TWO-LAYER REAL TIME OPTIMIZATION OF THE DRYING OF PASTES IN A SPOUTED BED: EXPERIMENTAL IMPLEMENTATION

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Abstract: This paper presents an experimental implementation of a real time optimization strategy applied to a spouted bed dryer where a paste of homogenized chicken eggs is drying. The regulatory and economical optimization problems are solved by a QP (Quadratic Programming) algorithm at the same frequency and in two steps (two-layer structure). The economical objective function was a quadratic function based on the energy supplied to an air heater. The best operational conditions are found and the use of energy is minimized. Future stationary outputs and stationary control actions are calculated from the inverse of the process gain matrix based on predictions upon a constraint QDMC (Quadratic Dynamic Matrix Control). The regulatory objective is to maintain the exit temperature of the spouted bed and the difference between outlet and inlet air humidity under control. The manipulated variables are the flow rate of paste and the power supplied to air heater. The algorithm was able to keep the controlled variables close to the best operational conditions. *Copyright © 2004 IFAC*

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1. INTRODUCTION

Nowadays, the large competitiveness has been forcing the companies more and more to reduce production costs. In this way, the control and optimization of industrial processes have been used to improve production of process units. Due to great relevance in the chemical industry, dryers have also been submitted to automatic control and optimization.

An interesting question concerning optimization and control is the following: which is the best form of interaction between the optimization layer and the regulatory control layer? Several forms of interaction exist:

- The optimization is performed off-line using a computer and the set points are implemented by the operator into the plant. Latour (1979) already said that this form of interaction does not use all the potential benefits of on-line, steady-state optimization. Open-loop operator control might achieve some fraction of automatic closed-loop optimization.
- The stationary optimization is performed on-line in a period of time longer than the sampling time of the regulatory actions.

- The optimization is performed in the optimization level, where optimal set points are calculated. These set points are then sent to an advanced control strategy (normally a predictive controller) located in the control level. The optimization and the control functions are executed with the same frequency (real time), however in a two-layer structure with strong interaction between them (Moro and Odloak, 1995).
- The optimization and the control problems are solved together in a one-layer structure. The economical optimization problem is directly included in the predictive controller (Yousfi and Tournier, 1991; Gouvêa and Odloak, 1998).

The last two interaction forms have become the most investigated Real Time Optimization (RTO) strategies nowadays. In the two-layer optimization structure proposed by Moro and Odloak (1995), the regulatory control layer is a conventional unconstrained multivariable Dynamic Matrix Control (DMC) and the optimization layer solves a Linear Programming (LP) problem based on the DMC formulation. The DMC defines the future (or predicted) steady-state of the process and the optimization layer includes all constraints of the process. Instabilities in the operation with such interaction form may occur if the process is disturbed at the same time the set points are changed, unless the tuning of the controller is made conservative (Gouvêa and Odloak, 1998).

In the beginning of the nineties, Yousfi and Tournier (1991) proposed a one-layer real time optimization structure using predictive control. A steady-state optimization is incorporated into a Model Predictive Control (MPC). To introduce the optimization into the regulatory control, the authors added an economical quadratic term to the objective function of the SMOC (Shell Multivariable Optimizing Control). Due to the linear nature of the economical problems (linear model and linear objective functions) considered by the authors, this approach is normally not suitable since most of the *real* problems are non-linear. Odloak and Gouvêa (1996) have considered a similar approach but they used a linearization of the economical objective function. This approximation in the DMC controller may make the closed-loop system unstable. However, according to Gouvêa and Odloak (1998), these approaches have the advantage of being tuned easily. The inclusion of an economical non-linear optimization problem directly into the DMC was implemented by Gouvêa and Odloak (1998) in a FCC (Fluid Catalytic Cracking) unit. A Non-Linear Programming (NLP) problem must be solved, which requires a robust and efficient solver that should guarantee the process under control. Several simulations were needed to select appropriate values

for the weighting matrices of the *predictive part* of the objective function. The authors compared the performance of the unit with the two-layer structure and with the one-layer structure. They observed that the one-layer structure presented a better performance.

Therefore, the objective of this paper is to present the results from experimental implementation of a real time optimization strategy applied to a spouted bed
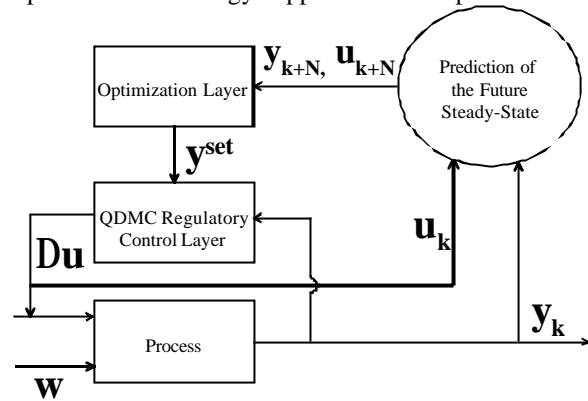

Fig. 1. Two-layer strategy.

dryer where a paste of homogenized chicken eggs is drying. Regulatory control and on-line search for optimum operational conditions are performed at the same frequency and in two steps (two-layer structure).

The main differences are: (1) future stationary outputs and stationary control actions have both a different formulation and they are calculated from the inverse of the process gain matrix based on predictions upon a constrained QDMC controller and (2) no constraints are imposed in predict outputs, but only in set points, so a convex problem may be generated, which can be solved with less sophisticated optimization algorithms. The two-layer strategy is sketched in Figure 1.

The two-layer optimization-control structure used in this paper was proposed by Schiavon Jr. (1998) and it follows the same idea of the proposed structure from Moro and Odloak (1995) with a few, but important modifications. The similarities among them are: (1) the optimization and regulatory control are performed in the same frequency and in two steps and (2) the future stationary outputs are predicted and supplied by a DMC controller.

2. FORMULATION OF THE STRATEGY

In this structure, at each sampling time, the regulatory control and search for optimum operational conditions are performed at the same frequency and in two layers with strong interaction between them.

The new values of the manipulated variables, $\mathbf{?}\,\mathbf{u}$, are supplied by the QDMC structure calculated from the following objective function

$$\min \Omega(\Delta\mathbf{u}) = (-\mathbf{A}\cdot\Delta\mathbf{u} + \mathbf{E}')^T \mathbf{Q}^T \mathbf{Q}(-\mathbf{A}\cdot\Delta\mathbf{u} + \mathbf{E}') + \Delta\mathbf{u}^T \mathbf{R}\Delta u \quad (1)$$

subject to the inequality constraints

$$\Delta\mathbf{u}_{min} \le \Delta\mathbf{u} \le \Delta\mathbf{u}_{max} \quad (2)$$

$$\mathbf{u}_{min} \le \mathbf{u} \le \mathbf{u}_{max} \quad (3)$$

Only the first value of $\Delta\mathbf{u}$ calculated from equation (1) is implemented into the process and used to determine $\mathbf{P_N}$, which is required in the optimization layer. $\mathbf{P_N}$ represents the effect from all last control actions over the future stationary outputs.

Optimal set points are calculated from the following economical objective function

$$\Phi\left(\mathbf{y}_{k+N}, \mathbf{u}_{k+N}, \Delta\mathbf{y}^{set}\right) \quad (4)$$

subject to the equality constraints

$$\mathbf{y}_{k+N} = \mathbf{y}_k + \mathbf{P}_N + \Delta\mathbf{y}^{set} \quad (5)$$

$$\mathbf{u}_{k+N} = \mathbf{u}_k + \left(\frac{1}{\mathbf{A}_N}\right)\Delta\mathbf{y}^{set} \quad (6)$$

and also subject to the following inequality constraints

$$\Delta\mathbf{y}^{set}_{min} \le \Delta\mathbf{y}^{set} \le \Delta\mathbf{y}^{set}_{max} \quad (7)$$

$$\mathbf{y}^{set}_{min} \le \mathbf{y}^{set} \le \mathbf{y}^{set}_{max} \quad (8)$$

A convex problem is generated when the constraints are represented by equations (7) and (8). Observe that no constraints are imposed in predict outputs, but only in their set points. In this case the constraints do not change and the search domain will be always convex (there is not crossing of constraints which could eliminate the feasibility domain).

3. EXPERIMENTAL SET-UP

Figure 2 sketches the experimental set-up used in all control implementations presented here. The spouted bed was assembled with several peripheral devices (including instruments) and a computer control. A motor frequency (fr) is manipulated to start and keep the spout. This frequency is applied in the blower's motor, which changes its speed rotation and, consequently, the air flow rate, Q. A frequency inverter is used to this purpose. The air flow rate Q is measured by a double orifice plate connected to a pressure transducer.

The $Q-fr$ loop is closed using a PI (proportional-integral) controller to maintain Q on its track. The temperature T_s is measured by a J-type thermocouple. The production rate, Pr, is obtained by a semi-analytical balance through the computer serial port RS232C. Another transducer measures bed pressure drop, ΔP. Polymeric capacitive meters measure air humidity in the outlet (Y_s) and inlet (Y_e). A thyristor is employed to manipulate electrical power, POT. A diaphragm pump is used to regulate the feed flow rate of paste, F_e. All electrical signals, except for the balance and thermocouples, are of type 4-20mA standard protocol. These signals, including thermocouples, are sent to a Personal Computer through an AD/DA (analog/digital, digital/analog) interface.

The spouted bed is built in steel and it has a conical cylindrical geometry (diameter = 15cm, air feed hole diameter = 3.5cm, height = 67.5cm, load height = 23.5cm, load = 3600g of glass particles as inert). Warm air is supplied with a flow rate in the range of $0 - 2.0$ m^3/min.
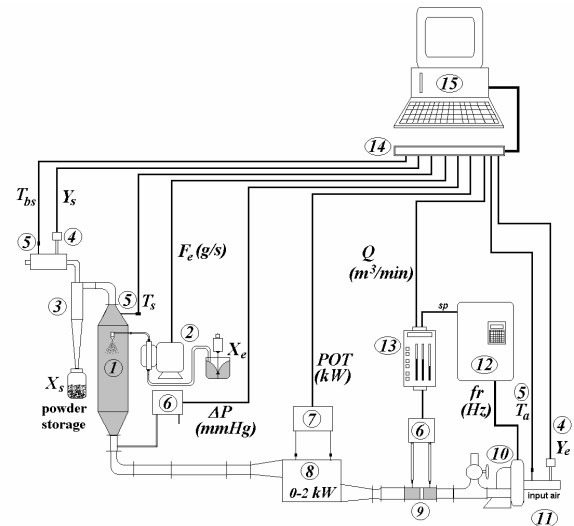

Fig. 2. Experimental system for the paste drying control in spouted bed. **1**- spouted bed; **2**- paste feed system; **3**- cyclone; **4**- air humidity sensor (capacitive); **5**- thermocouple (J type); **6**- pressure transducer; **7**- power module (thyristor); **8**- electrical heat exchanger; **9**- orifice plate flow meter; **10**- blower; **11**- psychrometer; **12**- frequency inverter; **13**- PI controller; **14**- signal conditioner; **15**- PC AT-486 with A/D-D/A interface.

The computer program for the experiments was written in C language and the sampling interval for acquisition and monitoring was 1s. The control algorithms were elaborated and tested in simulations using MATLAB® before being implemented in C.

The drying in the spouted bed was accomplished with the objective of obtaining powdered integral egg

with remaining moisture up to 5% in mass, under a temperature (at the bed exit) about $T_s \approx 70^o$ C.

It is possible to infer the product (powder) moisture contents (X_s) from measurements of T_s and $(Y_s - Y_e)$. This decision was made due to the high cost of an on-line humidity transducer for powders.

4. RESULTS FROM CLOSED-LOOP EXPERIMENTS

The control objective of the two-layer real time optimization strategy is to maintain under control the exit temperature of the spouted bed dryer, T_s, and the difference between inlet and outlet air humidity $(Y_s - Y_e)$. The manipulated variables are the feed flow rate of paste, F_e, and the electrical power supplied to heat the inlet air, POT.

The economical objective function considered was a quadratic function of the power supplied to an electrical heat exchanger. The real time optimization solution sought to find the best operational conditions while the consumption of energy in the heater is minimized. Both, regulatory and economical optimization problems were solved by a QP algorithm. The control algorithm was written with Microsoft Quick $C^®$ and it was implemented in a PC-type microcomputer.

First, a 2×2 transfer function matrix was identified as a first order with time delay model, equation (9), based on experimental input step responses of T_s and $(Y_s - Y_e)$, where time unit is given in minutes. Someone can argue that this is an inappropriate procedure nowadays. However, if you consider the difficulty of obtaining good models to predict the spouted bed behavior, the below proposed model, equation (9), seems to be fine.

$$\begin{bmatrix} T_s \\ (Y_s - Y_e) \end{bmatrix} = \begin{bmatrix} \dfrac{-76 \cdot e^{-0.8 \cdot s}}{19 \cdot s + 1} & \dfrac{23.34 \cdot e^{-2 \cdot s}}{14 \cdot s + 1} \\ \dfrac{0.0320 \cdot e^{-0.2 \cdot s}}{1 \cdot s + 1} & \dfrac{-0.0014 \cdot e^{-9 \cdot s}}{29 \cdot s + 1} \end{bmatrix} \cdot \begin{bmatrix} F_e \\ POT \end{bmatrix} \quad (9)$$

This model was used to calculate the convolution model (the dynamic matrix: $\mathbf{A}$) to perform the QDMC algorithm. Initial values of the QDMC parameters were estimated from simulation. Afterwards, the final values implemented were tuning from experimental tests. They are presented in Table 1. Two real time optimization tests were performed. In the first one (Figure 3), no disturbances were inputted in the process. In the second experimental test (Figure 4), some disturbances were accomplished in the feed flow rate of air (Q): one at $t = 0$ s and magnitude of +

5% and another at $t = 4700$ s and magnitude of - 5%. In all cases, constraints were considered in all the manipulated and the set points of controlled variables. Tables 2 and 3 presents the upper and lower values considered for all these variables.

The results from the first experiment, without disturbances, are showed in Figure 3. It displays that the real time optimization strategy was able to keep the controlled variables around the best operational conditions. The set points were gradually moved down to the lower bound constraints (Figures 3a e b). A decrease of the difference $(Y_s - Y_e)$ of the moisture contents, represents a low consumption of energy demanded by the system. Therefore, the values of the set points for this variable, $(Y_s - Y_e)^{set}$, were moved down in agreement with the economical objective, which indicates that the energy must be minimize (in fact POT^2 is minimized, Figure 3e). In the same way, a small value of temperature, T_s, suggested that a small amount of energy is also supplied to the system, minimizing POT^2 (Figure 3a).

Table 1 QDMC parameters

Parameters	Values	Parameters	Values
N	80	f	0.001
R	30	α	0
L	1	wpT_s	1
T	150	$wp(Y_s - Y_e)$	1000

Table 2 Bound constraints: first experiment

Process Variables	Steady-state	Upper Value	Lower Value
F_e (g/s)	0.25	0.35	0.15
POT (kW)	1.50	1.80	1.00
T_s^{set} (^{0}C)	66	68.5	63.5
$(Y_s - Y_e)^{set}$	0.0035	0.0045	0.0025

Table 3 Bound constraints: second experiment

Process Variables	Steady-state	Upper Value	Lower Value
F_e (g/s)	0.25	0.35	0.15
POT (kW)	1.50	1.80	1.00
T_s^{set} (^{0}C)	70	72.5	67.5
$(Y_s - Y_e)^{set}$	0.0035	0.0045	0.0025
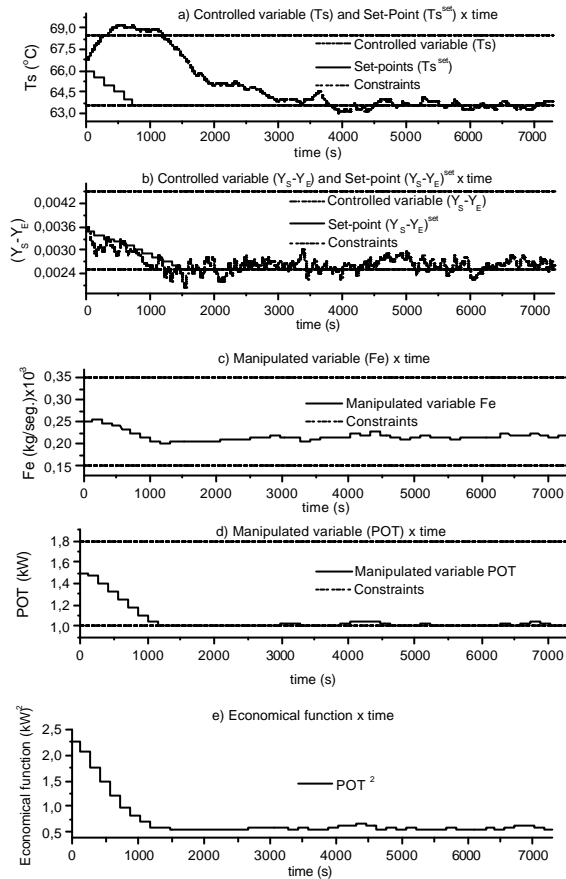
Fig. 3. Two-layer structure without disturbances; economical objective is $\phi = \text{minimize}\,(POT^2)$.

outputs. And no violations of the set points occurred during the experiments.

The second experiment, now with disturbances in air feed flow rate, Q, is presented in Figure 4. It displays that the real time optimization algorithm was able to lead the controlled variables to their set points, although oscillations have been observed in the difference $(Y_s - Y_e)$ of the moisture contents (Figure 4b). Those oscillations were caused by the initial disturbance in the air feed flow rate. Approximately after 3000 seconds, the control system was able to compensate the effect of the disturbance and, then, the oscillations were finally reduced.

As in the first experiment, sometimes the output variables exceeded their set point constraints. This behavior may be also caused by model uncertainties during the prediction of future stationary state values. However, and in a similar manner, no violations occurred on input constraints. Excess of cool air during the first part of this second experiment helped the control system to move the temperature, T_s (Figure 4a), into its set point, faster than in the first experiment (Figure 3a).

Observe that the set points for this variable, T_s^{set}, is also decreased to its lower bound constraint. In this current experiment, the control of the temperature depends mostly on POT, while the control of the difference $(Y_s - Y_e)$ of the moisture contents depends basically on the feed flow rate of paste. Because a low amount of paste fed into the system will require more heating, a decrease in the feed flow rate of paste is not the best choice to control the temperature, T_s. However, it is also necessary to control the difference of the moisture contents. Manipulation of the electrical power supplied to heat the inlet air, POT, will not be just enough to control $(Y_s - Y_e)$, which will demand an action of the feed flow rate of paste in this task.

Sometimes, the outputs variables did not track their set points accordingly. And they went beyond their desired values: the set point constraints (Figures 3a e b). However, no violations occurred on the inputs constraints (Figures 3c e d). This behavior of the output variables may be caused by uncertainties on the model used to predict the future stationary state, and not because of the real time optimization algorithm. Remember that, the optimization problem is subjected to constraints on set points and not on the
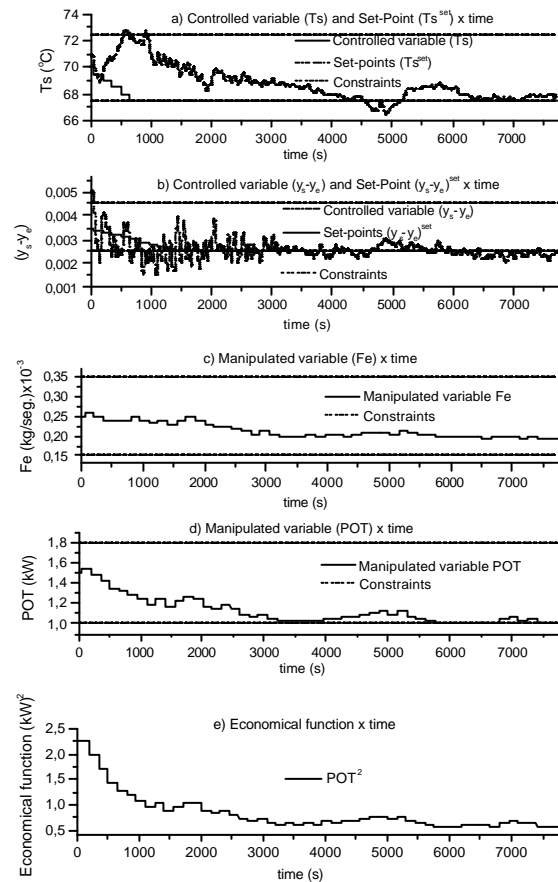

Fig. 4. Two-layer structure with disturbance in the air feed flow rate; economical objective is $\phi = \text{minimize}\,(POT^2)$.

5. CONCLUSIONS

A good control performance was obtained in the experimental implementation of the two-layer real time optimization strategy. The algorithm was able to keep the controlled variables around the best operational conditions and to compensate the disturbances in air feed flow rate accordingly. However, sometimes the output variables exceeded their set point constraints, whose behavior can be caused by the model used to predict the future stationary state and not by the proposed control algorithm. Remember that the predicted outputs are not under constraints.

ACKNOWLEDGMENT

GLOSSARY

$\mathbf{A}$	dynamic matrix	
$\mathbf{A_N}$	matrix of stationary gains	
$\mathbf{E'}$	predict error vector based on the current and future control actions in the QDMC	
F_e	mass feed flow rate of paste	g/s
f	suppression factor	
fr	motor frequency	Hz
L	control horizon	
N	model horizon	
$\mathbf{P_N}$	vector of the steady-state effect of all past control actions	
POT	electrical power supplied to inlet air	kW
Pr	production rate of dry powder	g/s
$\mathbf{Q}$	weighting matrix for the predict errors in the QDMC	
Q	volumetric feed flow rate of air	m^3/min
$\mathbf{R}$	weighted matrix for the control movements in the QDMC	
R	prediction horizon	
s	Laplace's domain variable	
T	sampling period	s
T_s	outlet air temperature	^oC
$\mathbf{u}$	manipulated variable	
$\mathbf{w}$	disturbance	
wp_{T_s}	weight of T_s on $\mathbf{Q}$	
$wp_{(Y_S-Y_E)}$	weight of ($Y_s - Y_e$) on $\mathbf{Q}$	
X_s	outlet dry powder humidity	
Y_e	inlet air humidity	
Y_s	outlet air humidity	
$\mathbf{y}$	controlled variable	

Greek Symbols

ΔP	bed pressure drop	mmHg
$\Delta\mathbf{u}$	control movement	
$\Delta\mathbf{y}$	changing in the controlled variable	
Ω	QDMC objective function	
Φ	economical objective function	

Subscripts

k	present time
k + N	future steady-state time
max	upper value
min	lower value

Superscripts

set	set point

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