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Industrial experiments for the application of ultrasound on scale control in the Chinese sugar industry ☆

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Abstract

The industrialized application of a technique of scale control by ultrasound was investigated in this paper. The results indicated that not only the viscosity of sugar solution was reduced, but also the heat transfer coefficient and evaporation intensity of the evaporation system were improved by 42.4% and 15.2% respectively, and the scale was removed remarkably with no significant effects on white sugar quality. In addition, chemical detergent was not necessary, so no chemical contamination existed and labour intensity was reduced in this technique. Furthermore, the ultrasonic equipment is easy to operate and has good performance in terms of high continuity and automisation.

Keywords: Ultrasonic wave; Evaporation; Scale deposition; Equipment

1. Introduction

Scale in evaporators, boilers or heaters is one of the difficult problems to solve in many industries such as sugar, papermaking or chemical fertilizer, where lots of liquids must be evaporated. It has caused many economic losses because of its low heat transfer capacity. In sugar factories in China alone, the losses are RMB 0.6 billion annually. In 1977, due to the increase of energy and decrease of production capacity resulting from scale, British national economic losses were estimated at 0.5 billion pounds [1].

At present, various methods (chemical, mechanical and physical) are commonly used for cleaning. However, because scale sticks to the walls of tubes or vessels strongly, its removal often requires synergistic methods. At the same time, whatever method is used, the evaporation process must be stopped and the evaporators tend to become worn and corroded. In order to solve this problem, many methods of scale prevention have been proposed, such as deploying antiscalants, ion exchange, electric or magnetic fields. Unfortunately, these methods have not been widely adopted in the sugar industry for various reasons [2].

Since ultrasound has been reported to have many effects on compounds in solution, its influence on scale in evaporators was studied in our laboratory. Experimental results indicated that ultrasound could not only inhibit the formation of scale, but also remove scale efficiently. Based on many researches, a new technique with equipment of scale control was developed in 1998, which has been used in a sugar factory until now. Its application in the factory, where the sulfurous acid method was adopted to refine sugar, was investigated below,

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before it passed the appraisal of scientific and technical achievement, which was overseen by Guang Dong Province, China.

2. Ultrasonic equipment design, its installation position and working principles

This equipment is made up of three parts: ultrasonic generator, ultrasonic transducers and rectangular reaction pipeline. Its working frequency is 20 kHz and ultrasonic power 2000 W. The transducers are installed on the outside of the bottom of the rectangular reaction pipe. The main part is a powerful ultrasonic wave generator. Its electrocircuit design is also special. Forty-eight transducers are divided into four groups (12 transducers/group) and each group is controlled by its own integrated circuit with one switch. Any group can be chosen to run so that ultrasonic power can be changed according to operation parameters. All transducers can endure a high temperature (95–105 °C) and protect themselves automatically. Through tracing ultrasonic frequency automatically, the ultrasonic generator and transducers can always run in a good condition. Based on special design, the whole equipment system can run for a long time without any care because of its high automation, and its operation is also easy.

As shown in Fig. 1, the ultrasonic equipment is installed between the juice sedimentation vessel and the evaporator.

Scale formation on the heating area of heat transfer equipment conforms to the mechanism of mass crystallization. For a clean heating surface, heterogeneous nucleation provides more nucleation spots since an uneven surface can decrease the surface energy necessary for nucleation. Adsorption action makes scale nuclei to first form on the uneven surface. Under the effects of ultrasonic cavitation, the induction period of nucleation of a various of materials that form scale is shortened, thus crystal scale nuclei are produced in a short time. A large proportion of the non-sugars, especially inorganic or organic impurities, can be deposited onto the nuclei, instead of on the surface of the heating tubes. These deposits remain suspended in the sugar solution, and flow out of the evaporators with the syrup. They can then be separated from it. Thus the amount of precipitate deposited onto the surface of evaporator tubes can be greatly reduced [3–6].

3. Method

Investigation on scale control by ultrasound was performed in a sugar factory with five evaporation systems. The heat transfer coefficients (HTC) of the evaporators were low, and scale deposition was a very serious problem so that lots of chemical reagents had to be used to clean it, and two evaporators had to be cleaned in turn every day, before the ultrasonic technique was introduced.

In order to make clear the performance of the ultrasonic technique, seven parameters were investigated: viscosity of juice/syrup, evaporation intensity (EI), HTC of evaporators, efficiency of removing scale (ERS), time to clean scale as well as usage of chemical detergents and effects of ultrasound on white sugar. The viscosities of clear juice and syrup were all determined by the viscometer with the sensitivity of 0.001 mPa s at 20 °C, However, the syrup in the end evaporator must be diluted to 36% (concentration) at 20 °C before determination.

The sampling method was as follows. Every half an hour, samples of clear juice and the syrup in each batch was taken once, and the pressures, temperatures of each evaporator as well as the flow rate of clear juice were recorded at the same time. Every four samples (over a period of 2 h) were mixed as a collected sample for analysis of concentration. EI and HTC were calculated according to the formulae mentioned in detail in Ref. [7].

The sampling and determination of the ERS was as follows. Before the evaporator was cleaned, its two heating tubes were used for sampling, the scale deposited on their surface was collected, examined, dried and weighed. ERS was expressed the percentage of removed scale, which equals the difference of scale weights (gram) with and without ultrasound divided by the scale weight without ultrasound. (Notice: when taking samples, the evaporation time should be the same.) In order to compare the time of cleaning of scale with and without ultrasound, the time spent on cleaning the two sampling tubes and evaporators must be recorded. The indices of white sugar were sampled and determined according to “Sugar Industry Analysis” [8].

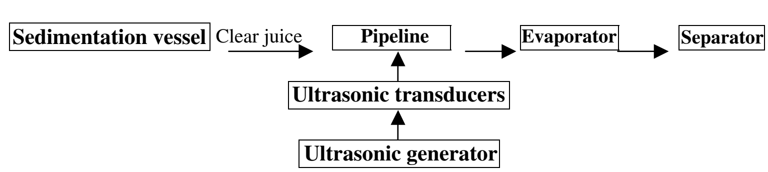

Fig. 1. Flow chart for the structure and installation position of ultrasonic equipment at a factory.

4. Results and discussion

4.1. Influence of ultrasound on syrup viscosity

A series of physical and chemical changes take place during the evaporation process, which affects the viscosity of syrup. Table 1 indicates that the syrup was less viscous when the ultrasound treatment was applied than when it was not. As shown in Table 2, after the clear juice was evaporated, the syrup viscosity increased whether ultrasound was used or not. However, the viscosity difference was smaller with ultrasound than without it, as further ultrasonic treatment decreased the syrup viscosity. Thus these results also supported the hypothesis that the viscosity of solution would be reduced by ultrasound.

Viscosity (i.e. inner friction) is defined as the force between two layers of liquids, so it is related to the force between liquids' molecular forces. Like any other sound wave, ultrasound is transmitted via waves which alternately compress and stretch the molecular structure of the syrup through which it passes. Thus, the average distance between the molecules in the syrup, will vary as the molecules oscillate about their mean position. When the acoustic pressure is the pressure on rarefaction, the molecular distance increases. Otherwise, it decreases if a sufficiently large negative pressure is applied to the syrup that the distance between the molecules exceeds the critical molecular distance necessary to hold the liquid intact, the syrup liquid will break down so that the inner friction force of molecules in syrup decreases. So the viscosity of syrup decreases with it.

4.2. Influence of ultrasound on the HTC and evaporation intensity

Table 3 shows the evaporation intensity (EI) of syrup in the end evaporator was improved by 15.2%, and HTC by 42.4%. As can be seen ultrasound has a significant effect on HTC and evaporation intensity.

The relationship between HTC and viscosity is: $K \propto a/\mu^{0.25}$ (K is HTC, a is heat conductivity coefficient and μ is solution viscosity). That is to say HTC is inversely proportional to viscosity. As the viscosity of the syrup declines (Table 2), HTC improves and EI also improves. Another reason that HTC and EI improves is that scale was inhibited and removed by ultrasound, as shown in Table 4. As a result of the EI and HTC being improved by ultrasound, the residence time of the syrup in the evaporators is reduced, and the sucrose losses due to inversion decreases. Therefore, it is beneficial for the processing and the quality of white sugar.

Table 1
The viscosity of syrup before/after ultrasound treatment

Sample no.	Syrup concentration (%)	Viscosity (before) (mPa s)	Viscosity (after) (mPa s)
1	26.82	1.721	1.659
2	30.42	1.744	1.683

Table 2
Average viscosity of syrup in the end evaporator (A) and clear juice into the first evaporator (B)

	Viscosity (A) (mPa s)	Viscosity (B) (mPa s)	Viscosity difference (mPa s)
With ultrasound	1.667	1.957	0.290
Without ultrasound	1.599	2.040	0.441

Table 3
Average EI and HTC of the end evaporator

Methods	EI ($kg\ m^{-2}\ h^{-1}$)	HTC ($w\ m^{-2}\ °C^{-1}$)	Remarks
With ultrasound	10.6	715	A
Without ultrasound	9.2	502	B
% Improved by ultrasound	15.2	42.4	

A—the average of 14 time's determination; B—the average of 11 time's determination.

Table 4
The results of the efficiency of scale removal by ultrasound

Evaporator no.	Scale weight (g) without ultrasound	Scale weight (g) with ultrasound	ESR (%)	Average ESR (%)
0	75.1	1.6	97.9	
1	120.2	16.9	85.9	
2	128.5	41.8	67.5	
3	147.5	45.4	69.2	
4	173.3	48.2	72.2	
5	198.5	68.5	65.5	76.4

4.3. Influence of ultrasound on the efficiency of scale removal

Table 4 shows that the scale in evaporator no. 0 was the least, ESR reached 97.9%, The ESR for evaporator no. 1 was also higher at 85.9%. The ESR of the other evaporators were between 65% and 72%. The average ESR of all evaporators was 76.4%. In addition, by detecting the physical characteristics of scale, the scale with ultrasound was found to be loose, soft and white in colour after being dried. It could be easily removed by tapping. In contrast, the scale without ultrasound was dense, hard and yellowish in colour after drying. It could not then be removed completely even by a steel brush. Therefore, not only could the scale be reduced significantly, but its physical character was changed by ultrasound. The reason why HTC was improved by ultrasound (Table 3) was also explained by the results in Table 4 since HTC was affected by the quantity of

Table 5
The thickness of scale deposit (TSD) and losses of heat transfer capacity (LHTC)

TSD (mm)	0.4	0.8	3.17	4.75	6.34	9.50	12.68	15.90	19.0
LHTC (%)	2	4	9	18	38	48	60	74	90

scale (See Table 5, LHTC decreases when TSD is reduced).

4.4. Influence of ultrasound on labour intensity to remove scale

4.4.1. Comparison of time spent on removing the scale from two defined tubes

See Table 6.

4.4.2. Comparison of time spent on removing evaporator's scale

Tables 6 and 7 indicate that the time spent in removing scale deposit on tubes of evaporators was less with ultrasound some 38–75% of that without ultrasound, as was significantly shown by the results of nos. 4 and 5 evaporators. In addition, during cleaning, scale was found to be removed easily after the treatment of ultrasound, compared with no ultrasound treatment, and some scale was also seen to fall down to the bottom of each evaporator with ultrasound. It could be inferred that some scale previously formed had already been removed by ultrasound. On the other hand, the number of scale breakers used to remove scale could also indicate the performance of ultrasound further. Before 1997, no ultrasound equipment was used to treat syrup, every 10,000 ton sugar cane needed seventy scale breakers. However, since the equipment was used, it was only twenty four. Thus it requires less labour to clean evaporators which employ ultrasound.

Table 6
Comparison of time spent on removing scale from two defined tubes

Evaporator no.	Evaporation time (day)	People × time with ultrasound	People × time without ultrasound
4	1	1 × 0:04	1 × 0:12
5	1	1 × 0:06	1 × 0:18

Remarks: people × time = 1 × 0:04 means one person spent 4 min on cleaning scale deposit on the two tubes, the others were expressed in the same way. The tubes scale was cleaned with no water in them.

Table 7
Comparison of time spent on removing evaporator's scale

EN	EHA (m^2)	ET (Days)	People × time with ultrasound	People × time without ultrasound
0	350	9	3 × 2:00	4 × 2:05
1	250	8	3 × 1:30	4 × 1:36
2	200	4	3 × 2:30	3 × 4:30
3	170	4	3 × 2:10	3 × 4:20
4	170	1	4 × 2:00	4 × 5:20
5	170	1	4 × 2:15	4 × 5:30

Remarks: EN—evaporator no, ET—evaporation time, EHA—evaporator's heating area; people × time = 4 × 2:05 means four persons spent 2 h and 5 min on removing scale deposit on all heating tubes of the evaporator, the others were expressed in the same way. The scale was cleaned when full of water in all tubes of the evaporator.

4.5. Influence of ultrasound on the usage of chemical detergent

Since ultrasound equipment was used in the factory in 1998, chemical detergents have seldom been used for cleaning evaporators. Between the years 2000 and 2001, more than 25,000 tons of sugar cane has been used to produce white sugar and no chemical detergent was used to clean scale because of the treatment with ultrasound. For example 0.7–1.0 ton Hua Qing no. 1 (a chemical detergent, about RMB 8000–10,000 yuan) and 2.0–2.5 ton hydrochloric acid (RMB 1600–2000 yuan) had been used for every 10,000 ton sugar cane for cleaning evaporators, before the ultrasonic technique was adopted in this factory. As a result of the reduction of chemical detergent usage, not only were evaporators not eroded seriously, but also production cost decreased.

4.6. Influence of ultrasound on quality of white sugar

The quality indices of the product, white sugar, were not significantly affected by the ultrasound treatment (as shown in Table 8). According to the White Sugar National Standard of China (GB317(1-91)), the products from the treatment of ultrasound were all within Grade One specifications although the colour, the haze and the impurity with ultrasound were a little higher than that without ultrasound. However, the quality of white sugar

Table 8
Influence of ultrasound on quality of white sugar

	Sucrose (%)	Color (IU)	Haze (°)	Impurity (kg/kg)	Reduced sugar (%)	Ash (%)
GB	⩾99.6	⩽180	⩽9	$\leqslant 6\times 10^{-2}$	⩽0.10	⩽0.10
WS	99.72	153	7.5	4.7×10^{-2}	0.041	0.045
WOS	99.73	139	6.3	4.4×10^{-2}	0.052	0.051

Remarks: GB—white sugar National Standard in China (GB317(1-91)); WS—with ultrasound, WOS—without ultrasound.

from ultrasonic treatment could be improved if an advanced syrup filtration method or relevant technique was used to improve the colour, the haze and the impurity.

5. Conclusions

1. With this ultrasonic technique and equipment, the HTC and evaporation intensity of evaporators can be improved greatly, and the viscosity of the sugar solution decreases with ultrasound. The investigation results of evaporators indicated the HTC and evaporation intensity were improved by 42.4% and 15.2% respectively.
2. The efficiency of removing scale ranged from 65% to 98%, and the average was 76.4% under ultrasonic treatment.
3. With the treatment of ultrasound, the time of cleaning an evaporator was reduced to 38–75% of that without ultrasound. Forty-six scale breakers were saved for every 10,000 ton sugar cane and thus labour intensity decreased significantly. Usage of chemical detergents (no. 1 HuaQing and hydrochloric acid) also decreased greatly.
4. There was no significant influence of ultrasound on the quality of white sugar. Its indices were all within the White Sugar National Standard of China.
5. The ultrasonic equipment is easy to operate, needs little maintenance and has a good automised performance.

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