PRELIMINARY RESULTS FROM A LONG TUBE CLIMBING FILM PILOT EVAPORATOR

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Abstract

The design characteristics and the operation of a long tube, climbing film pilot evaporator situated at the Felixton mill are described. This pilot plant has been designed to investigate the effects of both mechanical and operational factors on evaporator performance through the measurement of the heat transfer coefficient (HTC). Preliminary results show the HTC values achieved on the pilot evaporator to be higher than those generally found in similar industrial evaporators, typically 2,9 compared with 2,2 kW/m^2/°C. The data obtained at this stage suggest that high HTC values can be achieved when the operating conditions maximise the fraction of the tube under regions of high heat transfer, namely annular and bubbly flow.

Introduction

In recent years there has been some concern throughout the sugar industry that the evaporator stations at certain mills have not been performing optimally. In some mills the evaporator stations become the bottleneck, resulting in an inability to maintain high crush rates. Low heat transfer in the evaporators can result in lower syrup brix and/or lower extraction as a consequence of reduced imbibition. While the installation of sophisticated data logging equipment has in some instances enabled precise measurement of variables, a thorough examination of the problem has been hampered by the difficulty in obtaining reliable and reproducible information under specific controlled conditions. The final heat transfer rates will be the result of the interaction between design, operational conditions and juice quality. Since evaporator performance is of interest to a number of mills, a project to construct a pilot evaporator at the Felixton mill was undertaken by the industry as a whole.

Description of the plant

It was agreed that the pilot plant should be capable of investigating the following:

- The effect of operating conditions.
- Chemical and other cleaning methods.
- Techniques of preventing fouling.
- The effect of tube dimensions.
- The effect of tube materials.
- The effect of juice composition.
- Corrosion.
- Recycling.

A most important requirement was that "performance" could be measured accurately and reliably, with cross checking where possible. In this regard the overall heat transfer coefficient (OHTC) was considered the best indicator of evaporator performance. Three methods of measurement are possible and all are incorporated in the design of the pilot plant:

- Brix balance. By measurement of the flowrate and juice brix into the evaporator, compared to the syrup brix produced, the energy required to evaporate the necessary amount of water can be calculated. If some energy is used to raise the temperature of the juice to boiling in the evaporator tube then this measurement will be lower than the true value. Corrections can be made if the feed temperatures are known.
- Vapour condensate measurement. If all of the water evaporated is recondensed then, as explained above, the energy transferred can be calculated, with the same error occurring if juice is not fed at the boiling point.
- Steam (calandria) condensate measurement. This is the most accurate method of measurement, since it indicates the heat transferred across the tube wall. Errors are possible if lagging is poor or the steam is wet.

The equipment construction and design were carried out by both the SMRI and the Tongaat-Hulett Technical Management Department. Since it was intended that the results from the pilot plant be applicable to large scale evaporators the tube dimensions were designed to be similar. The evaporator was designed to accept three tubes of the same diameter and length as those found in the main Kestners. The designed flowrates of the pilot plant and, for comparison, the main plant are shown in Table 1. The overall plant layout is shown schematically in Figure 1.

Table 1

Design criteria for FX pilot plant - first effect

	Main plant		Pilot plant equivalent	
Flowrate juice in maximum	480	tph	4,8	kg/min
Flowrate juice in minimum	250	tph	2,5	kg/min
Flowrate syrup out maximum	288	tph	2,9	kg/min
Flowrate syrup out minimum	150	tph	1,5	kg/min
Flow vapour maximum	192	tph	1,9	kg/min
Flow vapour minimum	100	tph	1,0	kg/min
Tube number	5041		3	
Tube length	7,3	m	7,0	m

The following features were designed into the pilot plant:

- Flow measurement. The product feed, vapour condensate and calandria condensate flowrates are all measured by means of tanks suspended on loadcells. Lines from the evaporator and separator to the tanks are cooled prior to discharge into the tanks to prevent flashing. The tanks are fitted with autosiphons so that long runs can be performed. As a crosscheck on the flowrate a magflow meter is fitted as shown in Figure 1. This is essential if accurate recycle data are to be obtained. A variable speed, positive displacement pump to feed the juice to the evaporator allows a wide range of feed rates to be used.

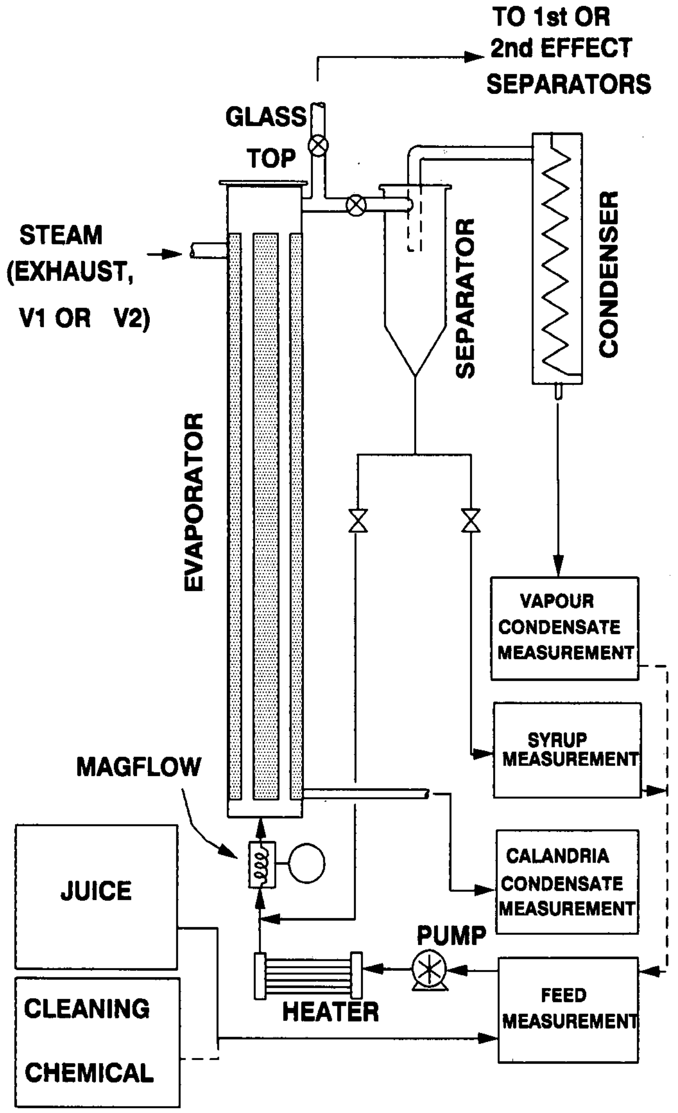

Figure 1 Pilot plant layout

- Datalogger and control. The plant is controlled and the necessary information is logged, using a computer programme written by Tongaat-Hulett Technical Management Department. The data obtained can then be imported into a standard spreadsheet programme for analysis and further manipulation. Data measured are: all flowrates, steam and vapour pressures, feed juice temperature and the pressure difference between the top and bottom of the tube. The juice height is estimated from measurement of the pressure difference over the tube, and is reported as a percentage of the tube length. Knowing the density of the juice enables an equivalent height to be calculated. Since the juice in the tube is a mixture of vapour and liquid this is only a relative measurement. A further check on the steam and vapour pressures is provided, in that the pressure difference between the head space and the calandria is measured. This difference can then be compared to the steam and vapour pressures actually logged. The datalogger allows measurements to be taken at various intervals, with a minimum interval of 15 seconds.
- Link to the main plant. The plant can run on exhaust steam, vapour 1 or vapour 2. This means that the maximum steam pressure possible is that of the exhaust range of the main plant. The juice feed can be taken from the clear juice line or the juice feed to the second effect. The vapour/syrup mixed flow from the pilot plant can be directed to the pilot plant separator, or to the first or second effect main plant separators. By using suitable combinations of these configurations, the plant can be run for extended periods under the conditions experienced by the main plant. Alternately, fixed conditions can be set for certain parameters during an extended run.
- Examination of special conditions. A mixing tank can be used to make up "synthetic" sugar solutions for strictly controlled runs where variations in juice composition may influence the results. Because of the independence from the main evaporators, the pilot plant can be run under extreme or widely different conditions. The syrup and vapour produced by the pilot plant can be recombined and recycled if necessary. A separate juice heater under the control of the datalogger enables the juice feed temperature to be examined. The mixing tank can also be used to make up special cleaning solutions for a study of chemical cleaning.
- Removable tubes. The tube fixing arrangement is designed to enable the relatively easy removal and replacement of the evaporator tubes. Thus the effects of different tube materials or surfaces can be considered, as well as the effect of different tube diameters (for instance, those smaller than 50 mm).

Theoretical considerations

Calculation of the heat transfer coefficient

The overall heat transfer coefficient (OHTC) is defined by the Fourier equation:

$$U = \frac{Q}{A \, \Delta T}$$

Where U = The overall heat transfer coefficient (OHTC) ($kW/m^2/°C$)
Q = Heat energy transferred (load) (kW)
A = Surface area (m^2)
ΔT = Temperature difference between the solution and the steam (i.e. across the tube wall) (°C)

While estimation of the amount of heat energy transferred (the load) is relatively straightforward and the surface area is known, the measurement of the temperature difference is fraught with difficulties. The OHTC calculation is sensitive to this value, particularly if the temperature difference becomes quite small. Assuming that the steam temperature is uniform, the difficulty is in finding the juice temperature profile up the tube, so that a best average temperature can be used. In practice, estimates of the juice temperature are made in two ways. The first and simplest method is to take the juice temperature to be that obtained by measuring the vapour pressure, reading the corresponding temperature from steam tables and adding the boiling point elevation (BPE) based on the brix change measurement or estimation.

A second, more complex, method assumes that the juice at the base of the tube is boiling and that the hydrostatic head results in an increased saturated steam pressure. The vapour temperature obtained from steam tables is then added to the BPE to obtain a temperature at the tube bottom, and the juice temperature can be taken as an average of the juice temperature at the bottom and that at the top, calculated as for the first method.

In practice it was found that the second method of calculation led to serious errors when the juice was not boiling on entering the bottom of the tube. Consequently the first method is that used in the analysis of all data. Furthermore the ΔT value quoted in the experimental section refers to that calculated using the first method above (i.e. the hydrostatic head is ignored).

Factors affecting the OHTC

The detailed analysis of the behaviour of liquids in climbing film evaporators is beyond the scope of this paper, but it is generally believed that the tube can be divided into regions, depending on the type of two phase flow which occurs. The first region (at the bottom of the tube) can be termed a non-boiling zone, where the juice is heated. Heat transfer is considered poor in this region. The second region is one of nucleate boiling or bubbly flow, and this region ends as large bubbles of vapour form slugs which then develop into the third region, termed annular flow. In annular flow a thin film of liquid is believed to travel rapidly up the tube walls. High rates of heat transfer are considered to occur in the regions of nucleate boiling and annular flow. Beyond annular flow, in certain cases, a liquid deficient region may form and "dryout" is said to occur, with consequent poor heat transfer (Collier, 1972). A model of a climbing film evaporator is currently under development and a typical heat transfer coefficient profile generated by the model is shown in Figure 2, which indicates the regions of heat transfer discussed.

For optimal performance, it can be seen that the regions of high heat transfer need to be as large as possible, while the areas of juice heating and dryout be minimised or avoided completely. It could be postulated that as the ΔT across the tube and juice feed temperature drop, the juice height will increase. This is because a greater area of the tube is used as a juice heater as the juice is slower to achieve boiling after entering the tube. Because the heat transfer over the fraction of the length of tube used as a juice heater (convective heat transfer or subcooled boiling) will be lower than that for annular flow, it could be postulated that the OHTC will be low for conditions of low juice feed temperature and small ΔT's, and increase with higher ΔT's and juice feed temperatures. However for a fixed juice feed temperature "dryout" of the tube should occur lower down the tube as the temperature difference across the tube wall (ΔT), and hence the heat flux, is increased (Collier 1972). Therefore there should be an optimum ΔT for each configuration and flowrate. Similar reasoning could be applied to considerations of juice flowrate, also suggesting an optimum. The influence of all the factors on the regions of heat transfer, and hence the OHTC, is not clearly established and the pilot plant is necessary to establish the relevant relationships, and ultimately develop a reliable model of the system.

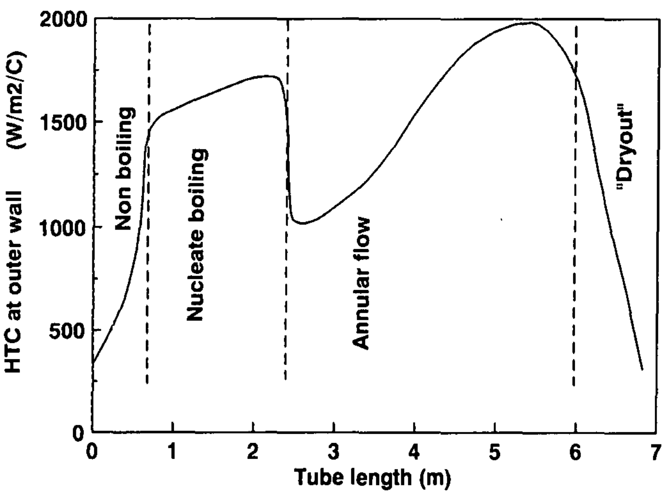

Figure 2 OHTC profile produced from a theoretical model of a climbing film evaporator.

Experimental

Simulation of the main plant

The pilot plant was commissioned during the 1993 season. During the commissioning stage the primary objective was to simulate the conditions prevailing on the plant (first effect Kestner) as closely as possible and compare the heat transfer coefficient with that calculated in the past by the process staff. During this phase of experimentation the pilot plant was run under various conditions for a total time of 140 hours. From all these runs a database could be set up from which runs meeting particular requirements could be extracted for analysis. By taking these grouped results, the change in HTC with time, if any, could be examined.

In all, the data obtained were sorted into three groups, corresponding to high, typical and low flowrates. The average conditions and the range over which these runs were carried out are shown in Table 2. Over all runs the average steam pressure was 85 kPa(g) (118°C), and the average vapour pressure was 52 kPa(g) (112°C). To make the data simpler to digest, the flowrate is given in "equivalent tons per hour", which is the flowrate at which the FX mill first effect Kestner would be operated if the pilot plant flowrate was scaled proportionally.

Table 3 shows the results from these three groups. In each case there was no perceptible change of the OHTC with the time of operation, and no significantly different measured OHTC between the three groups. This is shown graphically in Figure 3. The scatter in the data is a result of the varied conditions in all of the selected runs. Nevertheless this result

Table 2

Averages of selected runs at various flowrates

Equivalent flowrate in tons per hour (tph)			Temperature difference (°C)			Juice feed temp (°C)			Juice feed brix		
Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min
High 471	480	455	5,7	6,2	5,0	110	111	108	11	12	10
Typical 382	418	357	5,9	6,9	5,2	108	112	107	11	13	11
Low 243	328	205	5,6	6,1	5,0	111	113	108	11	12	6,5

Table 3

Results of selected runs at various flowrates

Flowrate	Juice height in the tube (% of maximum possible)			HTC (kW/m²/°C)			Product brix %		
	Average	Max	Min	Average	Max	Min	Average	Max	Min
High	9	15	3	3,0	3,3	2,9	16	18	15
Typical	6	14	0	2,9	3,2	2,6	20	30	17
Low	3	6	0	3,1	3,3	3,0	27	35	20

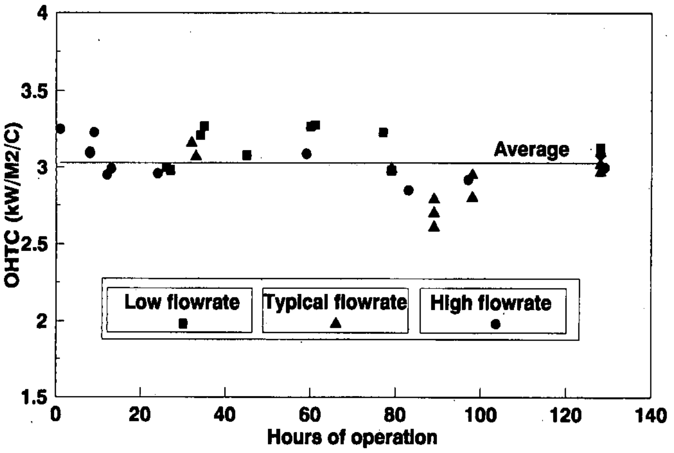

Figure 3 OHTC variation with time of operation.

suggests that the OHTC may be very sensitive to changes in the operating conditions. The OHTC values are generally higher than those calculated on the main plant, which typically gives values of about 2,2 to 2,6 on the first effect Kestners when calculated using the methods described above. The consistent OHTC value suggests that very little fouling occurred over the time of the run.

The apparent absence of appreciable fouling may be due to any, or all, of the following:

- The relatively high flowrates and low steam pressures during operation preventing sugar from "baking" on the tubes. At the same time almost perfect feed distribution ensured that no dead spots were able to develop.
- The precipitation of the main foulants in the FX first effect Kestners, calcium phosphate and silica, may be kinetically controlled. The clear juice is fed to the pilot plant via a feed drum with a residence time of about 30-50 minutes. Under normal circumstances, any precipitation in the feed drum would have taken place in the evaporator. The clear juice is passed through strainers in the feed line and this may be removing suspended matter which would otherwise be deposited in the tubes. Fouling of the strainers on the feed line to the pump was found to be significant, requiring regular daily cleaning.
- The average change in brix was not large (12-19° brix), suggesting that solubility limits of the foulants may not be reached. Similarly, the main plant does not experience a particularly severe fouling problem in the first effect Kestners.
- The pilot plant was not run continually for the 140 hours. Stops were followed by flushing with water which would serve to clean out some of the scale formed.

An unexpected feature of all results obtained from the pilot plant is the low apparent juice heights, all below 15% of the maximum, compared with 20 to 30% measured on the main plant Kestners. To confirm the readings, a gauge glass was installed and this corresponded well with the calculated levels. The reason for this difference has not been fully explained at this stage, but could be due to the small number of tubes on the pilot plant almost acting as an air lift pump as vapour slugs are generated, thus lowering the pressure at the tube base. It is clear, however, that the juice height reported here is not equivalent to that measured in the main plant Kestners, but should rather be considered a relative measurement at this stage.

Controlled tests

During the latter part of the commissioning phase, after 125 hours of operation, sets of experiments were carried out where only one variable was changed and the effects were noted. This was done to determine the viability of carrying out this type of experimentation in the future, with a view to optimisation.

Three tests were performed. In the first, the flowrate was varied from 250 to 480 tph equivalent, while the ΔT was set at 6°C, the feed temperature at 108°C and the feed brix at 11%. The effect on OHTC is shown graphically in Figure 4, and on juice height in Figure 5. The OHTC rose rapidly from about 2,5 to about 3,1 kW/m²/°C, at which value it appeared to stabilise. These two graphs suggest that there is a critical level in terms of tube height and that once this is achieved the OHTC is not appreciably improved for the set of conditions used in this test, namely ΔT, juice feed temperature and brix. It is also obvious that the flowrate cannot be increased indefinitely without the OHTC falling.

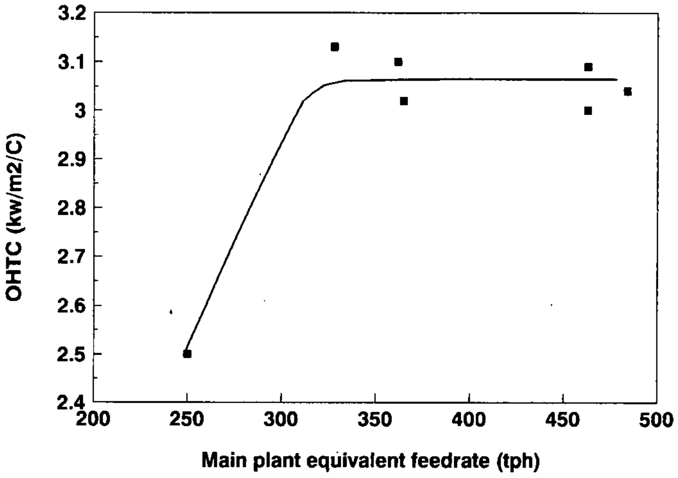

Figure 4 Variation of OHTC with flowrate.

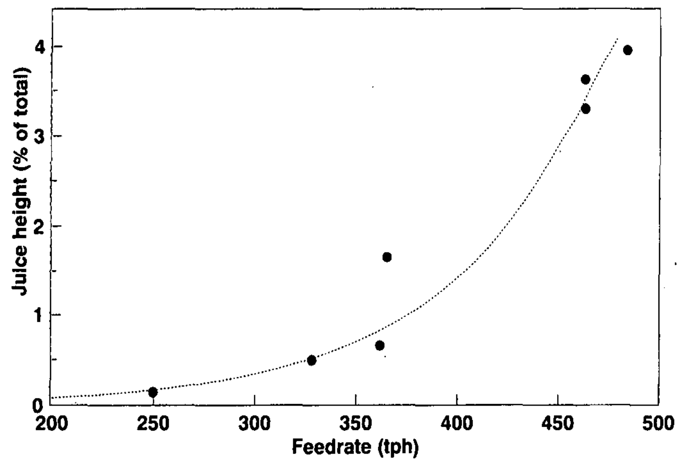

Figure 5 Variation of apparent juice height with flowrate.

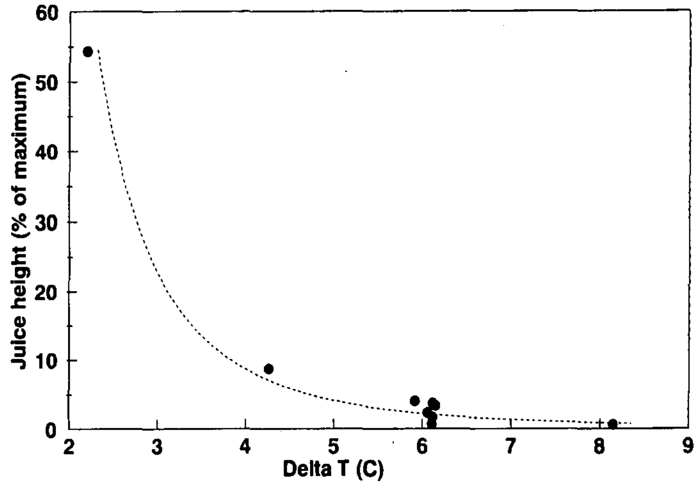

Figure 7 Relationship between apparent juice height and ΔT.

The second test involved varying ΔT, the temperature difference across the tube wall, from 2,2 up to 8,1°C, and the flowrate was kept between 360 and 480 tph equivalent (which is the range of normal operating conditions). Brix and feed temperatures were maintained as before. The result is shown in Figure 6. In Figure 7 the variation of the apparent juice height with ΔT is shown. These figures show that the juice height falls as the heat flux (due to the higher temperature difference across the tube wall) is increased across the tube, while at the same time the OHTC increases. This result supports the idea proposed above of the OHTC rising with a higher temperature difference across the tube wall, although a drop in OHTC was not found at higher ΔT values. This may simply be due to a sufficiently high ΔT not being tested. It should be noted that the graphs may be misleading due to y-axis scaling, since the lowest juice height shown in Figure 7 is still within the proposed critical region suggested from Figure 5.

The third controlled test examined the relationship between the feed juice temperature and the OHTC. As before the temperature difference across the tube wall was kept to about seven, the feed brix at 11 and the flowrate between 360 and 460 tph equivalent. The results shown in Figures 8 and 9 show clearly that the OHTC undergoes a step change as the juice feed is heated above 102-106°C but it is not clear whether any benefit will be achieved by further heating of the feed juice. This result is interesting in that the temperatures of the feed juice, even at the highest temperatures used, are not at the saturated steam temperature calculated for the conditions prevailing at the base of the tubes. As expected, the apparent juice height falls as the feed juice temperature is increased. This can be explained in terms of the fraction of tube length operating under high heat transfer flow regimes (for example, slug and annular flow), as the feed juice temperature is increased. Since the volume of juice in the tube will be less for slug and annular flow than for single phase flow, the pressure measured at the tube base will be correspondingly reduced, which will be monitored as lower apparent tube height.

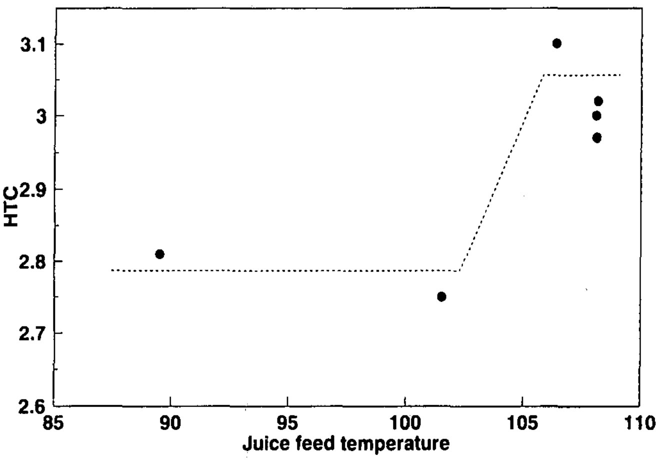

Figure 8 Relationship between HTC and juice feed temperature.

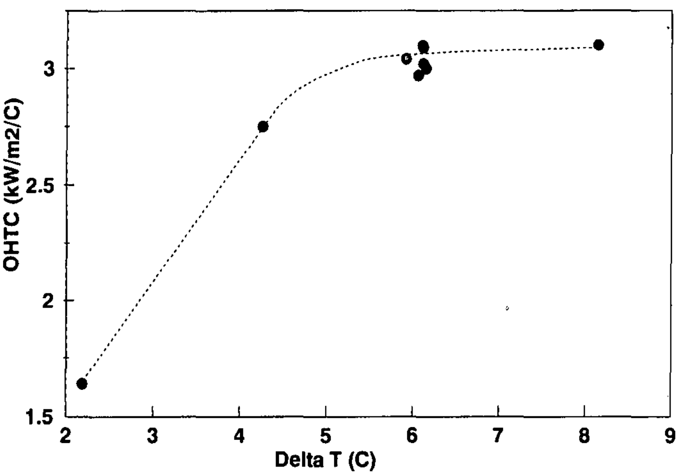

Figure 6 Variation of OHTC with ΔT.

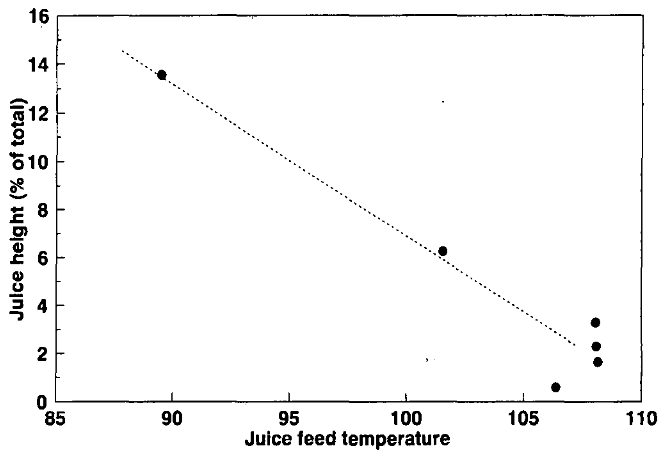

Figure 9 Relationship between apparent juice height and juice feed temperature.

Conclusions

The preliminary results obtained during the commissioning phase of the pilot plant have demonstrated that the equipment has the capacity to examine all possible factors which could influence performance. The results of controlled tests undertaken so far tend to reinforce conventional wisdom regarding the behaviour of climbing film evaporators. Most notable in these results is the apparent relationship between juice height and the measured HTC, suggesting that monitoring of juice height may be an effective indication of performance. The factors influencing the juice height and HTC are, however, complex and appear to interact, making a sound factorial set of experiments essential if all possibilities are to be considered.

It must be noted that the results presented here were obtained in an evaporator which did not foul appreciably, and some of the operating conditions, while giving high OHTC values, may also lead to high rates of fouling. Nevertheless the following can be cautiously proposed regarding operating conditions and OHTC:

- Juice feed temperature must be above a particular temperature, which may not necessarily be above the flash temperature calculated at the base of the tube. For the pilot evaporator this appears to be between 102 and 106°C. Nevertheless the effect of superheating the feed juice still needs to be investigated.
- For juice at a sufficiently high temperature, at "normal" flowrates, the OHTC seems to be optimum for a temperature difference across the tube wall of between 4 and 8°C. This could be explained in that, at too low a temperature difference, too great a length of the tube falls under the region of single phase liquid flow where heat transfer is poor. On the other hand too high a temperature difference results in "dryout" occurring over a greater length at the top of the tube.
- Acceptable OHTC's were measured for juice heights between 1 and 10% of the total tube height for the pilot plant. The applicability of the juice height values measured on the pilot plant to industrial plant Kestners is probably limited and a relationship between the pilot and main vessels still needs to be established.
- Flowrates in the range tested do not appear to have a strong influence on the OHTC, except for very low flowrates where "dryout" of the tube occurs very quickly.

Overall, the pilot plant appears to be capable of making a substantial contribution to the industry's knowledge regarding climbing film evaporators. The plant is to be used to examine the effect of operating conditions on the OHTC through factorial experiments.

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