REFEREED PAPER

INVESTIGATION OF FEASIBILITY OF MECHANICALLY REMOVING EVAPORATOR SCALE DEPOSITS WHILE EVAPORATORS ARE IN OPERATION

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Abstract

Evaporator scaling is still a major bottleneck in the sugarcane processing industry. It leads to reduced evaporation rates, increased operation costs due to cleaning and lost productivity due to downtime. Over the past years various evaporator scale prevention methods have been investigated by various authors. These include juice softening, the use of antiscalant chemical addition and the use of modified tube surfaces (e.g. polished tubes and non-stick coated tubes). At present, no intervention of this kind is being used in South African sugar factories. In 2014, the Sugar Milling Research Institute NPC (SMRI) investigated the use of scrubbing objects inserted into evaporator tubes for *in situ* prevention of scale formation. The scrubbing object diameter was chosen to be smaller than the tube diameter such that the object continuously oscillated up and down due to the bubbling nature of juice in the tubes. A number of objects with different densities and shapes were constructed and inserted into second effect factory evaporator tubes. The study aimed at quantifying the efficacy of these objects in minimising scale formation during evaporator operation. The scrubbing objects did not significantly reduce the amount of scale deposited in evaporator tubes. This paper looks at the trial procedure and results, and suggests reasons why the tube cleaning objects were not as effective as was originally hoped.

Keywords: evaporator scaling, continuous mechanical cleaning, scrubbing objects

Introduction

Evaporator scaling is still a major bottleneck in the sugarcane processing industry as it prohibits evaporators from operating continuously through a season. Evaporators are typically operated in cycles of between one and three weeks before the evaporators have to be stopped for removal of scale from the tubes. In addition to lost operating time, the scaling also leads to reduced heat transfer coefficients (HTC). This results in reduced evaporation rates during duty and increased operating costs. The evaporator scaling problem has affected the sugarcane processing industry for decades and a cost-effective solution to this problem would be of instant significant economic benefit to the industry.

Over the past years various evaporator scale prevention methods have been investigated by various authors (Table 1). No intervention of this kind is currently being used in South African sugar factories.

Table 1. Evaporator scaling reduction techniques investigated in the South African sugar industry.

Technology	Investigation outcomes	Limiting factors	References
Clear juice softening	Evaporator scaling reduced by about 50%. Proportion of calcium precipitates, amorphous phosphates and organic material reduced relative to silica deposited.	Major costs for NaCl required for regeneration of resins. Large quantities of waste generated. Potential loss of sucrose to molasses due to the melassigenic effect of added Na^+ in the softened juice.	Thompson, 1994 Davis *et al.*, 1997
Dosing antiscalant chemicals	Reduction of calcium oxalate. Increase in amorphous silica.	High HTC not maintained. No reduction in scale observed.	Ramaru, 2014 Walthew and Turner, 1995
Installation of polished tubes	Evaporator fouling not reduced.	No benefits observed.	Markham, 1997
Tube coating with 'non-stick' fluoropolymer	Most of the tube surface area remained free of scale. However, scale accumulated at the ends of the tubes where the coating was damaged when the tubes were fitted into the evaporator.	High costs of coating the tubes offsite. Coating layer reduces the overall HTC of a clean tube.	Purchase and Voigt, 2012

The concept of mechanically reducing scale deposits in evaporator or heat exchanger tubes whilst they are in operation has been widely used in large processes such as waste water concentration and steam generation plants (Anon, 2013a; Anon, 2013b; Klaren, 2000; Taprogge, 1957). Two examples of this technology are (1) the use of small particles in a fluidised bed evaporator; and (2) circulation of large compressible balls under a pressure gradient. Applications include concentrating waste water in various industries such as the pulp industry, medium density fibreboard manufacturing and food processing. Several commercial scale installations of the self-cleaning fluidised bed evaporators/heat exchangers are reported by Klaren (2000).

Small fluidised particles

The fluidised bed evaporator or heat exchanger uses small particles (1-4 mm glass, wire or ceramic objects) to scrape the scale off the heat transfer surface area at an early stage of formation before the scale builds up and hardens (Klaren, 2000). Particles enter with the fouling liquid into the evaporator/heat exchanger distribution system where they are pumped vertically up through the vessel. At the outlet section, particles are separated by an external downcomer which uses a cyclone to separate the particles from the fluid. It is reported that the HTCs can be kept constant for months of operation in evaporator systems which otherwise show rapidly decreasing HTCs. For example, the performance of a process which had HTC values of about 2.5 $kW/m^2.K$ that usually dropped to 0.5 $kW/m^2.K$ within 30 days of conventional operation was kept constant for more than 80 days in service when the evaporator was operated with fluidised solid particles (Klaren, 2000). Cleaning wire particles showed a weight loss of about 2% with no noticeable wear on the tubes after 12 months of operation; however, the lining of the cyclone required minor repairs (Klaren, 2000).

Compressible balls propelled under a pressure gradient

Another method of continuous cleaning of evaporator/heat exchanger tubes that has been implemented at industrial scale is the concept of self-cleaning of heat exchangers using compressible rubbing bodies. Taprogge (1957) patented the use of sponge balls with a diameter larger than the tube diameter to clean heat exchanger tubes while the heat exchanger is in the working mode. However, a high pressure gradient is required to force the balls through the heat exchanger tubes.

Application of scrubbing technologies to the sugar processing evaporators

To date, no application of self-cleaning evaporator technology has been reported in the sugar industry. For both the compressible ball and small fluidised particle technologies, there are specific challenges with adapting them for use in the sugarcane factory evaporators.

The compressible ball technology has been developed for heat exchangers in single phase flow. The typical velocities through the heat exchanger tubes are about 2 m/s, approximately 20-fold greater than the liquid velocities in Kestner and Robert type evaporators. It is anticipated that the compressible ball technology will not be suitable for current designs of Kestner and Robert type evaporators due to the high risk of blocking the tubes, resulting in the tubes drying out, which will promote scaling. In addition, it is anticipated that the probability of achieving even distribution of balls between tubes during the circulation of juice in the evaporators will be low.

On the other hand, the concept of using fluidised particles is unattractive in food processing streams because of the difficulty of achieving a clean separation. Therefore, extra capital and operating costs will be incurred due to the additional equipment required to separate the particles. In addition, the likelihood of small particles remaining in the final product would be substantial.

It was proposed that a hybrid approach for juice evaporators could eliminate these problems; a scrubbing object small enough to move within the tubes, but large enough to be retained in the tubes by a coarse mesh at the outlet, might be able to remove scale or prevent scale formation by friction with the walls at low fluid velocities without contaminating the product.

This work aimed to investigate the effect on scale formation of inserting an object of a diameter smaller than the tube into an evaporator tube, such that the object would continuously move up and down due to the bubbling nature of juice in the tubes. It was hypothesised that interaction of the inserted objects with the tube wall would scrape off the scale before the deposits built up and hardened.

It was proposed to retain the objects in the evaporator tubes by mounting a wire mesh on top and at the bottom of the evaporator plate, thus eliminating the need for a recirculation system. The objects needed to be small enough to reduce the risk of them becoming lodged in the tube, but large enough to promote contact with the tube wall as they moved up and down.

This was a preliminary investigation that aimed at identifying whether there was any potential for continuing investigations into oscillating scrubbing objects. Therefore, the experimental objective was to test a range of object geometries and densities to see whether a substantial reduction (greater than 50%) in evaporator scale deposited could be achieved.

Method

The project plan consisted of the following steps: (i) design of scrubbing objects; (ii) introduction of objects to the evaporator tubes; and (iii) assessment of scrubbing object performance.

Design of scrubbing objects

The scrubbing objects were selected to be less dense than the fluid as preliminary laboratory trials had showed that wider oscillation ranges in the tubes were obtained when the objects were less dense than the fluid (Ramaru and Foxon, 2014). The objects were designed for use in a second effect evaporator. Smith's correlation (as reported by Peacock, 1995) was used to estimate the brix of second effect syrup at approximately 30% with a corresponding calculated density of 1074 kg/m^3 at 100°C. Polypropylene (PP) was selected as a suitable material of construction due to its favourable density, temperature resistance and price.

Five trials were conducted to see whether a substantial reduction (greater than 50%) in evaporator scale deposited could be achieved. Table 2 shows the shapes, dimensions and densities of the scrubbing objects of each trial. Figure 1 shows the objects.

Table 2. Shapes, dimensions and densities of the objects inserted into the tubes.

Objects	Length (mm)	Diameter (mm)	Density (kg/m^3)	No. of objects per trial
Trial No. 1 (trial duration = 2 weeks)				
28 mm sphere	n/a	28	999	1
25 mm cylinder with bristle	110	25	946	1
35 mm double cone (grooved)	100	35	946	1
20 mm cylinder with cleaning sponge at the ends	95	20	946	1
Trial No. 2 (trial duration = 2 weeks)				
28 mm sphere	n/a	28	999	1
40 mm double cone (grooved)	100	40	946	1
20 mm cylinder with cleaning sponge at the end (facing down)	100	20	946	1
20 mm cylinder with cleaning sponge at the end (facing up)	100	20	946	1
Trial No. 3 (trial duration = 2 weeks)				
35 mm double cone (grooved)	100	35	946	2
25 mm cylinder with bristle	110	25	946	1
Trial No. 4 (trial duration = 4 weeks)				
28 mm sphere	n/a	28	999	1
28 mm cylinder	71	28	816	1
28 mm double cone (smooth)	71	28	816	1
28 mm single cone facing downwards	71	28	816	1
Trial No. 5 (trial duration = 4 weeks)				
28 mm double cone (smooth)	71	28	946	2
28 mm double cone (smooth)	71	28	816	3
25 mm double cone (smooth)	71	25	946	2

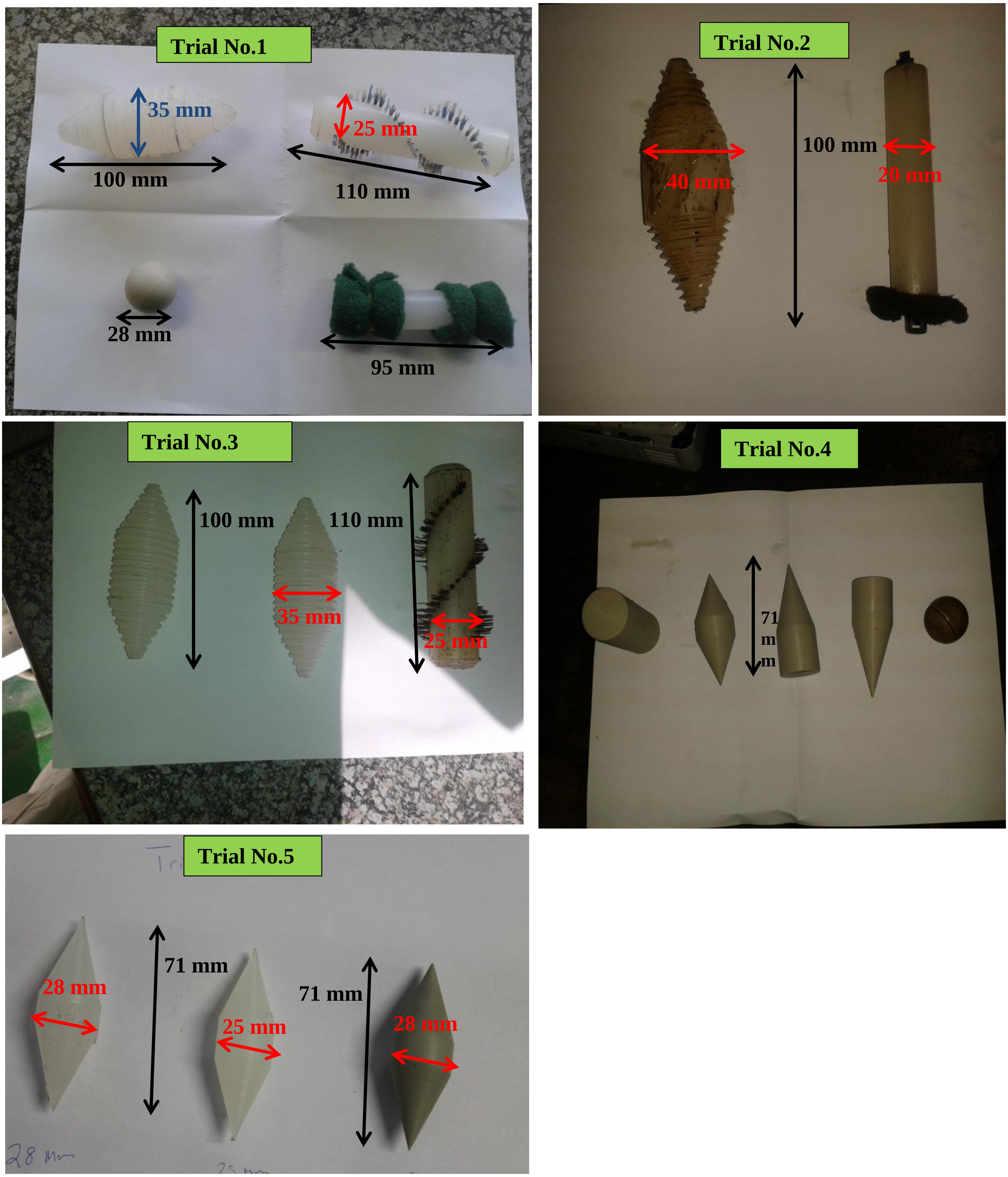

Figure 1. Images of the objects inserted into the tubes.

Introduction of scrubbing objects to evaporator tubes

The experiment was run on a second effect evaporator at Sezela sugar mill. During a scheduled maintenance day, each object was inserted into its own tube after the tubes had been mechanically cleaned. Second effect tubes at Sezela sugar mill are about 3.525 m long with an inner diameter of 0.049 m. Wire mesh was mounted on top and at the bottom of the evaporator tube plates to prevent the objects from exiting the tubes (Figure 2). The wire mesh covered an area in excess of 12 tubes. Tubes that were covered with wire-mesh, but did not contain the objects were used as the *control* tubes against which the *test* tubes could be compared at the end of the trial. The objects during trial Nos. 1 to 3 were left in the tubes for two weeks as the evaporator vessels at Sezela sugar mill are cleaned every second week. However, it was noted that the quantity of scale deposited per *control* tube was small. As a result, for trial No. 4 and trial No. 5 the objects were left for four weeks to allow for accumulation of larger quantities of scale deposits over a longer period so that a comparison between *control* tubes and *test* tubes could be made with larger sample sizes. The section that was covered with the wire mesh was deliberately not cleaned when the factory stopped for cleaning during the two week mark, but cleaned after four weeks for trial No. 4 and trial No. 5.

Figure 2. Wire mesh mounted on top of an evaporator tube plate.

Assessment of scrubbing object performance

At the end of the two or four week period, the scale deposits that had accumulated on the tube walls during evaporator operation were collected during routine physical scale removal. All recoverable scale deposits from all the *test* tubes and from four *control* tubes were collected for each trial. The scale was dislodged by descaling tools while water was added simultaneously to the tubes. A 25 L bucket was held in position below the evaporator tube plate to collect a mixture of scale deposits and water while the tubes were being cleaned. The scale deposits were filtered using a 15 µm filter paper, dried and weighed at the SMRI. The compositional analysis of two randomly selected scale samples of trial No. 5 was conducted by X-ray powder diffraction (XRD) and energy dispersive X-ray analysis (EDX) methods. Some dissolution of readily dissolvable precipitates could have occurred during the collection process; however, solubilities of species which are dominant in sugarcane processing evaporators are very low, so the losses should have been negligible (Walthew and Turner, 1995).

Results and Discussion

Figure 3 shows that the overall averages of the masses of scale deposits from the *control* tubes for two week and four week trials were 23 g and 92 g per tube, respectively. The error bars on the graphs represent the standard deviation calculated from all replicate measurements. For the inserted objects to be deemed to have achieved a substantial scale reduction the masses would need to be at least 50% less than the masses from the *control* tubes. Thus, the maximum amount of scale accumulated per tube would need to be 11 g per tube and 46 g per tube for the two week and four week trials, respectively. The values for *control* tubes appeared to be from two different populations for trial No. 4 and trial No. 5, indicating that scaling characteristics during the two trials may have been substantially different. However, because of the low number of replicates possible for these experiments (four in each case) the two data sets were lumped for the purposes of setting a target value to represent a conservative and consistent target for assessing the performance of the *test* tubes.

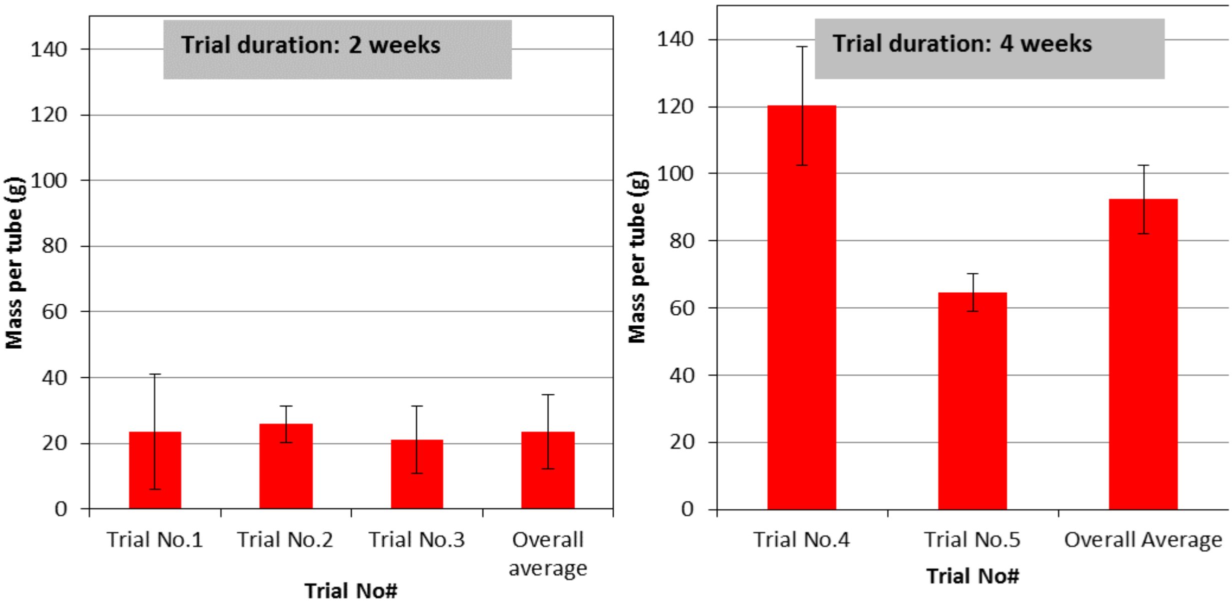

Figure 3. The overall averages of the *control* tubes for two week and four week trials. Error bars represent the standard deviation of the masses of scale collected from *control* tubes for all trials with length 2 and 4 weeks, respectively.

Figure 4 to Figure 8 show the masses of the scale deposits collected from the *test* tubes and the average masses from the *control* tubes for each trial. It was noted that there was no consistent substantial reduction in evaporator scale deposited across the range of object geometries and densities tested. In fact, it appears that the double cone objects with larger diameters promoted evaporator scaling rather than reducing it. This might be as a result of them hindering the flow of juice through the tubes, leading to reduced wetting rates. In trial No. 4, a 28 mm double cone object met the target. However, the result of the repeat trial using the same object (i.e. trial No. 5) showed no substantial reduction, so the results from trial No. 4 were not sufficient to suggest that the object itself was the cause of the low mass of scale recovered.

In trial No. 5, it was observed upon emptying the evaporator that two of the cleaning objects had become stuck in the middle section of tubes, probably due to scale build-up which eventually reduced the inner diameter of the tube. They dropped to the bottom when the tubes were cleaned by the descaling tools.

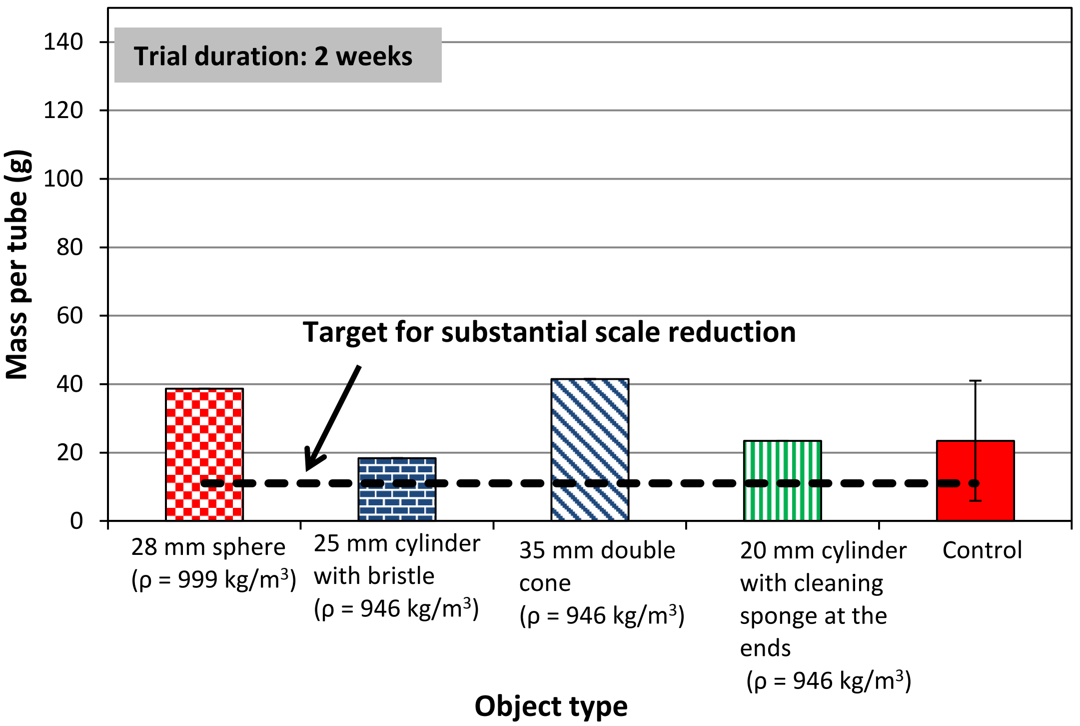

Figure 4. Masses of scale deposits collected from the tubes with the objects compared with the average mass from the *control* tubes for trial No. 1. The target scale reduction is calculated from the average mass of scale in *control* tubes over trial Nos. 1, 2 and 3. The error bar for the *control* tubes is the standard deviation calculated on the mean mass of scale collected from *control* tubes for trial No. 1.

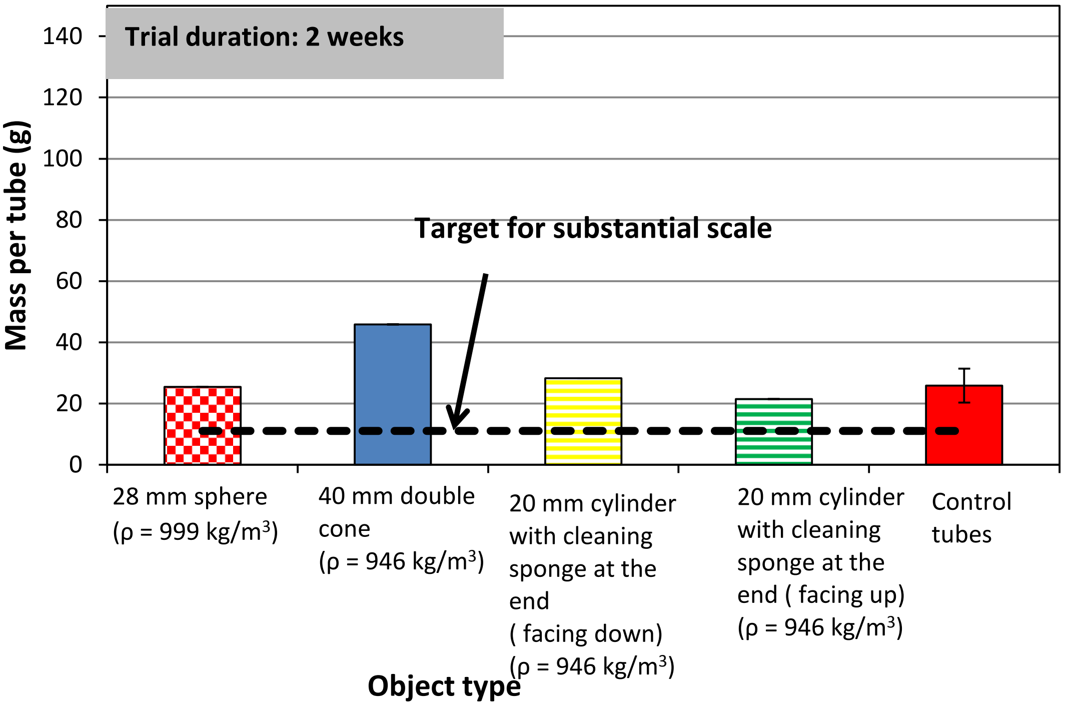

Figure 5. Masses of scale deposits collected from the tubes with the objects compared with the average mass from the *control* tubes for trial No. 2. The target scale reduction is calculated from the average mass of scale in *control* tubes over trial Nos. 1, 2 and 3. The error bar for the *control* tubes is the standard deviation calculated on the mean mass of scale collected from *control* tubes for trial No. 2.

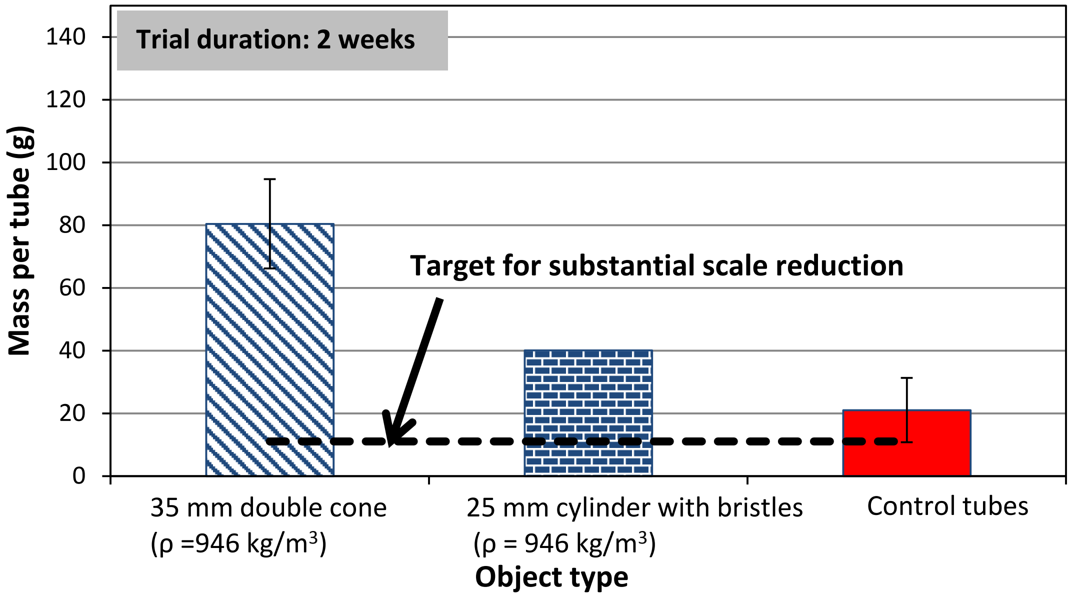

Figure 6. Masses of scale deposits collected from the tubes with the objects compared with the average mass from the *control* tubes for trial No. 3. The target scale reduction is calculated from the average mass of scale in *control* tubes over trial Nos. 1, 2 and 3. The error bar for the *control* tubes is the standard deviation calculated on the mean mass of scale collected from *control* tubes for trial No. 3.

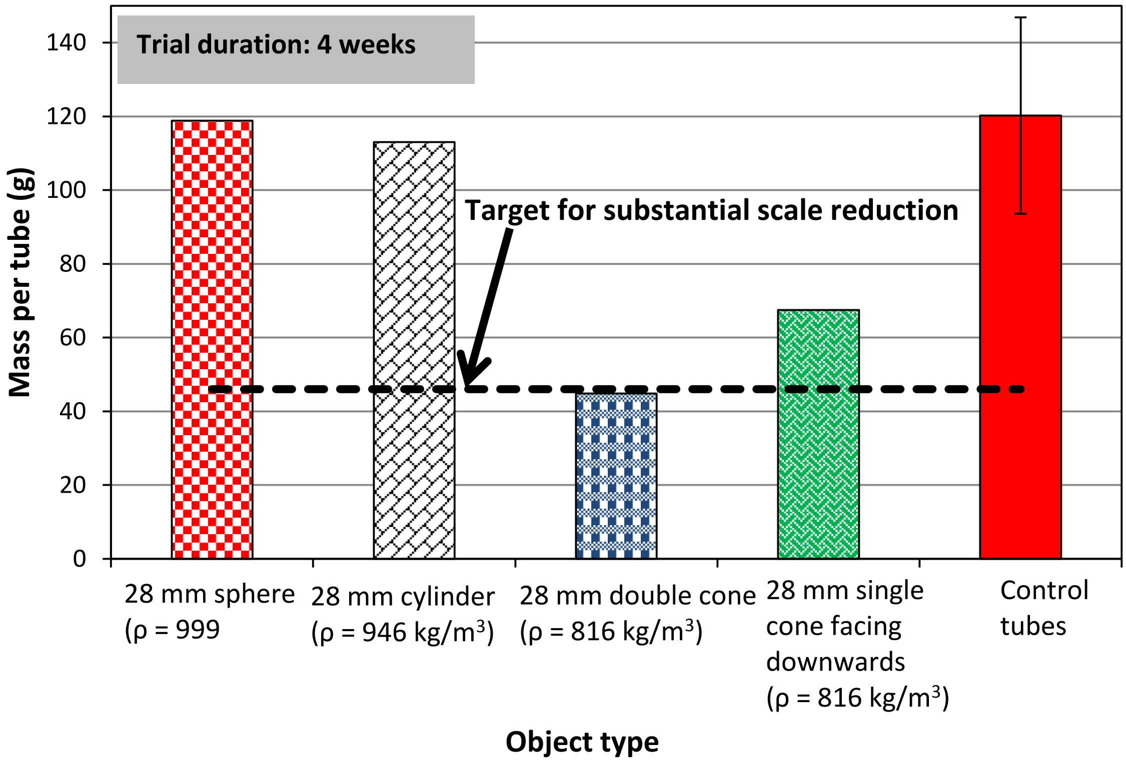

Figure 7. Masses of scale deposits collected from the tubes with the objects compared with the average mass from the *control* tubes for trial No. 4. The target scale reduction is calculated from the average mass of scale in *control* tubes over trial Nos. 4 and 5. The error bar for the *control* tubes is the standard deviation calculated on the mean mass of scale collected from *control* tubes for trial No. 4.

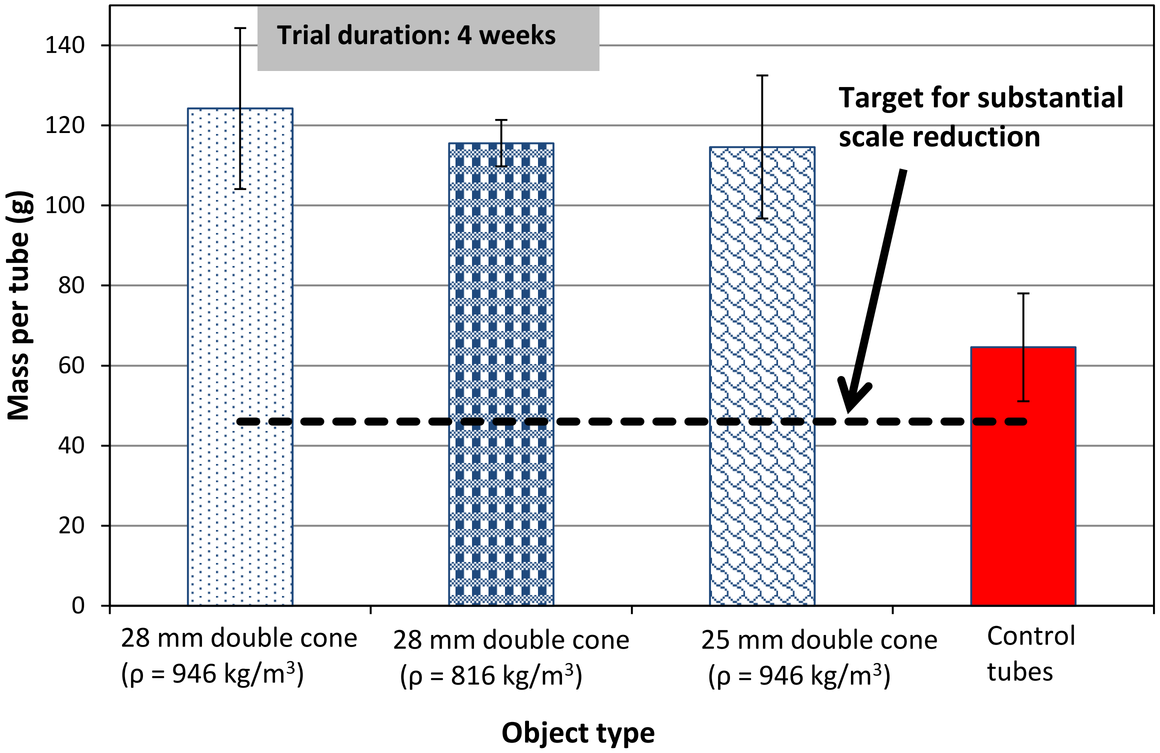

Figure 8. Masses of scale deposits collected from the tubes with the objects compared with the average mass from the *control* tubes for trial No. 5. The target scale reduction is calculated from the average mass of scale in *control* tubes over trial Nos. 4 and 5. The error bar for the *control* tubes is the standard deviation calculated on the mean mass of scale collected from *control* tubes for trial No. 5.

The objective of substantial reduction of scale of about 50% was not achieved and therefore the potential of extending the cleaning cycle of evaporators using this technology was too low to justify further investment in the project.

It was also noted that some scale was deposited on the cleaning objects surfaces that were expected to be in contact with the tube surface during operation (see Figure 9). This suggests that the contact of the objects with the tube wall was not aggressive enough to remove the scale deposits.

Figure 9. Objects after the trial showing scale deposits.

The XRD analysis showed the composition of both the *control* and *test* scale deposits from single samples from a 4-week trial to be mainly amorphous calcium phosphates, calcium oxalate hydrate and amorphous organic materials (see Table 3). The compositional analysis by XRD showed that there was no substantial difference in the percentage of the components between the *control* and *test* scale deposits. However, the XRD data was inconclusive due to very poor crystallinity of the samples. Nevertheless, C, O, Ca and P elements were identified as major components of both the *control* sample and the *test* sample by the EDX method confirming that the samples were indeed made up of amorphous organic and calcium phosphate phases in association with calcium oxalate monohydrate (Table 4). The XRD and EDX results also do not support the hypothesis that the scrubbing objects substantially alter the composition of the scale.

Amorphous organics and calcium phosphates are typical scale deposits found in second effect evaporators and are reported to be relatively easy to clean compared to composite silica and calcium oxalate scale deposits found in later effects (Doherty *et al.*, 2002 and Yu *et al.*, 2003). Given that the objects were unable to remove the 'easily removable' scale from the second effect, the chance of them being able to remove the harder scale from the later effects is minimal.

Table 3. The scale or crystalline phase analysis of samples from trial No. 5 by the XRD method.

Crystalline phase	**Chemical composition**	***Control* scale deposits**	***Test* scale deposits**
Crystallinity	-	Very poor	Very poor
Trace hydroxylapatite (HAP) and amorphous phosphates	$(Ca.Mg)x.(PO_4)_y.nH_2O$	Major>25%	Major >25%
Gypsum	$CaSO_4.2H_2O$	Trace<2%	Trace<2%
Calcium oxalate monohydrate (COM)	$CaC_2O_4.2H_2O$	Minor<20%	Major>25%
Soluble molasses salts	$K_2(Ca,Mg)\ (SO_4)2H_2O + KCl$	Not detected	Not detected
Amorphous silica including some MgO	$(Mg, Si, Al)\ O_2.H_2O$	Trace <2%	Trace <2%
Amorphous organic compounds	C-H-N-O	Major<50%	Major<50%

Table 4 Bulk chemical characterisation of samples from trial No. 5 by EDX method.

Weight % element	***Control* scale sample**	***Test* scale sample**
C	39.84	31.77
O	39.04	40.86
Mg	0.81	1.14
Al	2.86	0.64
Si	0.22	0.13
P	4.96	7.48
S	0.17	0.26
Cl	0.05	0.06
K	0.02	0.08
Ca	11.68	16.66
Mn	0.11	0.53
Fe	0.24	0.37

Conclusions

This study investigated the extent to which the objects of various shapes that were less dense than the process fluid and narrower in diameter than the evaporator tubes could continuously clean factory evaporator tubes on the juice side whilst the evaporator was in operation. It was found that the various objects inserted in the second effect vessel were not able to achieve a substantial reduction in evaporator scale deposited relative to *control* tubes. In fact, the double cone objects seemed to intensify the scaling in the tubes, probably due to the objects hindering the flow of juice through the tubes, leading to reduced wetting rates.

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