operating point of is quickly reached in less than 50 seconds . We note on all the curves 5, 6 and 11-16)

203 that disturbance is always rejected with both PID and ODC regulation. But comparison of the peak values as

204 well as the oscillations show us that ODC control acts more quickly than PID control.

205 9 VI.

206 10 Conclusion

207 In this paper, a TS multiple models obtained by linearization was used for the regulation of an industrial

208 absorption packed column used for gas washing. We take a reduced number of submodels, four, to ease

209 identification. The results obtained with output distributed feedback (ODC) are better than those by classical

210 PID regulation, for a method which is not significantly complicated. Further investigations will be undertaken

211 in the use of multiple models in control, multiple observers and multiple models in systems diagnosis. ^{1 2}

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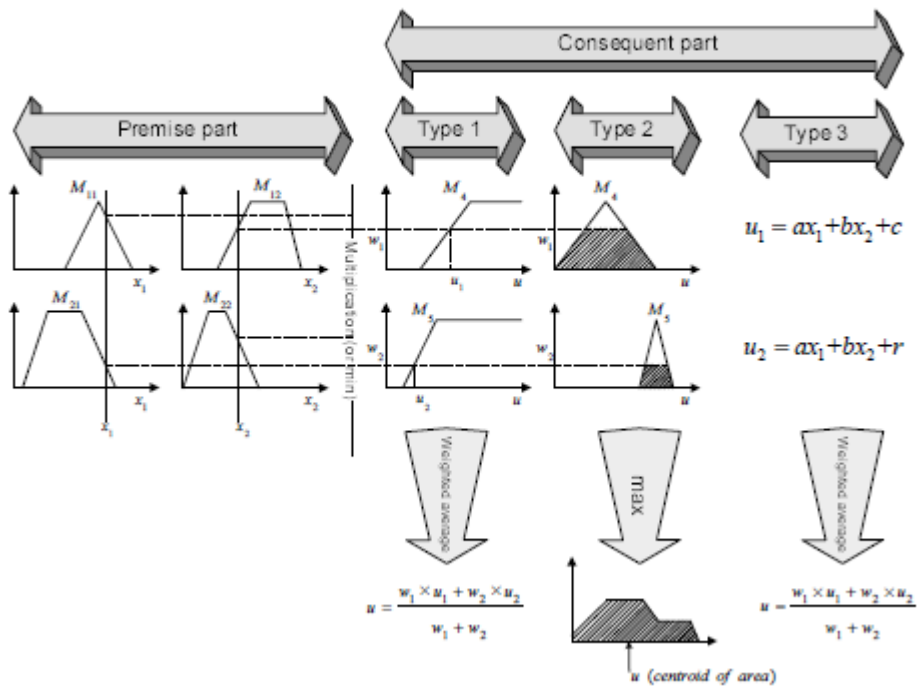
²Year 2014



Figure 1: Figure 1 :

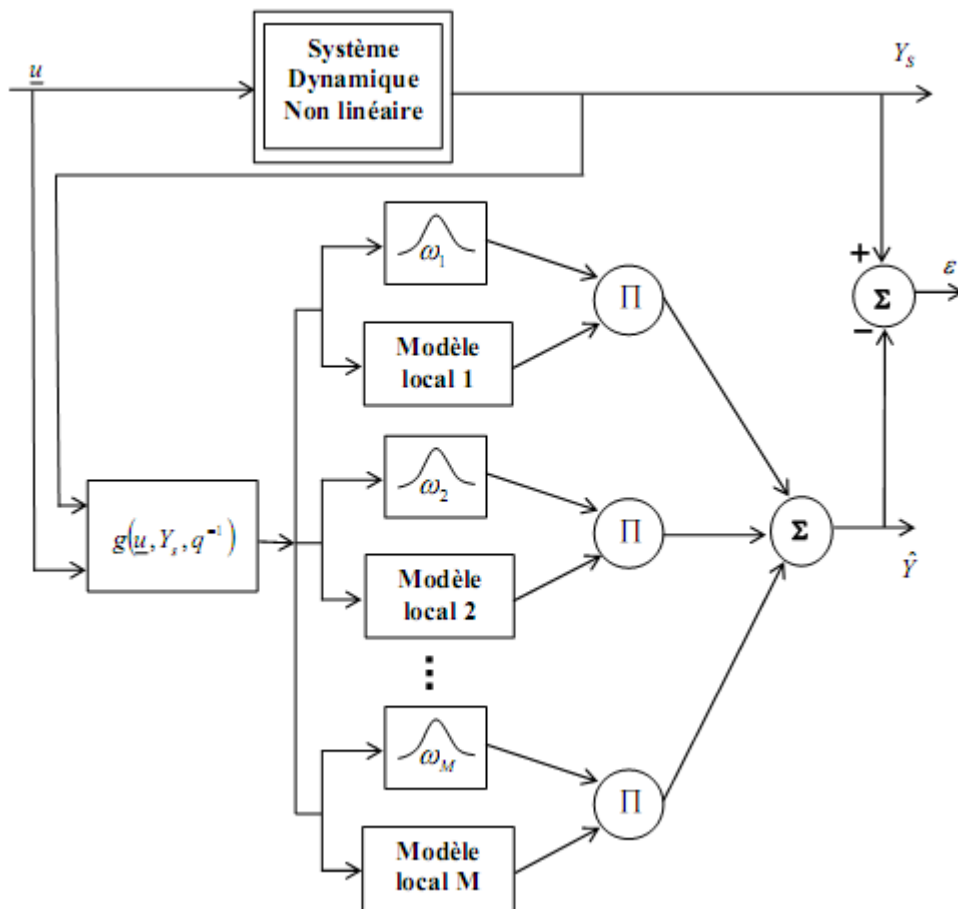


Figure 2: Figure 2 :



34

Figure 3: Figure 3 :Figure 4 :



56

Figure 4: Figure. 5 :Figure 6 :

- 212 [05 mole CO₂ /m³ .The parameters of the PID regulator were optimized using trial and error] 05 mole CO₂
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10 CONCLUSION

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