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Insights into Design Criteria for a Continuous Sonicated Modular Tubular Cooling Crystallizer

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ABSTRACT: A new designed sonicated continuous modular crystallizer was investigated and developed. The concept and design criteria for the designed crystallizer were examined and studied in cooling crystallization process with three model compounds which were K₂SO₄, CuSO₄ and phthalic acid. Results showed that ultrasound had significant effects, which can enhance the nucleation and avoid clogging in the tubular crystallizer. The present work shows the obtained results when different cooling strategies were studied. Equal supersaturation throughout the crystallization process was the best solution for designing temperature profiles for the modules. In addition to cooling strategy, the residence time is one of the key factors to get feasible operating conditions in the designed crystallizer. Higher yields using ultrasound with phthalic acid crystallization as a model compound were obtained compared to classical tubular flow reactor.
1. INTRODUCTION

When compared with batch or semi-batch crystallization process modes, continuous crystallization has many advantages such as smaller volumes required, higher efficiency, higher product reproducibility, less cost of labor and operation, and higher flexibility.\textsuperscript{1,2} All of these are considerably important for obtaining reproducible and narrow crystal size distributions, uniform particles and specific crystal morphologies. Various designs of continuous pipe crystallizers are nowadays getting much more popular than the mixed-suspension mixed-product-removal crystallizers because crystal classification effects can be minimized in the tubular reactor. Additionally, the scale up is much easier with continuous plug flow crystallizer. However, Hohmann et al.\textsuperscript{3} have pointed out the problematics of clogging and pipe blocking which can be minimized using seed generating systems.

One of the most popular continuous tubular flow crystallizer is the continuous oscillatory baffled crystallizer (COBC).\textsuperscript{2,4} Uniform products can be achieved with plug flow by proper control of nucleation and crystal growth rate. With the control of frequency and amplitude of the oscillation, particle fluidization and a narrow residence time distribution can be achieved due to intensive macro-structure tubular mixing. Meanwhile, the particle size is affected by the set-up and operational conditions.

NiTech\textsuperscript{®} Solutions Limited\textsuperscript{5} developed these kinds of crystallizers with different size suitable for various application such as chemical synthesis and crystallization. Kacker et al.\textsuperscript{6} investigated residence time distribution of dispersed liquid and solid phase in a commercial COBC from NiTech Solutions\textsuperscript{®} and pointed out that operation at relative low amplitudes leads to optimal plug flow behavior.

To overcome the challenge of curve cooling in plug flow crystallization, Hohmann et al.\textsuperscript{3} designed a continuous cooling crystallization on lab scale by applying the concept of a coiled flow inverter (CFI) based on blended helically coiled tubes. Linear cooling or curve cooling employed with counter-current
air cooling can be operated with this device. Recently, Hohmann et al.\textsuperscript{7} also analyzed the effect of crystal size dispersion in the designed tubular crystallizer by experiments and modeling and found that crystal growth and growth rate dispersion were both dominating the product size distribution. A narrow product size distribution can be obtained and revealed by simulation when using CFI crystallizer in homogeneous suspension flow regime. Small volume mean diameters due to decreased tendency of agglomeration and reduced time for crystal growth can be obtained at higher flow velocities\textsuperscript{8}. On the other hand, a clear fact is that crystal size decreases as sonication time increases.\textsuperscript{9} In ultrasound assisted continuous tubular reactors sonication is manipulated by changing residence time.

Ultrasound has been used in many areas including medical diagnostics, thermoplastic welding, cleaning of surfaces, wastewater treatment and food industry.\textsuperscript{10} It has also been employed in new fields such as preparation of amorphous and nanostructured materials.\textsuperscript{11,12} Recently, the use of sonocrystallization, that is crystallization assisted by ultrasound, in pharmaceutical and fine chemical industry has attracted more interest of researchers because of the viability of this technology. In addition, Zhang et al.\textsuperscript{13} had earlier reviewed the progress of continuous crystallization in pharmaceuticals. Sonocrystallization is considered as an easy to use and easy to control technique, and the end product with target crystal size, shape and polymorphs can be obtained.\textsuperscript{14} That is because the metastable zone width (MZW) can be narrowed by introducing ultrasound, and ultrasound can disrupt the formed crystal aggregates.\textsuperscript{1} Furthermore, the effects of ultrasound on crystal growth was theoretically studied in literature\textsuperscript{15} and was pointed out that the growth rate depends on the magnitude of the supersaturation driving force. Arakelyan\textsuperscript{15} also highlighted that the crystal growth rate can be doubled at low supersaturation by ultrasound, whereas there is no remarkable effect at high supersaturation. Induction time can also be affected by ultrasound, as induction time decreases with increase in ultrasound power.\textsuperscript{16} Besides these, the use of ultrasound can not only reduce the crystallization time but can also offer a clean and efficient tool to improve the existing process.
Some studies have demonstrated that the use of ultrasound can drastically reduce fouling in microchannel heat exchangers because of flow changes of the particle suspensions.\textsuperscript{17-20} As proposed by Rossi et al.,\textsuperscript{19} transient cavitation of bubbles induced by sonication played a significant role for promoting nucleation with observations from the experiments and numerical simulations. Recently, a sonicated tubular crystallization system, to control particle size without clogging, was successfully designed and specified for an active pharmaceutical ingredient (API) compound.\textsuperscript{21} In addition, a crystallizer cascade can offer economic advantages over a single-body crystallizer of the same volume.\textsuperscript{22} Several continuous MSMPR multistage cooling crystallizers have been reported in literature.\textsuperscript{23-25} Furthermore, Siddique et al.\textsuperscript{26} successfully applied sonication to initialize crystallization in COBC without fouling or agglomeration issues for lactose. However, the yield was relatively low compared to when operated with a sonicated batch crystallizer due to insufficient seeds produced by limited ultrasound power. Continuous sonocrystallization of acetylsalicylic acid in a tubular crystallizer with multiple cooling sections has been investigated in literatures.\textsuperscript{27,28} Ultrasound was used at the initial period to generate seed crystals before multiple cooling stages in their system. Lawton et al.\textsuperscript{2} have demonstrated continuous plug flow crystallizer operation with oscillatory baffled reactor (OBR), and Ruecroft & Burns\textsuperscript{29} have made patent application combining ultrasound and pipe modules for antisolvent crystallization. This is different from the current research work where ultrasound is applied continuously to each cooling stage. To our best knowledge, the cooling strategies of continuous tubular flow crystallization integrated with ultrasound have not been studied widely. Therefore, in the present work the ultrasound technology and continuous modular crystallization are combined to investigate operational availability of the whole process and crystal properties with different selected model compounds in order to design a tubular crystallizer for a specific application. It is expected to overcome the challenges of channel clogging and suspension pumping with ultrasound in the designed continuous tubular flow crystallizer. Three model compounds comprising of inorganic and
organic substances were selected to investigate the design criteria for the ultrasonically assisted crystallizer concerning cooling crystallization.

2. EXPERIMENTAL SECTION

2.1 Materials

Three model compounds, K$_2$SO$_4$ (≥ 99 % purity), CuSO$_4$ (100 % purity) and phthalic acid (99 % purity) with analytical grade, were used in the crystallization experiments of the present work. Deionized water was used as the solvent for all the compounds.

2.2 Experimental set-up and method

The experimental set-up shown in Figure 1 consisted of a stirred feed tank, a peristaltic pump (Masterflex Pump Easy Load II 77201-62), three modular crystallizers separately immersed into three ultrasound baths (Bandelin sonorex digitec DT102H, 35 kHz) equipped with thermostats (Lauda), and a collection unit. The feed tank was a jacketed glass reactor with a capacity of 4.5 L equipped with a pitched blade turbine impeller and a thermostat (Lauda). A modular crystallizer was made from a spiraled EN 1.4307 / AISI 304 L stainless steel pipe, which was 12 m or 18 m in length (depending on the experiment), had an inner diameter of 4 mm and 1 mm wall thickness. No polishing was done to the inner walls of the pipe. Each 12 m stainless steel pipe was wound in an oval shape of 14 cm in length and 9.5 cm in width, whereas the 18m stainless steel pipes were wound in an oval shape of 17.5 cm in length and 10.5 cm in width. The wound pipes were placed into a 3L ultrasound bath for each module. Three modules with same configuration were installed in series.

A certain amount of saturated solution was firstly prepared in the feed tank at temperature which was 5.0 °C higher than the equilibrium temperature of the saturated solution in order to dissolve all the solids at the beginning. The temperature of the feed solution was controlled by a thermostat. Different
temperatures were set at each modular tubular crystallizer according to the designed cooling strategy.

The final outlet temperature of the crystallized solution was fixed at 20.0 °C. Before the experiment, thermostats and ultrasound baths were started to keep the temperature and ultrasound power steady in the modular crystallizers. The feed solution was pumped by a peristaltic pump to the first, second and third modular tubular crystallizers serially. If the process can be operated without clogging for three or more times of residence time, then it was defined as a feasible operating condition.

Finally, the suspensions were filtered with a vacuum filter and the crystals were dried in an oven. Morphology and crystal size of the solids obtained from cooling crystallization were analyzed by an automatic image analyzer (Malvern Morphologi G3). About 75000 product crystals were analyzed for each experiment. The crystal yield was calculated from the total mass of the crystals obtained at the end of the experiments.

![Figure 1. Flow diagram of the modular continuous crystallization system](image)

**2.3 Effect of Residence time**

The residence time of the solution in the crystallizer is an important factor in continuous crystallization and it is determined by the set flow rate. Furthermore, the flow velocity should be high enough to avoid settling of crystals in the tube and still suitable to experience enough residence time for
crystallization in the system. The Reynolds number (Re) for the flow in the crystallizer were in the range of 260 – 1300. Hence, all the flow rates used in the experiment provided laminar flow in the tube. In order to get test runs of feasible operating conditions, various flow rates were firstly investigated with model compounds $K_2SO_4$ and $CuSO_4$. These preliminary experiments were carried out with pipes that were 12 m in length and had 4 mm inner diameter and 1 mm wall thickness. Table 1 shows the flow rates, their corresponding residence times and flow velocities in the pipe used in the current study.

Table 1. Flow rates, residence times and flow velocities in the modular crystallizer.

<table>
<thead>
<tr>
<th>Flow rate $Q$, ml/min</th>
<th>Residence time $\tau$, min</th>
<th>Flow velocity in the pipe $v_f$, cm/s</th>
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<tr>
<td>49</td>
<td>9.23</td>
<td>6.50</td>
</tr>
<tr>
<td>60</td>
<td>7.54</td>
<td>7.96</td>
</tr>
<tr>
<td>75</td>
<td>6.03</td>
<td>9.95</td>
</tr>
<tr>
<td>100</td>
<td>4.52</td>
<td>13.26</td>
</tr>
<tr>
<td>120</td>
<td>3.77</td>
<td>15.92</td>
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</tbody>
</table>

2.4 Effect of cooling strategy

The present study used modular tubular crystallizers in continuous cooling crystallization that enabled the supersaturation to be easily and accurately controlled. Control strategy plays a critical role to achieve feasible operating conditions, as employed in the current system. Three cooling strategies which were equal concentration difference (equal supersaturation), equal temperature difference and equal supersaturation ratio were used. The cooling temperature profile for each experiment was calculated on the basis of the selected cooling strategy, and calculated temperatures are maintained for each module.

Due to the results from the initial experiments regarding the influence of residence time, the flow rate of 75 ml/min as an optimal condition was used to study the cooling strategy. In addition, the length of the steel pipe in each module was increased to 18 m to accommodate longer residence times. Other
dimensions such as pipe diameter and thickness were kept the same. Thus, in order to keep a constant production rate because the residence times changes with the longer pipes, the initial concentration of model compounds used in the 18 m pipe was calculated in relation to the conditions used in 12 m pipe.

2.4.1 Supersaturation (ΔC)

The equal concentration difference in the three modules was initially considered. It ensures each module or crystallization stage to reach the same supersaturation as shown in Figure 2a, Figure 3a, and Figure 4a for the different model compounds. Since there were three modules in these set of experiments, the supersaturation (ΔC) was shared equally to each module by calculation from the initial and final concentrations based on the solubility curve. The corresponding temperatures of the resulting concentrations were then used to set the cooling temperature profile.
Figure 2. Solubility curve of K$_2$SO$_4$ showing equal supersaturation (a), equal temperature difference (b), and equal supersaturation ratio (c) in each module in a temperature range from 63.0 °C – 20.0 °C (adapted from docbrown.info$^{31}$).

2.4.2 Temperature difference (ΔT)

Mersmann and Rennie$^{22}$ introduced a continuous multistage cooling crystallization process involving eight countercurrent crystallizers in series. This concept can help to avoid excess local supersaturation in each stage. It means that the temperature drop should be equal in each module as shown in Figure 2b, Figure 3b, and Figure 4b for the different model compounds. In this case, the concentration difference in each module varies and it depends on the solubility of the model compound.
Figure 3. Solubility curve of CuSO₄ showing equal supersaturation (a), equal temperature difference (b), and equal supersaturation ratio (c) in each module in a temperature range from 53.2 °C – 20.0 °C (adapted from docbrown.info³¹).

2.4.3 Supersaturation ratio (S)

Supersaturation ratio (\(S=C/C^*\)) is another way to express supersaturation level in the system. The supersaturation ratio is calculated as the ratio of the initial concentration and expected final concentration at the exit of the module based on the solubility curve of the model compound. Thus, equal supersaturation ratio in each module was taken into account as a design method. In this case, the concentration difference decreases gradually with the modules, which can be clearly seen in Figure 2c, Figure 3c, Figure 4b and Table 2 for the different model compounds.
Figure 4. Solubility curve of phthalic acid having equal supersaturation (a), equal temperature difference and equal supersaturation ratio (b), in each module in a temperature range from 60.0 °C – 20.0 °C (adapted from Stephen and Stephen\(^{32}\)).

### 2.5 Effect of supersaturation ratio

To understand the influence of supersaturation ratio on crystallization more deeply, various experiments with phthalic acid with different supersaturation ratios in the range from 1.20 to 1.90, as shown in Table 3, were performed with 3-stage modular crystallizer. Same experimental procedure as shown in section 2.2 was used with the same residence time of 9.05 min in every experiment. Crystal size distributions were examined with Morphologi G3.

### 2.6 Effect of ultrasound

Effect of ultrasound was investigated with phthalic acid for the studied continuous crystallizer. Two steel pipes having lengths of 12 m and 18 m were used. Same configuration but only one module which had spiraled pipes was considered here for cooling crystallization of phthalic acid in the temperature range from 35.0 °C to 20.0 °C. 3 liters of feed solution saturated at 35.0 °C was first prepared. The temperature of the thermostat used for the tubular crystallizer was set to 20.0 °C. Seeding was done in coherence with Linga’s\(^{33}\) recommendation for seeding in industrial crystallizers. Hence, 0.2 g (about
0.3 % of final crystals) seeds with average size of 11 µm was added to the saturated solution to initiate crystallization. Five flow rates were used for the cooling crystallization processes of phthalic acid with ultrasound while three flow rates were used for the experiments without ultrasound. In this case, the product crystals were analyzed with Malvern Size Analyzer (Mastersizer 3000) to determine the particle size distributions. Clear filtrates were weighed and dried in the oven to determine the concentration of the soluble materials in the mother liquor. This method was used for crystal yield determination.

3. RESULTS AND DISCUSSION

3.1 Effect of residence time

Potassium sulphate. Various residence times shown in Table 1 were checked for K₂SO₄ with equal concentration difference (1.63 g/100g water) in the range of 46.8 °C to 20.0 °C. The corresponding supersaturation ratios in modules 1, 2 and 3 were 1.11, 1.13 and 1.15, respectively. The experimental results show that the system was blocked when operated with a residence time of 9.23 mins. All the other flow rates could offer feasible operations with the continuous modular crystallizer, their yield and average particle sizes are presented in Figure 5. The reason for the blockage might be the existence of excessive supersaturation in the module and low flow velocity, which is also pointed out by Furuta et al. Crystal yield relates to the supersaturation level of the whole cooling process. It means that the yield could be increased by increasing the initial concentration. Thus, two other experiments were carried out with higher initial concentration corresponding to a temperature of 60.0 °C, at residence times of 9.23 and 3.77 mins, to verify if a feasible operating condition could be achieved. Hence, a feasible operating condition was observed with the residence time of 3.77 mins. Whereas, a blockage occurred with the residence time of 9.23 mins due to the presence of excessive supersaturation in the module and low flow velocity. Furuta et al. also reported same reason for blockages in their tubular crystallizer.
Copper sulphate. Due to the blockage which occurred in the continuous crystallization of K$_2$SO$_4$ with the residence time of 9.23 mins, this residence time was not considered for CuSO$_4$ crystallization. Same cooling profile with equal concentration difference was firstly employed with cooling crystallization of CuSO$_4$ since feasible operating conditions were achieved while using the cooling strategy in K$_2$SO$_4$ crystallization. However, the blockage occurred for trial runs carried out with residence times of 7.54, 6.03 and 3.77 mins with equal concentration difference of 4.10, 4.77 and 6.43 g/100g water corresponding to the initial temperatures 49.2, 53.0 and 60.0 °C, respectively. Because of this, equal supersaturation ratio was considered with the same initial temperatures and flow rates, but there was not any operation that led to a feasible operating condition. As Figure 2 and Figure 3 show, the solubility of CuSO$_4$ in water is much higher than the solubility of K$_2$SO$_4$, and the solubility curve of CuSO$_4$ is more non-linear. Hence, sudden temperature decrease in the module leads to high supersaturation and thus results in clogging of the crystallizer. Due to the aforementioned reasons, the initial temperature should be decreased to achieve lower supersaturation level. Finally, three feasible operating conditions were observed from experiments carried out with residence times of 6.03, 4.52 and 3.77 mins in the temperature range from 43.0 to 20.0 °C by applying the cooling strategy of equal supersaturation ratio (1.13).

Figure 5 shows the average crystal sizes (D$_{[4,3]}$) based on volume distribution of different samples obtained from feasible operating conditions of various residence times and yields for both compounds, K$_2$SO$_4$ and CuSO$_4$. The crystal size of K$_2$SO$_4$ was always bigger than the size of CuSO$_4$ - crystals. This may be due to the differences in crystal properties that drive the nucleation and growth. For both compounds, the crystal size increased with the decrease of residence time and then reduced at shortest residence time. Raphael et al.$^{34}$ observed that average crystal sizes decreases with shorter residence times and was in line with results from Lawton et al.$^3$, whereas Ruecroft et al.$^{10}$ reported that with
Continuous sonication smaller crystals are formed with longer residence times. Hence, the reason for
the variation in average crystal sizes might be the combined effect of ultrasound and residence time.
Furthermore, higher yield was obtained with the residence time of 6.03 mins, equivalent to a flow
rate of 75 ml/min, for both compounds as shown in Figure 5. It indicates that the flow rate of 75 ml/min
for the 3 stage reactor gave better results for the both model compounds. Therefore, this flow rate was
used to investigate cooling strategy of the modular crystallizer shown in section 3.2.

Figure 5. Crystal sizes of different samples obtained from feasible operating conditions of various
residence times and yields for both compounds K$_2$SO$_4$ and CuSO$_4$.

3.2 Effect of cooling strategy
Due to the increase of pipe length, the residence time was 9.05 mins when flow rate 75 ml/min was
used. In order to keep constant production rate after increasing the pipe length, the initial temperatures
used in the new configuration which was scaled up based on the observed feasible conditions obtained
from section 3.1 for K$_2$SO$_4$ and CuSO$_4$ were 63.0 °C and 53.2°C, respectively. Based on these parameters,
supersaturation, supersaturation ratio and temperature in each module were calculated as shown in
Table 2 and used for comparison of investigated cooling strategies.
Potassium sulphate. Feasible operating conditions were obtained with the design method of equal concentration difference and equal temperature difference from continuous cooling crystallization of K$_2$SO$_4$, but the experiments designed by equal supersaturation ratio (S) failed. As shown in Table 2, the first module had much higher supersaturation (ΔC) than module 2 and 3 when equal supersaturation ratio (S) was used. It also indicates that equal supersaturation ratio provided faster cooling rates in the first module compared with the other two methods which led to crash nucleation. Hartel$^{35}$ reported that rapid cooling can cause the formation of higher amount of nuclei and high supersaturation can lead to encrustation. Those may be the main reasons for clogging with the equal supersaturation ratio cooling strategy. Crystal size distribution of K$_2$SO$_4$ with different cooling conditions are presented in Figure 6a. It can be seen that larger crystals were obtained from the conditions with equal supersaturation (ΔC) compared to equal temperature difference.

Copper sulphate. Continuous cooling crystallization of CuSO$_4$ in the continuous pipe were carried out with the three designed cooling strategies in the temperature range from 53.2 °C to 20.0 °C. Figure 6b shows the crystal size distribution of CuSO$_4$ obtained from continuous sonicated crystallization with different cooling strategies. It shows that crystals were largest with equal temperature difference. Then, slightly bigger particles were crystallized from equal supersaturation ratio (S) than with equal supersaturation (ΔC).

Phthalic acid. An organic compound, phthalic acid, was selected to be used in the modular reactor. In temperature range from 60.0 °C to 20.0 °C, continuous cooling crystallization experiments of phthalic acid in the tubular crystallizer offered feasible operating conditions with three different cooling strategies. As shown in Table 2, equal supersaturation ratio provides the same cooling profile with equal temperature difference due to its solubility curve (adapted from Stephen & Stephen$^{32}$) shown in Figure 4. The crystal size distributions of phthalic acid obtained by various cooling conditions are shown in Figure 6c. As can be seen, there are no significant differences in crystal sizes between equal
supersaturation and equal temperature difference (or equal supersaturation ratio). However,

agglomerates are observed in Figure 6c since the CSDs were analyzed using the Morphologi G3 which

measures crystal sizes by surface imaging. The potential reason for the agglomeration, hence the

uneven CSDs, is that the supersaturation step in the last module is larger with equal temperature

difference compared to equal supersaturation.

Table 2. Investigated cooling strategies for modular cooling crystallization with the residence time of 9.05 mins and the obtained product yields of the model compounds.

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<th>Compound</th>
<th>Equal Condition</th>
<th>Unit</th>
<th>Conc., g/100g H2O</th>
<th>ΔC, g/100g H2O</th>
<th>S</th>
<th>ΔT, °C</th>
<th>Equivalent temp, °C</th>
<th>Yield*, %</th>
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"Not a feasible operating condition"
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<td>13.35</td>
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<td>33.3</td>
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<td>0.38</td>
<td>1.77</td>
<td>13.35</td>
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</tbody>
</table>

310 \( a = \) yield calculated from recovered dry product crystals, \( x = \) filter cloth torn during recovery

311
Figure 6. Crystal size distribution of K$_2$SO$_4$ (a), CuSO$_4$ (b) and phthalic acid (c) crystallized by applying different cooling operating conditions at constant residence time of 9.05 mins in the continuous sonicated reactor.

As a summary, almost all the model compounds crystallized from different cooling profiles in the continuous sonicated cooling crystallization process with a constant residence time achieved the highest yield when equal supersaturation was chosen as is shown in Table 2. Although, equal supersaturation ratio gave the highest actual yield for CuSO$_4$ but the actual yield was in the same range with that was obtained with equal supersaturation. It indicates that the supersaturation in each module is equally constant and this implies that the supersaturation in each crystallizer can be controlled accurately. This is consistent with the recommendation that was pointed out by Mersmann and Rennie. They suggested that cooling rates could be fixed by constant supersaturation in the cooling period. Therefore, equal
supersaturation between modules is the optimal cooling strategy in the modular crystallizer. However, there are no clear trends corresponding to crystal size distributions probably because the kinetics and crystal properties of different compounds are different. An additional reason may also be the impact of ultrasound as there are possibilities of the crystals to observe a growth – attrition – growth sequence. It means that crystal size can increase or decrease due to ultrasound because the induction of ultrasound at different stages have different effects on crystals.\textsuperscript{14,36} Further studies of induction times are needed.

### 3.3 Effect of supersaturation ratio

Different initial temperatures were used to achieve different supersaturation ratios for phthalic acid cooling crystallization at equal $\Delta S$ in each module as shown in Table 3. Continuous cooling crystallization experiment of phthalic acid with equal supersaturation ratio of 1.20 did not result in crystal production. This may be due to the extremely low supersaturation of the whole process. The experiment with supersaturation ratio of 1.90 failed due to blockage problems, which were most probably caused by too high supersaturation and faster cooling rate in the first module which led to encrustation and high nucleation rate.\textsuperscript{35,37} Finally, there was blockage in the crystallizer. However, the continuous experiments with other supersaturation ratios could be carried out without blockage.

The crystal size distributions and average crystal sizes of phthalic acid obtained from the feasible operating conditions are presented in Figure 7. It shows that the crystal size distribution is getting narrower with the increase of supersaturation ratio as presented in Figure 7a and the average crystal size ($D[4,3]$) decreases with increase in equal supersaturation ratio as shown in Figure 7b. It can be attributed to the effect of ultrasound and the supersaturation level in the first module which increased with the increase of supersaturation ratio and thus lead to generation of small nuclei which provided much more interface for crystal growth. Although Ni & Liao\textsuperscript{38} and Kaneko et al.\textsuperscript{39} reported that bigger crystals are produced with higher supersaturation, however, the inverse relationship of the average
crystal size and supersaturation ratio is coherent with production of smaller crystals at high supersaturation as reported by Sarig et al.\textsuperscript{40} The yield as shown in Table 3 indicates that the highest yield was obtained with the supersaturation ratio of 1.54 with the residence time of 9.05 mins which might be the optimal condition for this specific residence time.

\begin{table}[h]
\centering
\begin{tabular}{llllll}
\hline
Unit & C*, g/100 g H\textsubscript{2}O & S & ΔC, g/100 g H\textsubscript{2}O & Saturation temp., °C & Yield\textsuperscript{a}, % \\
\hline
Feed & 0.86 & & & & 32.8 \\
Module 1 & 0.72 & 1.20 & 0.14 & 28.5 \\
Module 2 & 0.60 & 1.20 & 0.11 & 24.2 \\
Module 3 & 0.50 & 1.20 & 0.10 & 20.0 \\
\hline
Feed & 1.24 & & & & 41.4 \\
Module 1 & 0.91 & 1.36 & 0.33 & 34.3 \\
Module 2 & 0.67 & 1.36 & 0.24 & 27.1 \\
Module 3 & 0.50 & 1.36 & 0.17 & 20.0 \\
\hline
Feed & 1.80 & & & & 50.2 \\
Module 1 & 1.17 & 1.54 & 0.63 & 40.1 \\
Module 2 & 0.76 & 1.54 & 0.41 & 30.0 \\
Module 3 & 0.50 & 1.54 & 0.26 & 20.0 \\
\hline
Feed & 2.50 & & & & 57.8 \\
Module 1 & 1.46 & 1.71 & 1.04 & 45.2 \\
Module 2 & 0.85 & 1.71 & 0.61 & 32.6 \\
Module 3 & 0.50 & 1.71 & 0.35 & 20.0 \\
\hline
\end{tabular}
\caption{The saturation concentrations of phthalic acid at equilibrium for each module and equivalent temperatures showing equal module supersaturation ratios.}
\end{table}
<table>
<thead>
<tr>
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<th>Module 3</th>
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<td>1.77</td>
<td>1.77</td>
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<td>1.19</td>
<td>0.67</td>
<td>0.38</td>
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<td>60.0</td>
<td>46.7</td>
<td>33.3</td>
<td>20.0</td>
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</table>

Not a feasible operating condition

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<td>50.0</td>
<td>35.0</td>
<td>20.0</td>
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</tbody>
</table>

a = yield calculated from recovered dry product crystals

Figure 7. Crystal size distributions (a) and average crystal size D[4,3] (b) of phthalic acid obtained from continuous sonicated cooling crystallizer with equal supersaturation ratio in each module with different supersaturation ratios (different initial temperature) at a residence time of 9.05 mins.

3.4 Effect of ultrasound

For all of the studied experimental conditions without ultrasound, small amount of crystals were obtained from the crystallization process, which were not enough for analysis. This was because the residence times were short as shown in Table 4 and there was no ultrasound to induce nucleation in the system. With ultrasound, only one experiment had similar problem, of no produced crystal, when a
flow rate of 150 ml/min and 12 m pipe were used because of the short residence time which was
probably lower than the induction time, hence there was a reduced effect of ultrasound with this
operating condition. From Table 4, it is observed that the actual yield was always higher for sonicated
experiments compared to non-sonicated experiments at a specific residence time. Thus, it indicates that
the crystallization process was enhanced significantly by ultrasound. Moreover, encrustation can be
avoided by using ultrasound assisted crystallization.37

Figure 8 shows the crystal size distributions and average crystal sizes of phthalic acid obtained from
cooling sonocrystallization process. The CSDs show wider distributions for lower flow rates (higher
residence time) for the 12 m and 18 m pipes, represented in Figure 8a and Figure 8b respectively,
compared to the higher flow rates in the experiment. However, the CSDs were not consistent probably
due to the effect of ultrasound and the possible relationship between available residence times and
induction times of phthalic acid.

More so, a sequence of decrease in average crystal size and yield was observed with increase in flow
rate as presented in Table 4 and Figure 8c respectively. This was due to the short residence time crystals
spent in the crystallizer, not giving enough time for crystals to grow immediately after nucleation
induced by ultrasound. Another reason for this is the possibility of the residence time being very close to
the induction time which was not studied. Using the 18 m pipe and the flow rate of 150 ml/min without
using ultrasound, the yield was unreliable due to temperature variation during the filtration of the
product suspension. When the flow rate of 50 ml/min and 18 m pipe were used, the particle size was
very similar with the crystals obtained with flow rate of 100 ml/min. This might be due to the
classification of crystals in the pipe with such low flow velocity.

Interestingly, the yields obtained from ultrasound experiments were higher compared to those
without ultrasound, at the same condition as seen in Table 4. Since ultrasound can reduce the induction
time,\textsuperscript{1,10} hence, nucleation begins earlier for such experiments carried out with ultrasound thereby offering more yield.

Table 4. Results of phthalic acid samples obtained from cooling crystallization with and without ultrasound in the one module crystallizer having inner diameter of 4 mm.

<table>
<thead>
<tr>
<th>Pipe length, m</th>
<th>Ultrasound</th>
<th>Flow rate, ml/min</th>
<th>Residence time, mins</th>
<th>Conc. of mother liquor, g/100g water</th>
<th>Yield\textsuperscript{b}, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 ON</td>
<td>50</td>
<td>3.02</td>
<td>0.69</td>
<td>59</td>
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<tr>
<td></td>
<td>75</td>
<td>2.01</td>
<td>0.81</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>1.51</td>
<td>0.78</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>1.26</td>
<td>0.79</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>1.01</td>
<td>0.81</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>18 OFF</td>
<td>50</td>
<td>3.02</td>
<td>0.74</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>1.51</td>
<td>0.83</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>1.01</td>
<td>0.83</td>
<td>27</td>
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<tr>
<td>18 ON</td>
<td>50</td>
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<td>0.71</td>
<td>54</td>
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<tr>
<td>18 OFF</td>
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<tr>
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<td>150</td>
<td>1.51</td>
<td>0.76</td>
<td>42\textsuperscript{*}</td>
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</table>

\(\text{b} = \) yield calculated from mother liquor concentration, \(\text{\textsuperscript{*}}\) = unreliable.
**Figure 8.** Crystal size distributions of phthalic acid from 12 m pipe (a) and 18 m pipe (b) and their average crystal sizes (c), obtained from cooling sonocrystallization process with one module.

4. CONCLUSION

Continuous cooling crystallization of three model compounds (K₂SO₄, CuSO₄ and phthalic acid) were carried out in a new modular sonicated tubular crystallizer. Feasible conditions were obtained from successful operating processes running without pipe blockage for three or four times of the residence time. The residence time is a critical factor for yield and crystal size according to results. The yield is affected by nucleation and crystallization time which can relate to supersaturation left in the reactor outlet with short residence times.

The cooling strategy did not have a clear relation to the crystal size distributions. This might be due to the difference of solubilities, crystal growth, nucleation kinetics, and crystal properties for each
compound. Equal supersaturation could be used as the best option to design temperature profiles for cooling crystallization. This is because each module would ideally have equal concentration difference and thus leads to moderate local supersaturation which could reduce the opportunity of crystals to block the pipes. More so, equal supersaturation produces higher yields in cases where short residence times are used. This is favoured especially in targeting production increase with continuous systems. Furthermore, the design criteria were evaluated with the studied three model compounds. Ultrasound plays a critical role, which can enhance the crystallization process significantly and avoid clogging. From results, the use of ultrasound offered higher yields compared to experiments without ultrasound. Boundary conditions such as residence time and cooling strategy as the key issues have to be taken into account when designing a continuous tubular sonocrystallizer. As further studies optimization between the process residence time and the supplied ultrasound intensity is needed.

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**Notes**

The authors declare no competing financial interest

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REFERENCES


Process parameters were studied in a continuous sonicated modular cooling crystallizer with inorganic and organic model compounds. Equal supersaturation as a crystallization design strategy allows high yields especially with short processing times. Smaller crystals and higher yields can be obtained using ultrasound in continuous crystallization systems. Residence time is an important design variable of such systems.