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# DEPOSITION OF Na<sub>2</sub>CO<sub>3</sub> IN SUPERCRITICAL WATER OXIDATION SYSTEMS AND ITS MITIGATION

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## ABSTRACT

Supercritical water oxidation is a technique to destroy wet organic waste. The oxidation reaction takes place at high temperature and pressure. Organics are miscible at these conditions but inorganic salts are not soluble and present fouling problems. Examples of these salts are sodium sulfate and sodium carbonate.

Research is being done in the University of British Columbia to study the fouling behavior of Na<sub>2</sub>CO<sub>3</sub> in the SCWO reactor. The working fluid is heated by passing alternating current through the reactor wall. Since the tube surface was hotter than the bulk fluid, the salt was expected to nucleate on the tube wall. Due to the fouling thermal resistance, the tube surface temperature increased quite rapidly. As a fouling mitigation measure, the salt was encouraged to nucleate in the bulk fluid. It was noticed that the buildup of scale due to homogeneous nucleation of the salt was not steady. Once the deposited layer reached a certain thickness, it was removed by the flowing fluid. In some experiments there was a steady rise in the reactor surface temperature and the reactor did eventually get plugged. However, when the salt was made to nucleate in the bulk fluid, the salt net deposition was reduced and we were able to run the system for longer period of time. This paper discusses the modified procedure to enable homogeneous nucleation of salt in order to extend the operating time of the SCWO system. The results of these experiments are presented and compared with the heterogeneous nucleation case.

## INTRODUCTION

Supercritical water oxidation (SCWO) is a technology for decomposition of toxic organic materials. Above the critical point (i.e., water above 22.1 MPa and 374.14°C) hydrogen bonding between water molecules decreases greatly and water acts as a non-polar solvent. Thus organic compounds and oxygen can dissolve in one phase and mass transfer limitations reduce greatly. The high diffusivity and

excellent transport properties of water decompose the organics rapidly and completely during the SCWO process. However, the inorganic compounds are not soluble at these conditions. Inorganic salts are produced during the treatment of some wastes or they might be present in the waste itself. These salts precipitate out of the supercritical water, agglomerate and usually stick to the reactor wall. In a tubular reactor a flow restriction is thus produced, in addition to a heat transfer resistance across the reactor wall, thus reducing the thermal-hydraulic performance of the reactor. It is believed that plugging of reactors caused by precipitating salts is one of the major problem delaying the commercialization of this waste treatment process (Kritzer and Dinjus, 2001).

Several studies have been carried out to determine the deposition rates of inorganic salts at SCWO conditions. Teshima (1997) carried out experiments to study the Na<sub>2</sub>SO<sub>4</sub> deposit in a SCWO pilot plant. Preliminary experiments were conducted to determine the solubility of Na<sub>2</sub>SO<sub>4</sub> in water at 25 MPa and for a temperature range of 370-500°C. It was reported that the solubility decreases rapidly around the pseudo-critical temperature. The deposition experiments were done with a maximum salt concentration of about 1 wt.% and the tubular reactor was plugged within 20 minutes of operation. It was observed that the salt deposition profiles were influenced by mass transfer limitation in addition to the solubility. Rogak and Teshima (1999) developed a simple heat and mass transfer model to estimate Na<sub>2</sub>SO<sub>4</sub> deposition for a tubular reactor. Since the tube walls were heated and hence at a higher temperature compared to the bulk fluid, salt molecules were crystallizing at the wall. This type of nucleation is known as heterogeneous nucleation. On the other hand if the salt becomes supersaturated in the bulk fluid, salt particles nucleate and this type of nucleation is known as homogeneous nucleation. It was reported that the bulk solution never became supersaturated, so homogeneous nucleation was not modeled.

Hodes (1998) studied Na<sub>2</sub>SO<sub>4</sub> deposition on a heated cylinder. Salt concentration and time in the deposition

experiments were varied between 2 & 8 wt.% and 6 & 12 minutes. The salt solution was preheated to about 5°C below the solubility temperature corresponding to the concentration in the bulk solution surrounding a cylinder. The cylinder was heated beyond the solubility temperature to drive deposition. No homogeneous nucleation was observed through the visually accessible test cell during the experimental run. The purpose of the study was to develop an understanding of salt deposition kinetics and nucleation phenomenon in SCWO reactors. The results of the deposition study were presented by Hodes et al. (1997). Experimental deposition rate data have been provided for sodium sulfate and a predictive model based on the data was developed. Smith et al. (2002) developed a model to predict whether or not homogeneous nucleation would occur in a natural convection boundary layer around a cylinder heated beyond the solubility temperature corresponding to the concentration of salt in the surrounding aqueous salt solution. Lewis number was found to be a critical property in this regard. The model was applied to the experiments run by Hodes (1998) and yielded consistent results, i.e., homogeneous nucleation was absent.

Chan et al. (1994) at Sandia National Laboratories studied solubility and salt deposition kinetics in the Na<sub>2</sub>SO<sub>4</sub>-H<sub>2</sub>O system at conditions relevant to SCWO in a tubular reactor. A 50-cm long, Inconel 625 tube served as a tubular reactor. The OD and ID of the reactor were 14.3 and 4.7 mm respectively. In the deposition experiments a 0.5 wt.% salt solution was pumped through the reactor and the fluid temperature at the exit of the reactor was near 400°C. The reactor got plugged in about 30 minutes for majority of the test runs.

Several approaches have been tested to overcome the fouling problem. Some studies (Kritzer and Dinjus, 2001) suggest increasing the system pressure and thus increase solubility of some salts. However, at higher pressure corrosion problems are also enhanced. Another approach is to use a special reactor design (Barner et al., 1992) in which salt sinks down to zone of lower subcritical temperature where they are dissolved again. However, in such designs, the low settling speed and high vertical turbulence present a problem. Alternatively, salts precipitating in the reactor zone have to be dissolved before the deposition at the wall. Crooker et al. (2000) implemented a transpiring wall reactor to address the technical problems of corrosion and salt plugging in SCWO systems. The transpiring platelet liner flows supercritical water that forms a film barrier from sticky salts. The higher running cost and long time tests have yet to prove the suitability of this technique. Online removal of the scale by mechanical means has also been suggested (Modell et al. 1993, Gairns and Joustra, 1999). These techniques are yet to be tested in an actual SCWO plant. The plugging of the reactors cannot be avoided by variation of the process parameters without simultaneously

triggering or rising of a new problem (Kritzer and Dinjus, 2001). The current possible ways of reducing the problem have so far not been totally effective and seem to be susceptible to fail in long term application. Thus none of these approaches has achieved any commercial success and scaling of inorganic salts remains a major obstacle in long term SCWO operation treating organic waste with inorganic compounds.

The present work has been carried out to study the deposition of Na<sub>2</sub>CO<sub>3</sub> in the UBC-NORAM SCWO pilot plant. Initially, solubility of Na<sub>2</sub>CO<sub>3</sub> was experimentally determined and the results have been presented elsewhere (Khan and Rogak, 2003). Experiments to study the deposition and possibly mitigate the rate were then performed. The experimental setup is discussed below.

## EXPERIMENTAL SYSTEM

Figure 1 shows the schematic of the UBC-NORAM SCWO pilot plant. It has about 160-m long alloy 625 tube. The inner and outer diameters are 6.2 and 9.5 mm respectively. The pre-heaters, test section and reactor section are electrically heated by running alternating current through the tube walls. All these section are horizontal and insulated with Kaowool.

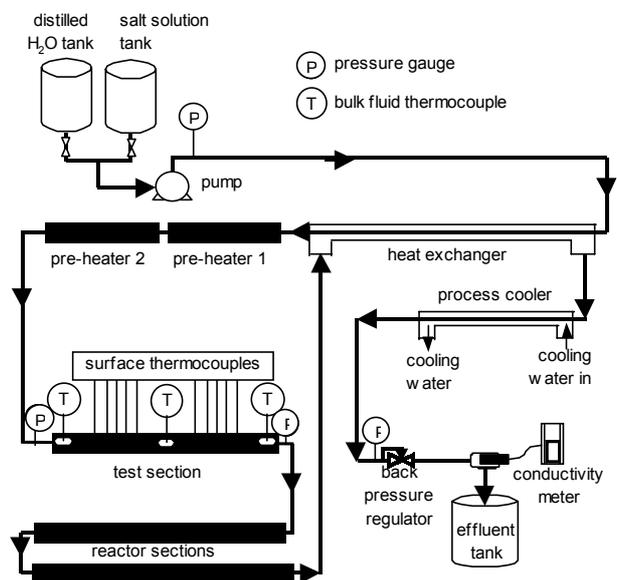


Fig. 1 Schematic of the UBC-NORAM SCWO pilot plant

Two polyethylene tanks are used to store distilled water and salt solution separately. A high-pressure triplex positive displacement-metering pump is used to pump the liquid in to the system. A pulsation damper is used to reduce the flow fluctuations. The speed of the pump is controlled by a variable frequency drive. Fluid gains some enthalpy in the

regenerative heat exchanger. The pre-heaters then heat up the fluid to achieve the required fluid temperature at the inlet of the test section. The test section is 2.9 m long and is divided into two equal segments. Pressure transducers, located at the inlet and outlet of the test section, are used to measure the gauge pressure and were monitored during the test run. The pressure transducers were calibrated with a digital calibrator (Cole Parmer 68036 series). The uncertainty of the pressure measurement, considering the errors in the data acquisition system and variation along the test section is approximately 0.1%. In the test section, K-type thermocouples are used to measure the outer tube surface and bulk fluid temperatures. The surface temperatures are measured at 8 locations in the first segment and 6 locations in the second segment of the test section. There are three thermocouples, which are used to measure the bulk fluid temperature. These are located at the inlet, outlet and middle of the unheated segments of the test section. The error in the temperature measurement is less than 1 K. The calibration procedure of the thermocouples has been discussed elsewhere (Khan and Rogak, 2003).

After passing through the test section the fluid enters a long reactor section. Then it enters the regenerative heat exchanger where it heats up the incoming feed from the influent tank. Finally, the fluid is cooled down further in a process cooler. A back-pressure regulator is used to control the system pressure. A gas dome back-pressure regulator is used in the system. High-pressure nitrogen gas is used to load the pressure regulator to achieve the desired pressure. An online conductivity meter is used to measure the conductivity of the effluent before it is collected in the effluent tank. Salt concentration was inferred from the effluent conductivity measurement. The conductivity meter was calibrated, prior to the experiments, for various concentrations of salt solutions.

## EXPERIMENTAL PROCEDURE

### Heterogeneous nucleation

As mentioned earlier, experiments were initially carried out to determine to solubility of Na<sub>2</sub>CO<sub>3</sub> at SCWO conditions. The experimental method was to pass the salt solution through a near isothermal test section and the salt above solubility limit was assumed to be depositing on the tube surface. The solution leaving the test section would thus be at saturation limit. The test section was set to be the hottest section in the system such that the concentration of salt in the effluent should be the saturation limit corresponding to the test section temperature. Further details of the experimental procedure and calculation of temperature corresponding to the saturation limit are presented by Khan and Rogak (2003). The salt solution was heated by passing alternating current through the tube walls.

The tube surface temperature was thus higher than the fluid temperature and thus the salt was nucleated on the tube surface and homogeneous nucleation was unlikely. Salt solution was passed for a short period of time (less than 20 minutes), in order to avoid plugging or excessive tube surface temperature rise. The flow was switched to pure water afterwards to dissolve the deposited salt.

The solubility of Na<sub>2</sub>CO<sub>3</sub> drops drastically around the pseudo-critical temperature and then the decrease is not very rapid (Khan and Rogak, 2003). The fluid was heated in the preheaters to achieve temperatures above pseudo-critical temperature. It was therefore noticed that the pre-heaters were most susceptible to plugging and/or overheating. The system had to be shut down due to that and thus these test runs could not be run for longer period. These experiments are similar to those performed by Teshima (1997) and later modeling work carried out by Rogak and Teshima (1999) indicated only heterogeneous nucleation was occurring.

### Heterogeneous and homogeneous nucleation

As a possible fouling mitigation technique, the salt was made to nucleate in the bulk fluid just before the test section. The salt particles nucleating in the bulk fluid agglomerate and are more likely to flow with the surrounding fluid through the system due to their larger size. In order to check this hypothesis, the experiment set up was modified as shown in Fig. 2.

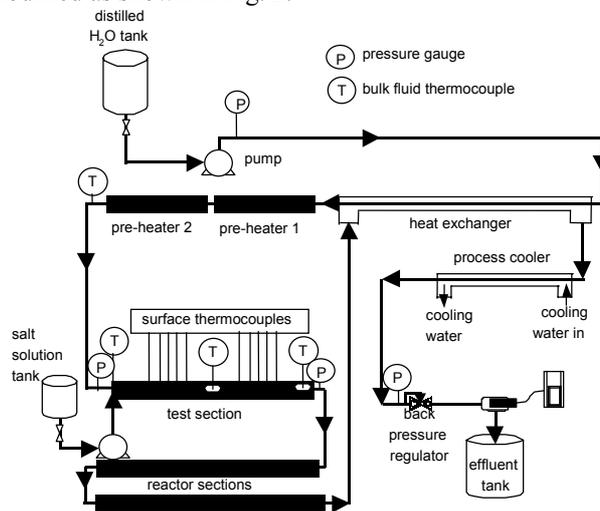


Fig. 2. Schematic of the modified pilot plant

Instead of the salt solution, only pure water was passed through the pre-heaters such that no salt deposition occurs before the test section. Salt solution was then injected into this stream of water using a metering pump. The flow rate of the metering pump was set to 10% of the total flow. The pure water stream was heated such that the temperature after

mixing is beyond the solubility temperature corresponding to the salt concentration in the mixed streams. Thus the salt particles are expected to nucleate in the bulk fluid. Since the test section was heated in these runs, therefore heterogeneous nucleation may also be expected. The experiment was terminated when the test section was plugged due to the salt deposition and the relief valve opened due to excessive pressure. Pure water was then pumped through the metering pump to dissolve the salt deposited on the tube walls. During the test runs, due to the salt deposition a pressure increase at the inlet of the test section was noticed. The reactors were set to a temperature of about 5-10°C lower than the test section temperature. The pressure at the outlet of the test section remained constant thus indicating that nearly all the deposition was taking place in the test section.

### Homogeneous nucleation only

For this set of experiments, a similar procedure was followed as mentioned in the last section. However, in order to avoid heterogeneous nucleation, the test section was not heated in these test runs. This set of test runs was carried out to check if we are able to reduce the net salt deposition further in the absence of the heterogeneous nucleation.

Some sample test runs from each of the above three types of experiments are discussed below.

## RESULTS AND DISCUSSION

### Heterogeneous nucleation

As mentioned earlier, we were not able to run these experiments for more than 30 minutes and the test run had to be terminated due to excessive pre-heater surface temperature and/or pressure. The rate of salt deposited, among other parameters, depends on the salt solution concentration and how fast the solubility is decreasing along the length of the tube. The surface temperature in the pre-heaters, which were at higher power input compared to the test section, increased quite rapidly due to the deposition of salt. However, there were not many thermocouples on the surface of pre-heaters and we could not measure the temperature over their entire length. The test section surface temperature rise for a sample experiment is shown in Fig. 3. The flow rate in this test run was 0.66 kg/min with  $\text{Na}_2\text{CO}_3$  concentration of 0.19 wt.% in the influent tank. Thus the salt delivery rate at the system inlet was 1.25 g/min.

Based on our assumption that the salt solution leaving every section is at saturation limit corresponding to the section temperature, the fluid entering the test section would be at the saturation limit corresponding to the pre-heater 2 temperature. The fluid salt concentration entering the test

section is thus 0.018 wt.% and the actual salt delivery rate at the inlet of the test section would be 0.12 g/min.

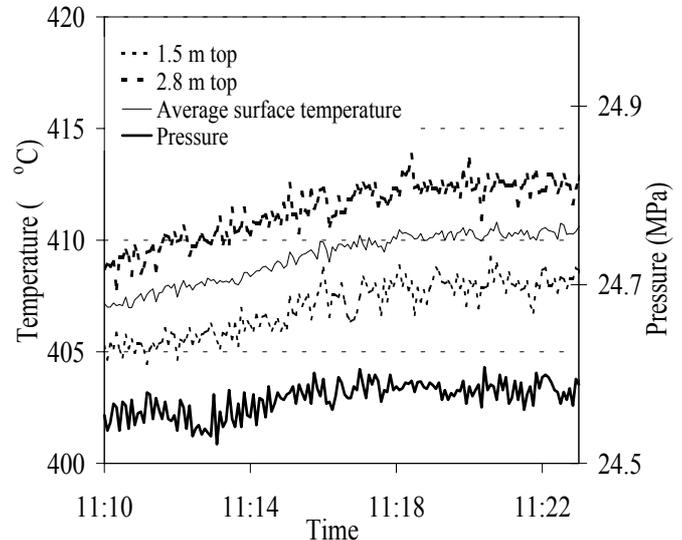


Fig. 3. Temperature and pressure behavior for a heterogeneous nucleation run

After operating for 15 minutes, a pressure increase of about 70 kPa was noticed at the inlet of the test section. However, it is to be noted that for this type of test runs, major deposition was taking place in the pre-heaters and we were not monitoring the pressure at the inlet of the pre-heaters. A monotonic increase in test section surface temperature was observed which indicates a steady buildup of the salt on the tube surface. The concentration of salt leaving the system was also constant and thus all salt above the solubility limit was depositing on the heat transfer surface. Thus the ratio of salt concentration in the effluent to the saturation limit was 1.

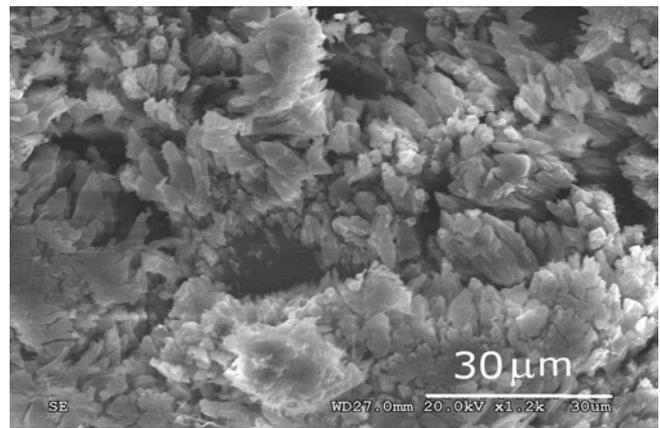


Fig. 4. SEM photograph of the  $\text{Na}_2\text{CO}_3$  deposition on test section wall due to heterogeneous nucleation.

Recently, we have developed a nitrogen purge procedure that allows us to collect and examine the deposit. Figure 4 shows the SEM images of Na<sub>2</sub>CO<sub>3</sub> scraped from the test section after a heterogeneous nucleation experiment.

In this test run the system pressure was 24.8 MPa. Fluid temperatures at the inlet and outlet of the test section were 392 and 436°C respectively and remained almost constant during the experiment. The maximum test section surface temperature was about 455°C.

### Heterogeneous and homogeneous nucleation

These experiments were carried out to reduce the net salt deposition rate in order to increase the duration before the test run is terminated due to either excessive surface temperature and/or pressure. In other words we would like to have a higher ratio of salt concentration in the effluent to the saturation limit compared to our last set of experiments. A sample run is shown in Fig. 5.

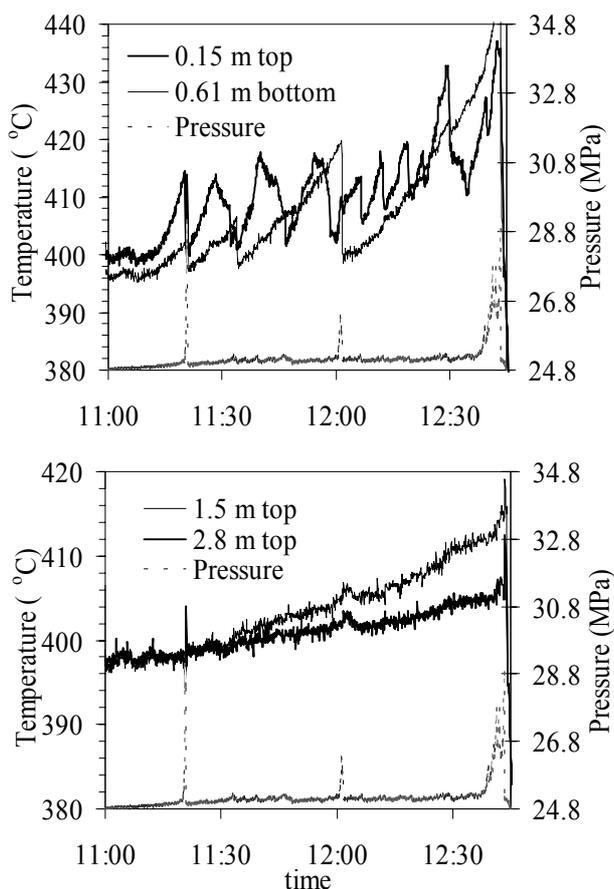


Fig. 5. Temperature and pressure behavior for a combined homogeneous and heterogeneous nucleation run

The flow rate for this run was 1.32 kg/min with a salt concentration of 0.1 wt. %. The salt delivery rate at the inlet

of the test section would thus be 1.32 g/min. The temperature of pure water at the outlet of pre-heater 2 was maintained at 416°C. We were able to run the system for about 90 minutes before the run was terminated due to excessive pressure at the inlet of the test section. However, pressure at the outlet of the test section remained constant throughout the test run, indicating all deposition was taking place in the test section.

It can be observed that the temperature rise (and thus the salt deposition thickness) is not continuous. The average clean test section inner-surface temperature was about 396°C. A temperature rise of about 15°C was noticed at 0.15 m location in ten minutes and then it dropped suddenly. This indicated that the salt deposited was removed at the end of the cycle. This 10-minute cycle was repeated nine or ten times during the 90-minute run. It seems that the salt was depositing and then at the end of the cycle the deposition was removed due to an increase of pressure. During the period when pressure was increasing, the fluid temperature at the exit of pre-heater 2 also increased thus indicating a plug-like condition. During the test run, the conductivity in the effluent fluctuated, indicating the salt deposition and removal were taking place in the system. At 0.61 m location, three such cycles were observed but at the end of each cycle the temperature did not drop all the way to the clean condition thus a small deposit was left over. There was a steady temperature rise noticed at locations after 1.5 m and no sudden removal of deposit occurred. The thermocouple at 1.5 m location showed a temperature increase of about 18°C over the 90 minutes of operation. Similarly at 2.8 m location the temperature increased steadily by about 8°C. The system relief valves were set to a pressure of about 29 MPa and once the relief valve opened the test run was terminated. The flow from the metering pump was switched to pure water to clean the system.

The deposition/removal cycles were studied by observing temperatures at different locations. In all of these cycles, the temperature at 0.15 m location showed a different trend as compared to temperatures at later locations. When it was close to plugging the pressure and the pre-heater 2 temperature increased very quickly and only the thermocouple at 0.15 m behaved in the same manner. The temperatures at later locations either remained same or reduced until the plug was removed and then a sudden increase in temperature was noticed. Thus the location of the plug was just after the 0.15 m location. Another observation was that after the salt was removed from the 0.15 m location, no sudden temperature increase was noticed at the later locations. Thus the removed salt was not sticking at other locations in the test section.

During the time when salt solution was being passed through the system, the effluent was collected in a tank. The salt concentration in the effluent tank was 0.075 wt.%. The saturation limit corresponding to the test section temperature

was 0.018 wt.%. The ratio of effluent concentration and saturation limit is thus 4.2, which is four times higher as compared to the heterogeneous case. Thus due to homogeneous nucleation more salt was able to flow through the system and resulted in longer running time before the test run had to be terminated.

### Homogeneous nucleation only

These runs were made to further reduce the salt deposition such that more salt flows through the system. The test section was not heated in this run in order to reduce the heterogeneous nucleation. A sample test run from this set of experiments is shown in Fig. 6.

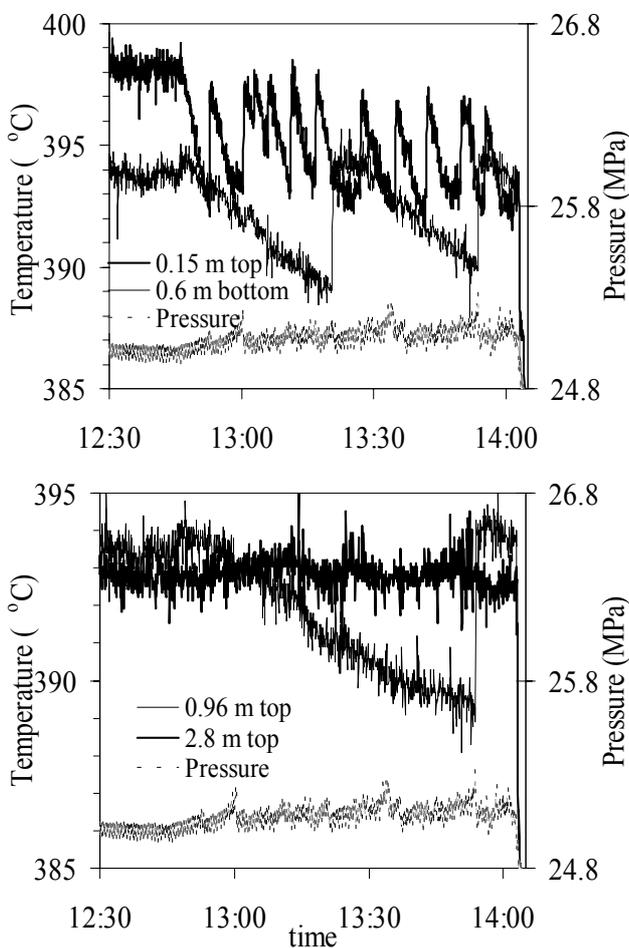


Fig. 6. Temperature and pressure behavior for a homogeneous nucleation run

The flow rate for this run was 1.32 kg/min. The salt delivery rate at the inlet of the test section would thus be 1.32 g/min. The average clean test section inner-surface temperature and bulk fluid temperature leaving the test section was about 396°C. The bulk fluid temperature at the

end of the long reactor sections, which were also not heated, was 383°C. Thus a temperature drop of less than 15°C was noticed due to heat losses.

While the salt was being deposited, the surface temperature dropped due to the insulating salt layer. This is different as compared to the other runs in which the surface temperature increased since the test section was being heated in those cases. There was no sign of plugging and the test run was terminated after running for 75 minutes.

A number of deposition/removal cycles were noticed in this type of experiments also. At 0.15 m location, there were about 10 of these cycles and at 0.6 m location three such cycles occurred with temperature reducing back to clean surface conditions thus indicating that all of the deposit was being removed. One such cycle was observed at 0.96 m location. During the 90 minute run the temperature at 2.8 m location remained constant thus there was no deposition at that location. There was a pressure drop of about 138 kPa over the test section and pressure at the end of the test section remained constant.

Table 1. Comparison of deposition experiments with three types of particle nucleation,  $C_o/C_{SAT}$  is the ratio of effluent salt concentration to saturation concentration

Experiment Type	Salt delivery rate (g/min)	$\frac{C_o}{C_{SAT}}$	Comments
Heterogeneous nucleation only	1.25	1	Expected time to terminate test run about 20-30 min.
Homogeneous & heterogeneous nucleation	1.32	4.2	Plugging in 90 minutes.
Homogeneous nucleation only	1.32	5.0	No sign of major plugging in 75 min.

Salt concentration going into the test section was 0.1 wt.%. During the time when salt solution was being passed through the system, the effluent was collected in a tank and the effluent salt concentration was 0.09 wt.%. The saturation limit for the test section temperature was 0.018 wt.%. For the run in which the test section is not heated the surface temperature was calculated as the average of the first few thermocouples in the test section. The ratio of concentration in tank and saturation limit is 5, which is even higher than the last type of experiments. In the absence of heterogeneous nucleation, more salt was able to flow through the system thereby increasing the time before the system is plugged. Table 1 shows a comparison of these three types of particle nucleation experiments.

## CONCLUSION

Three types of Na<sub>2</sub>CO<sub>3</sub> deposition, on the heat transfer surface at SCWO conditions, have been studied in this paper. In the presence of heterogeneous nucleation of salt on the tube surface, fluid leaving the tube is at the saturation limit corresponding to the surface temperature and all the undissolved salt sticks to the tube wall. The system could not be run for more than 30 minutes for typical SCWO conditions and periodic removal of deposition need to be done to operate the system. However if the salt is made to nucleate in the bulk fluid the net deposition rate of the salt on the tube surface was reduced and we were able to run the SCWO apparatus for a longer period of time. For a test run in which both heterogeneous and homogeneous nucleation of salt was occurring the test section plugged after 90 minutes of operation. Salt concentration leaving the test section was four times higher than the saturation limit. The net deposition rate was further reduced when homogeneous nucleation was occurring only.

For an actual SCWO plant, this means that the waste treatment can be carried out for a longer period of time. The fouling of pre-heaters can be eliminated in this manner, since only water (and oxygen) would be flowing through them. Once the required fluid temperature is achieved at the end of the pre-heater sections, the waste can then be injected thereby encouraging homogeneous nucleation. The inorganics nucleated in this manner are thus more likely to flow through the tubular reactor.

The third type of experiments discussed in this paper showed that the net deposition rate is further reduced if the section after mixing chamber is not heated. It was noticed that almost all of the salt deposited within the 3-m long test section with most of it immediately after the point of injection. Thus if the problem of plugging occurs during the process, the deposited salt has to be removed from only this short length of the reactor tube. This can be achieved online by mechanical means (Modell et al., 1993, Gairns and Joustra, 1999). The other option may be rapid cooling of this short tubular section; as a result the salt deposited on the tube surface would dissolve back into the bulk fluid again. In this type of experiment a temperature drop of less than 15°C was noticed over the 140-m long unheated reactor. During the treatment of actual waste, which is an exothermic reaction, this temperature drop will be further reduced; thus the reaction should be self-sustaining. Otherwise, some fuel may be added, in the aqueous waste, which oxidizes and produces heat enabling the reaction to be self-sustainable. Since the reactor wall may not be heated in this case, therefore heterogeneous nucleation would be reduced.

## Acknowledgements

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## REFERENCES

- H.E. Barner, C.Y. Huang, J. Johnson, G. Jacobs, M.A. Martch, W.R. Killilea, 1992, "Supercritical water oxidation: an emerging technology", *J. Hazardous materials*, Vol. 31, No. 1, pp. 1-17
- J.P.C. Chan, C.A. LaJeunesse, and S.F. Rice, 1994, "Experimental Techniques to Determine Salt Formation and Deposition in Supercritical Water Oxidation Reactors", *HTD-Vol. 296, Fire, Combustion and Hazardous Waste Processing*. Eds. S. Acharya, K. Annamalai, C. Presser and R.D. Skocypec.
- P.J. Crooker, K.S. Ahluwalia, Z. Fan, and J. Prince, 2000, "Operating Results from Supercritical Water Oxidation Plants", *Ind. Eng. Chem. Res.* Vol. 39, No. 12, pp. 4865-4870
- S.A. Gairns and J. Joustra, 1999, "Apparatus for self cleaning of process tubes", US Patent 5,890,531
- M.S. Hodes, 1998, "Measurements and modeling of deposition rates from a near-critical, aqueous, sodium sulfate and potassium sulfate solutions to a heated cylinder", Ph.D. thesis, Massachusetts Institute of Technology.
- M.S. Hodes, K.A. Smith, W.S. Hurst, W.J. Bowers, W.J. and P. Griffith, 1997, "Measurements and Modeling of Deposition Rates from a Near Supercritical Aqueous Sodium Sulfate Solution to a Heated Cylinder", *HTD-Vol. 350, National Heat Transfer Conference*, Vol. 12, pp. 107-119
- M.S. Khan and S.N. Rogak, 2003, "Solubility of Na<sub>2</sub>SO<sub>4</sub> and Na<sub>2</sub>CO<sub>3</sub> and their mixture in supercritical water" paper accepted for publication in *Journal of Supercritical Fluids*
- P. Krtizer and E. Dinjus, 2001, "An assessment of supercritical water oxidation (SCWO) Existing problems, possible solutions and new reactor concepts". *Chemical Engineering Journal*, Vol. 83, pp. 207-241
- M. Modell, E.F. Kuharich, F. Evan, M.R. Rooney, 1993, "Supercritical water oxidation process of organics with inorganics", US Patent 5,252,224
- S.N. Rogak, P. Teshima, 1999, Deposition of sodium sulfate in a heated flow of Supercritical Water, *AIChE Journal*, Vol. 45, pp. 240-247
- K.A. Smith, M.S. Hodes, P. Griffith, 2002, "On the potential for homogeneous nucleation of salt from aqueous solution in a natural convection boundary layer", *ASME Journal of Heat transfer*, Vol. 124, pp. 930-937
- P. Teshima, 1997, "Fouling rates from a sodium sulfate-water solution in supercritical water oxidation reactors", Masters thesis, The University of British Columbia.