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Benefits in using model based predictive control (MPC) during drying and lyophilisation

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Abstract

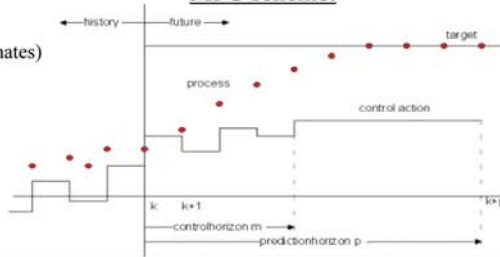
Model based predictive control (MPC) techniques may be used for drying and lyophilisation processes to improve their efficiency in term of production (like in other industrial application domains since 30 years). Indeed, drying is a highly energy operation and it represents from 10% to 25% of the national industrial energy, whereas a majority of industrial dryers operate at low energy efficiency: the ratio theoretical energy required for the drying to the actual energy consumed ranges from a disappointing 10% to 60%. Due to the energy costs and global competition, these performances have to be improved. This may be done using process control tools [1]. Since 1998, the yearly mean publication rate of papers using a first principle model for control in drying has been multiplied by 11 [1]! This increase is similar to the increase of control papers in drying based on optimal control strategies, like MPC.

Model predictive control (MPC) strategy

MPC strategy needs:

- 1: a control problem and, if needed, output constraints for the measures (or for the on-line estimates)
- 2: u : manipulated inputs=control actions
- 3: y_p : plant measures (or on-line estimates)
- 4: a dynamic model:
$$\begin{cases} \frac{dx_m}{dt} = f(x_m, u) \\ y_m = g(x_m) \end{cases}$$

MPC scheme:



MPC algorithm:

- At each current sampling time k , do:
- update the plant measurements for use in the control loop;
 - use the plant model to predict in the future the process response to a hypothetical set of future control actions sequence;
 - solve the constrained optimization problem, including the cost of future control actions and the cost of future deviations from a reference behavior, to give the optimal future control actions sequence;
 - apply the first movement of the optimal control sequence on the process.
- These operations are repeated at next time $k+1$.

MPC@CB software features

The development of the MPC@CB software [2] with Matlab [3] started in 2007. It allows realizing the MPC of a process under constraints (due to safety, operations, ...). The originality of these codes is first the ease of their use for any process modeled, through the user files that are synchronized by few main standards files (where the user has to make few (or no) changes). MPC@CB helps the user to solve any of his control problems by various tuning and choices:

- The user defined model may be linear or nonlinear, time variant or time invariant, based on ordinary differential equations (ODE) and/or on partial differential equations (PDE).
- MPC for a user defined cost function (trajectory tracking, processing time minimization...), with or without user defined output constraints,
- Closed loop control with PID in order to compare control performances with the MPC,
- A software sensor (observer) can be introduced,
- Do open or closed loop control,
- Simulation or real time application.

Until now, MPC@CB has been used on several processes: a pasta drying process [4], a lyophilisation process [5], a painting film curing process [6], a polymerisation process [7].

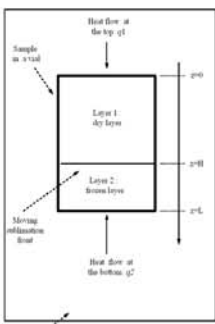
MPC@CB application example: lyophilisation process

This strategy needs:

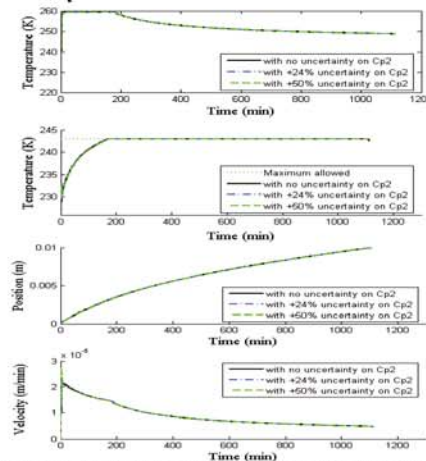
- 1: control problem: minimize the processing time (sublimation time) while keeping the temperature below a prescribed value of 243K (for product quality), in spite of uncertainty in the heat capacity of the frozen layer $Cp2$ [8]
- 2: control action: temperature in the chamber
- 3: plant measures: the temperature at the bottom of the vial and the sublimation front position (assumed estimated [9])
- 4: non-linear PDE model [5] for the temperature profile inside the frozen and dried layer, the sublimation front position, and the concentration of bound water

Results:

In spite of a large uncertainty of the value of the heat capacity in the frozen layer, MPC@CB allows decreasing the sublimation time, while keeping the measured temperature below a prescribed value. Compared to the 3 scenario in open loop, the sublimation time with closed loop MPC is minimized and has a lower variability (0.2% vs up to 7.5%): a real repeatability of the runs is possible, even with parameter uncertainty.



A schematic of the freeze drying process during the primary drying stage.



$Cp2$ uncertainty (%)	Time with open loop constant control (h,min)	Time with closed loop MPC@CB (h,min)
0	21h18	18h29
24	20h32	18h30
50	19h42	18h31

Comparison of the sublimation time between open loop and closed loop with MPC@CB; for various uncertainties in the heat capacity of the frozen layer.

From top to bottom: temperatures in the chamber and at the bottom of the vial, sublimation front position and velocity, all vs time; for various uncertainties in $Cp2$, with MPC@CB.

Conclusion

With 60 000 products dried and 100 dryer types used worldwide, a real potential exists with control tools like MPC: it is expected that the industrial drying operations will continue to improve their energy efficiency while enhancing product quality and reducing the negative environmental impact of dryers. Here, it was shown how a MPC is able to decrease the sublimation time while keeping the prescribed product properties defined by constraints. In spite of a large model parameter uncertainty in the heat capacity of the frozen layer, MPC@CB allows decreasing the variability of the sublimation time by a factor 35 (compared with open loop control), hence helping in the repeatability of different runs.

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