Model-based Optimal Control of Industrial Batch Crystallizers

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A substantial amount of materials in the pharmaceutical, food, and fine chemical industry is produced in crystalline form. Batch crystallization is a key separation and purification unit in such industries, with a significant impact on the efficiency and profitability of the overall process. Improved control of such processes offers many possibilities to achieve the stringent requirements of the final product quality, namely crystal size, purity and morphology, and also enhance the process efficiency.

The control of batch crystallization processes is traditionally done by tracking predetermined batch recipes using PID controllers. As the recipes are largely based on operator's experience, they often lack the ability to systematically push the process to its most optimal operating regime while various operational and quality limitations are met.

In the recent years, the development of computationally powerful modeling and optimization tools has considerably facilitated the use of first principle models in devising optimal batch recipes. Current practice of this off-line optimization approach can however be rather ineffective as plant-model mismatches and process disturbances often deteriorate the effectiveness of the off-line optimized operating policies. A remedy for the latter deficiency is real-time optimal control of the batch process based on the feedback of system states that are estimated by an observer, i.e. soft sensor, using the process model and the available in-situ process measurements. The real-time optimal control approach continuously optimizes the system based on its current status and, therefore, drives the process to its most optimal operation at any time during the batch.

In this work, an industrial model-based control framework has been developed for the optimal operation of batch crystallization processes. The control philosophy is founded on the basis that the batch crystallization process should be optimally operated within the metastable zone such that a trade-off is being made between the production capacity and the product quality. To realize this goal, the control architecture utilizes either a Model Predictive Controller (MPC) or a dynamic optimizer for on-line computation of the optimal input profiles, in addition to an observer (Extended Kalman Filter / Extended Luenberger-type observer). The observer is utilized to keep the process model aligned with the real process and also estimate the unmeasured process variable, namely crystal growth rate. The crystal growth rate is a key parameter in the crystallization process as it is closely related to the product quality. All the components in the control architecture are based on a non-linear moment model.

The model predictive controller and the dynamic optimizer have been applied to crystallization of ammonium sulphate in a 75 liter draft tube evaporative crystallizer. The model predictive controller has also been tested on an industrial 14 m^3 forced circulation evaporative crystallizer of Lactitol Monohydrate. In both cases, the optimal operation is realized by manipulation of the supersaturation level in the crystallizer such that a maximum growth rate is maintained in the course of the process to avoid product quality degradation stemmed from irregular crystal growth.

The real-time implementation of the proposed strategy on both crystallization processes leads to substantial increase of productivity, i.e. more than 10%, which translates to higher production capacity due to shortening of the batch time. Besides preservation of the product quality owing to the tight crystal growth control throughout the batch, the model-based control strategy also facilitates the control of the process to its equilibrium conditions at the batch end. Automatic process stabilization, which is a prerequisite for the industrial applicability of a control strategy, cannot be achieved solely by supersaturation control in evaporative and anti-solvent crystallization.