The effect of scaling on heat transfer in a first-effect falling-film evaporator

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Abstract

In recent times, falling-film type evaporators have gained attention in the cane sugar industry owing to their ability to operate at lower temperature differences, a good heat-transfer coefficient at high brix, and low juice residence time in the evaporator. The falling-film type (tubular) evaporator station at the ICPL sugar mill has been in operation since 2011. The station was reconfigured in 2013 with additional heating surface area to increase the juice processing capacity and further reduce the exhaust steam consumption. After seven years in operation, a second evaluation of the evaporator performance was undertaken. One of the performance evaluation objectives was to understand the effect of scaling on the heat transfer of the first-effect falling-film evaporator over 34 days of operation without cleaning. A scaling formation theory is postulated to predict the build-up of scale for uninterrupted operation. The paper provides an insight into the operation of a first-effect falling-film evaporator in a cane sugar factory.

Keywords: falling-film evaporators, heat-transfer coefficient, scale thickness, scale formation

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Introduction

In the last two decades, the cane sugar industry has invested heavily in co-generation plants and technologies to reduce steam consumption for process operations. From installing high-pressure boilers to replacing steam turbines with electrical drives for the extraction station (shredder and mills) and much more, the industry has come a long way in achieving the low steam consumption it so greatly seeks. The evaporator station is the largest consumer of low-pressure steam (typically 200 to 250 kPa abs) in the sugar factory. It concentrates the clear juice (15 brix) to syrup (nearly 70 brix) in multiple-effect evaporators taking into account energy efficiency and the capital costs of the installed heat-transfer area (Thaval 2019).

The Robert type remains by far the most common evaporator design for cane sugar mills worldwide. The Kestner type is a popular design in the South African sugar industry and is usually employed for the first and second effects, followed by a Robert. However, alternative technologies have now emerged and proven to be better than the conventional Robert type. The falling-film evaporator has gained attention over the past years owing to its ability to operate at lower temperature differences, a good heat-transfer coefficient at high brix, and low juice residence time in the evaporator. Additionally, the possibility of vapour bleeding from later effects in the evaporator set helps reduce the exhaust steam consumption for process operations. These operational features and the smaller footprint of the evaporator make it an attractive option for cane sugar mills (Thaval, 2020).

Ashtiani Abdi *et al.* (2020) reported the performance of a 4 000 m^2 BMA type falling-film evaporator in the first-effect position at the Bingera sugar mill in Australia. The experimental programme undertaken throughout an entire crushing season included heat-transfer measurements, juice residence-time distribution, sucrose-loss measurements, de-entrainment efficiency and practical recommendations for falling-film evaporator (FFE) operation.

Thaval (2020) presented the heat-transfer coefficients of BMA type falling-film evaporators, measured at the ICPL sugar mill in India over two weeks to assess the performance of the evaporator station compared to an evaporator station comprising entirely of Robert's vessels. The assessment included the heat-transfer performance, operational strategies and predicted sucrose losses in falling-film and rising-film evaporators.

This paper presents the effect of scale on the heat transfer of the falling-film evaporator in the first-effect position at the ICPL sugar mill over 34 days without cleaning. A scale formation theory is postulated to predict the build-up of scale throughout the uninterrupted operation.

Falling-film evaporators at ICPL, India

The BMA type falling-film evaporator (FFE) station at Indian Cane Power Limited, Uttur, has been in operation since 2011. Lehnberger *et al.* (2014) detail the results of the first performance evaluation undertaken after the commissioning of the station. The station was designed for a crushing capacity of 6 000 TCD, with double-sulphitation (juice and syrup) clarification for producing plantation white sugar.

In 2012, two additional falling-film evaporators were installed, each with a heating surface area (HSA) of 4 000 m^2, replacing FFE-3 and FFE-4. The original FFE-4 with an HSA of 1 000 m^2 is employed as a standby evaporator for FFE-5. Post the modifications, the HSA for the falling-film evaporators were as follows: FFE-1 to FFE-4 – 4 000 m^2 each; FFE-5 – 1 000 m2 (Brahim *et al.*, 2018). Installing the falling-film evaporators and optimising the sugar house with the installation of continuous vacuum pans on A massecuite with BMA type (VKT) and batch pans, the cane processing rate was increased to 9 000 TCD, and the steam consumption was reduced to 28 % on cane (Brahim *et al.*, 2018).

Configuration of existing falling-film evaporator set

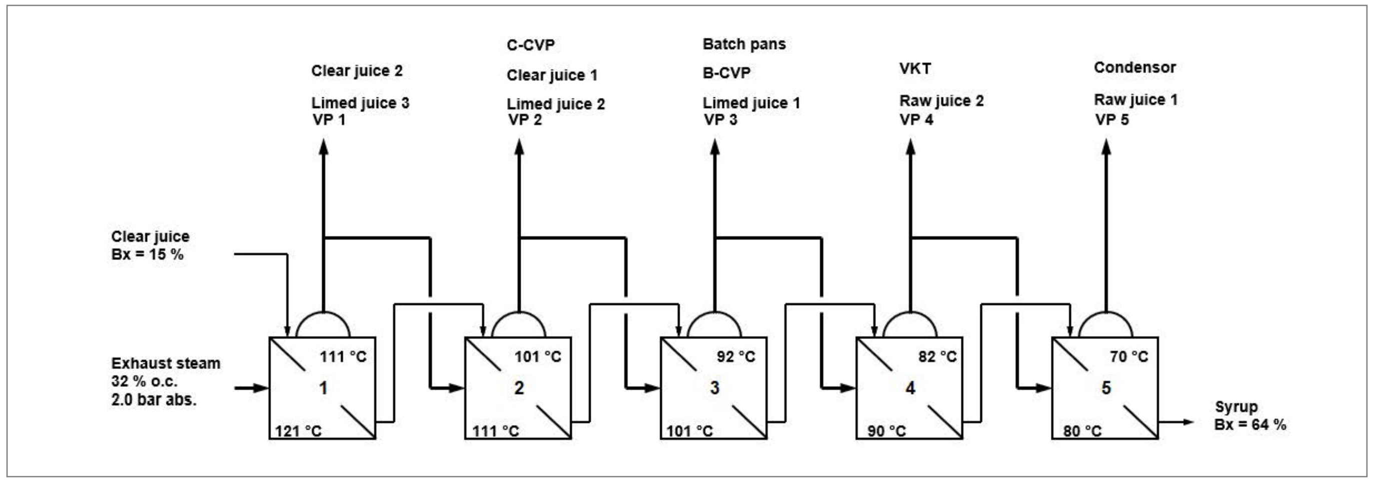
Figure 1 shows a schematic diagram of the evaporator station, typical operating conditions and the vapour bleeding scheme for the experimental programme. The falling-film evaporators operate with an independent juice circulation system. The heating tubes are accessible from the top tube plate for inspection and, if required, hydraulic cleaning with a high-pressure water jet (Lehnberger *et al.*, 2014).

Thaval (2020) summarises the configuration and the cleaning schedule of the falling-film evaporators.

Heat-transfer performance of falling-film evaporators

Thaval (2020) details the experimental programme undertaken on the falling-film evaporators at the ICPL sugar mill in December 2019 over two weeks. Composite samples of clear juice from the clear juice tank and exit juice from each of the five falling-film

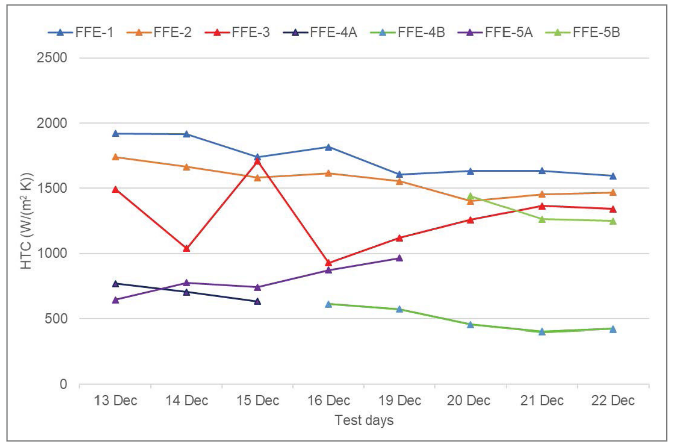
Figure 1: Evaporator station at ICPL with typical operating conditions and vapour bleeding scheme



evaporators were collected over two hours. Two sets of samples were collected in the morning shift and another two sets in the afternoon shift, with a total of 24 samples throughout the day. The samples were placed in a cold-water bath to reduce the temperature to 30 °C.

The heat-transfer coefficients of the individual falling-film evaporators were calculated for each of the days in the testing period; they are presented in Figure 2. The HTC of FFE-1 and FFE-2 are shown to be decreasing with an increase in the number of days without cleaning. The HTC of FFE-3 is shown to be oscillating; this is attributed to the inefficient removal of non-condensable gases. The calandria pressure of FFE-2 is just above the atmosphere (1.04 bar abs), as shown in Table 2. With a change in vapour bleeding demand from vapour 2, the pressure will reduce, and the venting of non-condensable gases will be hampered, causing a build-up of gases in the calandria and affecting heat-transfer performance.

Figure 2: Heat-transfer coefficients of individual falling-film evaporators during the test days (daily averages)



Effect of scaling on heat-transfer coefficient

For a defined temperature difference across the evaporator set, the juice processing capacity of the evaporator station decreases due to scale formation in the heating tubes. The scale build-up on the inner surfaces of the tube acts as additional resistance to heat transfer and reduces the heat-transfer coefficient.

Ashtiani Abdi *et al.* (2020) reported the heat-transfer efficiency of a 4 000 m² BMA type falling-film evaporator processing clear juice (ESJ) at 400 m3/h. The vapour condensation coefficient or vapour loading on the falling-film evaporator was typically 27.5 kg/h/m2. The heat-transfer coefficient immediately after a clean was in the range of 3 000 – 3 250 W/m²/K and, after five days in operation, typically ~2 750 W/m²/K or slightly higher. On average, the rate of HTC deterioration was 65 W/m²/K per day. Ashtiani Abdi *et al.* (2020) assumed the average value for the scaling factor of 0.10 (Broadfoot and Dunn, 2007) to represent the scaling expected for the falling-film evaporator over two weeks. Using the scaling factor, the HTC was predicted to decline from 3 150 W/m²/K after a clean to ~2 300 W/m²/K after 14 days of operation.

Operating conditions of FFE-1 at ICPL sugar mill

To better understand the effect of scaling on the heat-transfer coefficient over a longer period, the heat-transfer coefficient of FFE-1 at ICPL sugar mill, India, was calculated over six weeks from the factory DCS data. The DCS measurements include the exhaust condensate flow, FFE-1 calandria and headspace pressure. Thaval (2019) details the equations to calculate the heat-transfer coefficient of an evaporator based on condensate flow measurements.

Exhaust steam pressure at the onset of the crushing season was 1.53 bar abs; it gradually increased as the scale in the FFE-1 started to build up. On day 34 of operation since the last clean, exhaust steam pressure had reached 2.3 bar abs, and the entire evaporator station was stopped to clean the FFE-1 and FFE-2 effects. The clear juice flow rate was ~250 m3/h at the onset of the season. As the crushing gained momentum, the clear juice flow rate increased to 340 m3/h and was maintained by increasing the exhaust steam pressure and temperature difference across FFE-1, as shown in Figure 3. Table 1 summarises the operating conditions of FFE-1 with weekly average values.

Figure 3: Exhaust steam and FFE-1 vapour pressures and clear juice flow rates (daily averages)

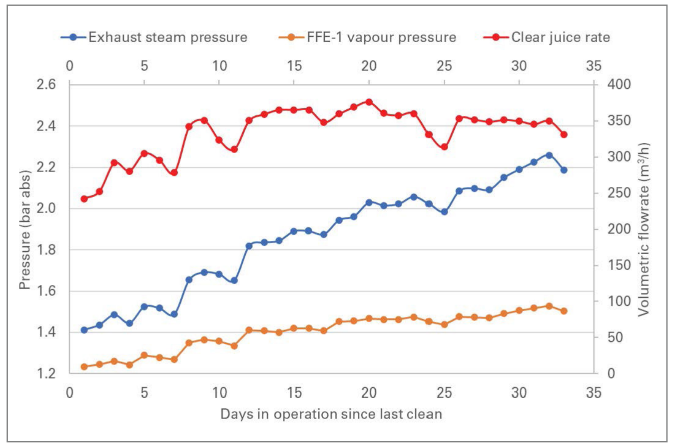


Table 1: FFE-1 operating conditions (weekly average values)

Parameter	Unit	Week 48/19	Week 49/19	Week 50/19	Week 51/19	Week 52/19
Number of days since crushing has commenced*		8	15	22	29	34
Exhaust steam temperature	°C	111.2	116.4	119.6	121.3	122.7
FFE-1 vapour temperature	°C	106.5	108.9	110.3	110.7	111.2
Clear juice feed	t/h	311	398	430	399	405
Clear juice temperature	°C	106.0	105.8	105.5	104.9	105
Clear juice dry substance content	Bx	15.02	15.10	15.2	14.9	15.01
Clear juice purity	%	85.6	85.2	85	84.5	84.6

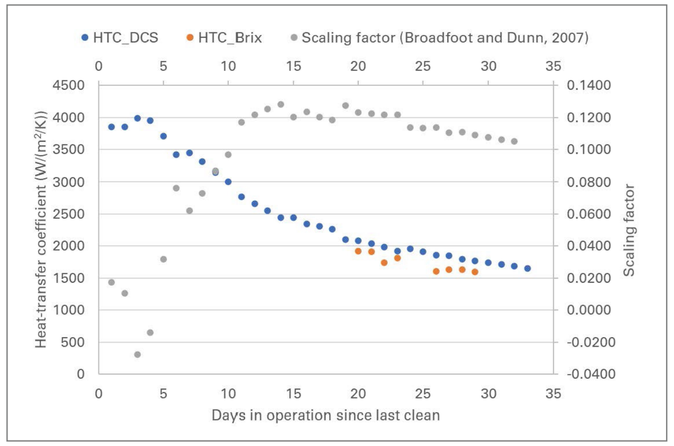
* Calculated to the end of week

Heat-transfer coefficient of FFE-1 and scaling factor

The heat-transfer coefficient of FFE-1 was determined from the data mentioned above over 34 days. Anti-scale reagents were added to the clear juice tank and to all falling-film evaporators, the total addition not exceeding 18 ppm. Based on factory experience, anti-scaling reagents can extend the cleaning interval by seven to ten days beyond regular operation.

Figure 4 shows the heat-transfer coefficient since the last clean. The blue plot represents the HTC calculated from the DCS data, while the orange plot represents the HTC calculated during the test period (from brix measurements). The differences between the HTC measurements from the DCS data and the brix measurements are, on average, 9 % (ranging from 6 to 14 %). This difference could be attributed to heat losses, errors in condensate and/or brix measurements etc. However, the gradient of the plot for both measurements is very similar.

Figure 4: Heat-transfer coefficient and scaling factor of FFE-1 since last clean



At the onset of the crushing season, the heat-transfer coefficient was ~3 800 W/m2/K, with relatively clean tubes. Over the next five days in operation, it increased to 4 000 W/m2/K and subsequently started to decline. The rise in the heat-transfer coefficient could be attributed to an increased sensible heat load in heating the juice in FFE-1 until the crushing is steady. Plotting a linear regression on the HTC_DCS data shows a rate of decline in HTC of 76 W/m2/K per day, which is slightly higher than the HTC deterioration of 65 W/m2/K per day reported by Ashtiani Abdi *et al.* (2020).

The scaling factor from the relationship proposed by Broadfoot and Dunn (2007) is shown in Figure 4. Ashtiani Abdi *et al.* (2020) found the values to lie between 0.01 and 0.17, with an average value of 0.10 and a standard deviation of 0.05. Since the falling-film evaporator's performance at the Bingera mill could not be assessed over two weeks, Ashtiani Abd *et al.* (2020) assumed that the scaling factor would be around 0.10 and constant over time. Using the expression proposed by Broadfoot and Dunn (2007), the scaling factor was determined over six weeks, as shown in Figure 4. The scaling factor rises sharply in the first two weeks of operation. After that, it gradually decreases with an increase in the number of days of operation since the evaporator was last cleaned. It is evident from Figure 4 that a constant scaling factor assumption would result in too low a prediction of HTC, especially in the early days of operation. Therefore, an alternative model for scale build-up on the heating surface and the influence on HTC is proposed.

Scale build-up on evaporator tubes

Scale formation theory

For the scale formation model, it is assumed that the scale thickness in clean conditions is zero. However, from practical experience, this is not entirely true. Even in a meticulous cleaning procedure, for example, chemical cleaning followed by mechanical and/or hydraulic cleaning, it is difficult to remove 100 % of the scale.

The heat-transfer coefficient HTC is a function of the scale thickness tk_{scale} and the scale thermal conductivity λ_{scale}, as shown in Equation 1. When the scale thickness is negligible, the heat-transfer surface is depicted as clean, and the heat-transfer coefficient is denoted by HTC_{clean}.

$$HTC_{tk_{scale}} = \left(\frac{1}{HTC_{clean}} + \frac{tk_{scale}}{\lambda_{scale}}\right)^{-1} \qquad 1$$

where $HTC_{tk_{scale}}$ is the heat-transfer coefficient at any value of scale thickness, W/(m² K)
HTC_{clean} is the heat-transfer coefficient at negligible value of scale thickness,
W/(m² K)
tk_{scale} is scale thickness, mm
λ_{scale} is the thermal conductivity of the scale, W/(m K)

The thermal conductivity of the scale (λ_{scale}) is taken as 1.0 W/(m K) (Bubnik *et al.*, 1995). The scale build-up is potentially a linear function of time t, with the scaling coefficient c_{scale} being the constant as shown in Equation 2. This results in a linear function of time t for the thermal resistance R, which is the inverse of HTC. Equation 3 starts at the point in time t = 0 with clean conditions.

$$tk_{scale}(t) = c_{scale} * t \qquad 2$$

where c_{scale} is the scaling coefficient expressed in mm/day
t is time, days

$$R_t = R_{clean} + \frac{c_{scale}}{\lambda_{scale}}\, t \qquad 3$$

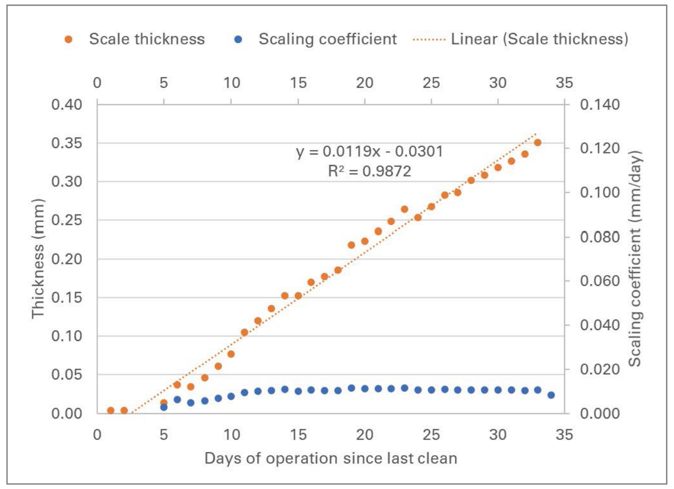
where R_t is thermal resistance at the point in time t, (m² K)/W
R_{clean} is the thermal resistance at negligible value of scale thickness, (m² K)/W

As shown in Figure 5, scale thickness grows linear with the increase in the number of days of operation since the last clean. The scaling coefficient remains more or less constant at 0.01 mm/day.

Application of the scale formation theory

The heat-transfer coefficient measurements made on the FFE-1 at the ICPL sugar mill and the scale formation theory described above were used to determine the scale thickness and the scaling coefficient for FFE-1. The scale thickness ranges from 0 mm on the first day of operation to 0.34 mm after 34 days in operation since the FFE-1 was last cleaned. The increase in scale thickness causes a subsequent reduction in HTC by 60 %. The scaling coefficient is relatively constant at 0.01 mm/day (Figure 5). This value would reflect the cane quality, extraction of impurities during milling or diffusion and clarification techniques undertaken

Figure 5: Linear scale thickness (tk_{scale}) and scaling coefficient (c_{scale}) of the FFE-1 at ICPL



in the factory. Walthew *et al.* (1998) showed the effect of changing the lime quantity in clarification on the proportion of silica components in evaporator scale in individual effects. Moreover, they showed that the pH of the juice during the extraction process influences the leaching of silica compounds from cane, which dominate the scale in the last effect.

The composition of scale in cane sugar mill evaporators varies across individual effects. Several investigations have been undertaken to determine the composition of scale in different evaporator positions. In the early evaporator stages, the scales are largely phosphate compounds. In subsequent effects, oxalate and silicate compounds are found in different proportions in the evaporator scale, as well as sulphates (when juice sulphitation is undertaken) (Walthew *et al.*, 1995; Rackemann *et al.*, 2011; Lehnberger *et al.*, 2014).

Fouling on the surface of heat exchangers is generally described by different types and phases (Yu, 2004). Yu *et al.* (2004) derived other trends concerning time for the fouling factor. Yu (2004) investigated the fouling mechanisms in the conditions in Australian (Robert) evaporators for three substances: sugar, silicates and oxalates. The model developed with crystallisation fouling without significant removal of the formed deposits results in a linear fouling rate.

Compared to the Robert evaporators investigated by Yu, falling-film evaporators operate across very low-temperature differences; they have negligible subcooled boiling but surface boiling, and the shear forces of the juice film on the scale are low. Hence, linear growth of the scale layer without a temporal component for removal is plausible for falling-film evaporators. This relationship should apply to falling-film evaporators at all stages of the evaporation plant and should always result in a linear increase in scale thickness, as shown in Figure 5.

Plotting a linear regression of the scale thickness would allow the scale thickness of other falling-film evaporators to be determined, and the reduction in the heat-transfer coefficient of the evaporator could be calculated from equation 1. Suppose the evaporator is fitted with a condensate flow meter. In that case, the heat-transfer coefficient could be calculated from the equations detailed by Thaval (2019) and the scale thickness and scaling coefficient could be calculated from the equations 1, 2 and 3 presented in the previous section.

In hindsight, the scaling coefficient is an important indicator in evaluating the scale formation in the evaporator. It indicates the effect of cane quality, extraction process and clarification techniques on scale build-up in evaporator tubes.

Conclusions

A performance evaluation of the falling-film evaporator configuration at the ICPL sugar mill was undertaken. One of the objectives of the evaluation was to understand the effect of scaling on the heat-transfer of the first-effect falling-film evaporator over 34 days of operation without cleaning. A scale formation theory was postulated to predict the build-up of scale for uninterrupted operation.

The heat-transfer coefficient of FFE-1 was ~3 800 W/m²/K with relatively clean tubes, increasing to 4 000 W/m²/K over the next five days in operation, post which the heat-transfer coefficient started to decline. The scale thickness and scaling coefficient for FFE-1 were calculated using the heat-transfer coefficient measurements and the scale formation theory. The scale thickness ranged from 0 mm on the first day of operation to 0.34 mm after 34 days of operation since the FFE-1 was last cleaned. The increase in scale thickness caused a subsequent reduction in HTC by 60 %. The scaling coefficient was relatively constant at 0.01 mm/day.

A linear regression of scale thickness was developed, which would allow the scale thickness of other falling-film evaporators to be determined and the reduction in heat-transfer coefficient of the evaporator to be calculated. Suppose the evaporator was fitted with a condensate flow meter. In that case, the heat-transfer coefficient could be measured, and the scale thickness and scaling coefficient could be calculated based on the scale formation theory.

At the onset of the crushing season, the exhaust steam pressure was 1.53 bar abs, which gradually increased to 2.3 bar abs at the end of the six weeks as the scale in the FFE-1 started to build up. As a result, the average juice processing capacity of the evaporator station was consistent at 346 t/h.

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References

Ashtiani Abdi I, Zahn RA, Kumar SS, Sichter NJ, Broadfoot R (2020) Performance of the falling-film evaporator at Bingera mill. Proceedings of the *Australian Society of Sugar Cane Technologists* 42: 196-207.

Bubnik Z, Kadlec P, Urban D, Bruhns M (1995) Sugar Technologists Manual. Chemical and Physical Data for Sugar Manufacturers and Users. *Bartens*, Berlin.

Brahim F, Lehnberger A, Mallikarjun SS, Nasim R, Shafqat Ali Shah S (2018) Further reduction of steam demand at modern cane-sugar mills. *International Sugar Journal* 120: 688-696.

Lehnberger A, Brahim F, Mallikarjun SS (2014) Falling-film evaporator plant for a cane sugar factory: presentation of the concept and operating results. *International Sugar Journal* 116: 604-609.

Rackemann DW, Doherty WOS, East CP (2011) Development of descriptor tools for the characterisation of Australian sugar mill evaporator scale. *International Sugar Journal* 113: 282-288.

Thaval OP (2019) Investigating the effects of tube dimensions and operating conditions on heat transfer performance in a rising-film vertical tube evaporator. *PhD Thesis*, Queensland University of Technology, Brisbane.

Thaval OP (2020) Assessing the heat-transfer performance, operational strategies and sucrose losses of falling-film and rising-film evaporators. *Proceedings of the Australian Society of Sugar Cane Technologists* 42: 289-298.

Walthew DC, Khan F, Whitelaw R (1998) Some factors affecting the concentration of silica in cane juice evaporators. *Proceedings of the South African Sugarcane Technologists Association* 72: 223-227.

Walthew DC, Turner LM (1995) Analysis of scale from some South African sugar mills. *Proceedings of the South African Sugarcane Technologists Association* 69: 138–143.

Yu H (2004) The mechanisms of composite fouling in Australian sugar mill evaporators by calcium oxalate and amorphous silica. *PhD Thesis*, The University of New South Wales, Sydney.

Yu H, Sheikholeslami R, Doherty WOS (2004) The effects of operating parameters on composite fouling in sugar mill evaporators by calcium oxalate and amorphous silica. *Proceedings of the Australian Society of Sugar Cane Technologists* 26: (electronic media).