CLEAR JUICE HEATERS – DO WE NEED THEM?

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Abstract

Current practice is to install clear juice heaters ahead of first effect evaporators to ensure that the juice entering the evaporator is above its boiling temperature, allowing flashing to occur on entry. The alternative, of allowing the juice heating to take place in the evaporator, is sometimes rejected on the basis that heating transfer performance of an evaporator is very poor when operating in the juice heating regime. To allow this alternative to be evaluated on a quantitative basis, available data on the relative heat transfer performance of juice heaters and Kestner evaporators have been collated, providing estimates of the difference in heating surface area required. By combining this information on heating surface area requirement with equipment costs, it is possible to make a rational assessment on whether it is advisable to dispense with clear juice heaters by installing extra heating surface area in the first effect evaporators.

Keywords: heaters, clear juice, evaporators

Introduction

In the past few years there have been a number of SASTA papers questioning the necessity of items of equipment that have long been considered essential requirements in a standard cane sugar factory.

Examples are B-crystallisers (Jullienne, 1991), A-crystallisers (Jullienne, 1992) and filters for clarifier muds (Meadows *et al*., 1998).

The ideas expressed in these papers are not extreme views and have had an influence on the design of new plants and modifications to existing operations. For example, the new Komati mill was designed and built without B-crystallisers, and many South African mills have now abandoned their filters by converting to a system of recycling mud to the diffusers.

This paper continues this trend of questioning conventional practice by examining whether clear juice heaters are cost effective process equipment. Could the heating that they achieve not be performed more cost effectively in larger first effect evaporators? An answer to this question is unlikely to influence existing operations but can be particularly useful in making decisions for new factories, factory expansions or replacement of worn out equipment.

The purpose of clear juice heaters is to raise the temperature of juice leaving the clarifiers to (or just above) the boiling temperature of juice within the first effect evaporator. The rationale for doing this appears to be based on the assumption that heat transfer in properly designed juice heaters is much more effective than that which occurs in that portion of a first effect evaporator's heating surface area which is operating in heating mode (if the juice enters at below its boiling temperature).

There has been a concern that this is particularly relevant in more modern factories when first effect evaporators are of the climbing film (Kestner) type as opposed to the older Robert design.

To provide a properly reasoned opinion on the advisability of using clear juice heaters, it is necessary to quantify both the relative performance (in terms of heat transfer) and the relative cost of clear juice heaters and evaporators. It is important to note that, if clear juice heaters are to be dispensed with entirely, it is the cost of extra evaporator heating surface area (i.e. the marginal cost) which must be compared with the total installed cost of clear juice heaters.

Published information on the advisability of using clear juice heaters

Webre (1963/64) published some calculations to show that clear juice heaters (if they were not currently installed) could be added so as to increase the capacity of an existing evaporator station. The magnitude of the benefit he calculated is based on simplistic assumptions which are highly unlikely to represent practical operation. The paper does not address the issue of whether the expanded capacity could be achieved more cheaply (at the original design stage) by installing extra first effect evaporator area.

Perk (1963) directly addressed the issue of whether clear juice heaters were cost effective equipment for the case of Robert type first effect evaporator vessels. Using published correlations on heat transfer performance, Perk considered an example factory and estimated both the size of clear juice heaters which would be required (in terms of heating surface area) and the extra first effect evaporator area that would be required to perform this heating duty if clear juice heaters were not used. Although the extra evaporator area for heating was greater than the juice heaters by a factor of 2.07, Perk's costings of the two alternatives showed that clear juice heaters were *not* cost effective equipment for a new installation. This clearly does not mean that clear juice heaters have no benefits, and Perk went on to show that installing clear juice heaters can be a cost effective means of providing a small increase in the capacity of an existing evaporator station if they are not already installed.

de Viana and Coleman (1995) reported that clear juice heaters (called evaporator supply juice, ESJ, heaters) were relatively recent equipment in the Australian industry although they were popular elsewhere in the world. In 1994 only 11 of the 28 Australian sugar mills employed clear juice heating. de Viana and Coleman reported on the improvements in overall evaporator capacity achieved at the Mossman mill by installing a plate heater for clear juice heating. Their results indicate an average increase in evaporator capacity of 6%. Their measurements focussed on overall evaporator capacity and, although they provide information on the heat transfer coefficients achieved within the evaporator vessels, these are obtained by fitting an overall evaporator model to the plant results rather than detailed individual vessel measurements.

Greenfield (2001) reported on an innovative design where simple modifications to the internals of a Kestner evaporator allowed an effective clear juice heater to be created within the body of the evaporator vessel. This design has the advantage of maintaining the forced convection benefits of conventional clear juice heaters, while achieving it at the marginal cost of extra evaporator surface area. Problems in maintaining an equal flow split between two identical vessels of this design at the Maidstone mill caused them to be converted back to conventional Kestner vessels. There was also a concern that the distribution of juice across the bottom tube plate was inadequate, particularly when compared with a properly designed feed ring. Both the flow split and juice distribution problems can be addressed by modifications to the design and operation of vessels constructed according to this concept.

This current paper evaluates the cost effectiveness of using conventional shell and tube clear juice heaters in conjunction with Kestner type evaporators in the light of the best available current information.

Answering the question

It would be extremely difficult to provide a definitive answer to the very general question of whether clear juice heaters are cost effective equipment, as should become clear in the subsequent sections of this paper. Rather it is necessary to consider a specific, and hopefully broadly representative, case and to estimate the costs of the two alternatives of a factory design which uses clear juice heaters and a factory design where the clear juice heating takes place in the first effect evaporators.

Hypothetical factory as the basis for comparison

As a basis for comparison, the data displayed in Table 1 have been used to determine the operating conditions for a hypothetical 'standard' sugar factory. These conditions are based roughly on average values for the South African sugar industry during the 2001/02 crushing season (Davis, 2002).

Table 1. Basic conditions used for the 'standard' mill.

Parameter	Value
Tons cane crushed per hour	300 t/h
Sucrose % cane	13.1%
Sucrose extraction achieved	97.7%
Clear juice % cane	120%
Clear juice sucrose purity	85.2%

By calculation from the data presented in the table (neglecting any filter cake losses), the clear juice flow rate in the 'standard' mill would be 360 t/h, at a brix of 12.5%. It is assumed that the clear juice exits the clarifiers at a temperature of 98°C and is heated by the clear juice heaters to a temperature of 115°C. The estimated specific heat for the clear juice is 3.998 kJ/(kg°C). Exhaust steam at 200 kPa(a) will be used for both the clear juice heaters and first effect evaporators.

The evaporator station is assumed to be a quadruple effect, with V1 vapour bleed at a pressure of 160 kPa(a). Based on the design calculations for the Xinavane mill as presented by Love *et al.* (1999), the V1 bleed flow is assumed to be 31% on clear juice flow (equivalent to 111.6 t/h).

Sizing of a conventional clear juice heating station

Published data on the heat transfer performance of clear juice heaters is relatively sparse (e.g. Hugot, 1986) although some of the information presented for mixed juice heating (e.g. Buchanan, 1966) can probably be extrapolated to cover clear juice heating. The two major factors affecting the practical heat transfer performance of heaters are juice velocity and the extent of fouling. Fortunately, fouling is of little concern in clear juice heaters, making it easier to predict the heat transfer performance. Reasonable practical design parameters for clear juice heaters under South African conditions appear to be a juice velocity of between 1.5 and 2.0 m/s and a heat transfer coefficient (HTC) of 1.0 kW/(m^2·°C). At this level of performance, 578 m^2 of clear juice heater capacity will be required to achieve the necessary heating. Based on the sizes of current heater designs, this area would be provided as two equally sized heaters of 289 m^2 each.

As a cross-check, the heater sizing may be compared against data for installed juice heater capacity in the South African sugar industry. According to Wienese (2000), installed clear juice capacity ranges between 0.4 and 2.7 m^2/TCH, with an average value of 1.5 m^2/TCH. The 578 m^2 calculated for the 'standard' sugar mill thus corresponds to a relatively conservative 1.93 m^2/TCH when compared with the industry data.

Sizing of a conventional evaporator station

The THS evaporator design program was used to determine the heating surface area required in each effect of the evaporator station (following the approach described by Love *et al*., 1999). The design used an HTC of 2.6 kW/(m^2·°C) for the first effect, and determined that a heating surface area of 6297 m^2 would be required for this effect.

A comparison of this required first effect evaporator surface area with values for installed capacity in the local industry would, however, not be valid because the size of installed first effect Kestners is strongly dependent on a number of unrelated factors, such as the number of effects in the evaporator station, the degree of energy efficiency and extent of vapour bleeding from the first and second effect vessels and the presence or absence of a back-end refinery.

Heat transfer performance of evaporators operating in heating mode

If clear juice heaters are to be eliminated, it is necessary to know what the heat transfer performance of the first effect evaporator surface area will be when it is operating in the heating (single phase flow) mode rather than in its normal evaporation (two phase flow) mode.

There is a rule of thumb that the heat transfer coefficient of a tubular liquid heater varies with liquid velocity to the power of 0.8 (inherent in the heat transfer correlation of Sieder and Tate, 1936). Based on this principle, it is easy to dismiss the concept of juice heating in the bottom portion of Kestner tubes as being too poor for any serious consideration, given the very low juice velocities. In contrast, however, heating coils are often used effectively for heating in tanks without any forced circulation by relying on natural convection to promote heat transfer. Clearly, a more detailed evaluation is required to provide a reasonable estimate of the performance of Kestner tubes operating in heating mode.

Data on heat transfer have been obtained from a wide range of sources and interpreted to provide estimates of the heat transfer coefficient that can be expected in that portion of each Kestner tube which operates in heating mode. From the estimated heat transfer coefficient, it is relatively simple to calculate the extra first effect area that will be required and to express it as a ratio to the area of clear juice heater surface area that would otherwise be required. Much of the available information relevant to this type of heat transfer is not in a directly applicable form. Appropriate calculations and interpretation are necessary in many cases to provide estimates of performance in terms of an average heat transfer coefficient. As an example, the published correlations for forced and natural convection predict HTC as a function of the length (height) of the heating zone. The length of the heating zone in turn depends on the value of the HTC. Determining the HTC thus involves the simultaneous solution of the heat transfer correlation and an enthalpy balance specific to the Kestner design under consideration.

The interpreted data are presented in Table 2 and in Figure 1.

Table 2. Estimated performance of evaporator operating in heating mode.

Heat transfer coefficient data	Heat transfer coefficient [W/(m²·°C)]	Relative surface area ratio	Surface area required [m²]
Forced convective heat transfer			
Kern (1950)	57 – 171	5.85 – 12.47	3379 – 10 586
Coulson *et al.* (1990)	96	10.42	6020
Branch and Muller-Steinhagen (1993)	241	4.15	2400
Heat transfer in heating coils			
Perry and Green (1984) - Table 10.8	50 – 240	4.16 – 15.82	2407 – 11 552
Perry and Green (1984) - Table 10.13	250 – 500	2.00 – 4.00	1155 – 2310
Natural convective heat transfer			
Coulson *et al.* (1990)	551	1.81	1046
Perry and Green (1984)	643	1.55	898
Gorenflo (1994)	753	1.33	768
Climbing film evaporator data			
Gudmundson *et al.* (1972)	500	2.00	1155
Williamson[1] - Komati mill data	736	1.36	785
Walthew *et al.* (1994)	724 – 1044	0.96 – 1.38	553 – 798
Rein and Love (1995) - Darnall trials	1017	0.98	568
Gupta and Holland (1966)	1420	0.70	407
Coulson and McNelly (1956)	1700	0.59	340
CHOSEN DESIGN POINT	350	2.86	1650

The data have been collected into four groups. The first group (Forced convective heat transfer) predicts very low heat transfer, and almost certainly underestimates performance. This is probably because these correlations are outside their range of applicability at the very low juice velocities which prevail within the Kestner tubes, and because the correlations do not take account of the increasing importance of natural convection at these lower velocities.

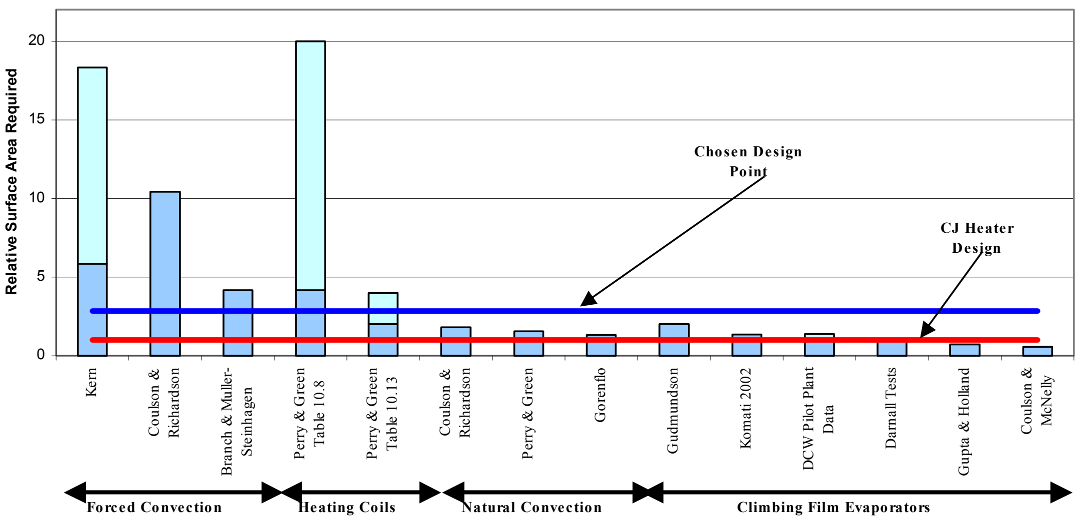

Figure 1. Evaporator surface area required for heating relative to clear juice heater area.

[1] A Williamson, personal communication, February 2003.

The data in the second group (Heat transfer in heating coils) are not directly applicable, but they do confirm that the forced convection correlations are substantially underestimating performance. These data probably reflect the lower limit of performance to be expected (i.e. the worst possible case).

The group of data covering 'Natural convective heat transfer' are more directly applicable and tend to confirm that the heating coil data underestimate heat transfer performance.

The most relevant group of data (Climbing film evaporator data) directly concerns heating taking place within portions of the tubes of a climbing film evaporator. The most applicable data from within this group is obviously that collected on sugar mill Kestner evaporators (i.e. the data of Williamson[1], Walthew *et al*. (1994) and Rein and Love (1995)). Although the data of Williamson[1] are operational rather than experimental, they are particularly interesting in that they relate to a full season (2002/03) of operation at the Komati mill without the use of clear juice heaters. Surprisingly, the data in this group indicate that the HTC for heating within Kestner tubes could be equal to that achieved in clear juice heaters (1.0 kW/(m^2·°C)). A possible explanation for this could be the presence of sub-cooled nucleate boiling.

Without a more extensive body of data from either plant experience or experiment results it is necessary to select a conservative value of HTC for design calculations, and in this light a value of 350 W/(m^2·°C) has been selected. This corresponds to a requirement for an extra 1650 m^2 of heating surface area in the first effect evaporator, a factor of 2.86 times the heating surface area of the clear juice heaters which it replaces. Thus the required size of the first effect evaporator is 7947 m^2.

The assumption in these calculations is that extra heating surface area can be added to a Kestner evaporator to meet the heating requirements of juice that enters below its flash temperature, and that if this is done the remaining heating surface area will continue to perform as well as it did when the evaporator was fed with heated juice.

It is possible to analyse the original data reported by both Love and Rein (1995) and Walthew *et al*. (1994) to check this assumption by estimating the heat transfer coefficient for that portion of the tubes which is operating in evaporating mode (the evaporative HTC) and comparing it with the HTC achieved when the evaporator is fed with heated juice.

The two tests reported by Love and Rein (1995) showed a reduction in evaporative HTC of 12% and 1.6% respectively. The tests reported by Walthew *et al*. (1995) showed an increase in evaporative HTC of 1.2% in one instance and a decrease of 5% in the other. These limited data indicate that, if there is a reduction in performance of the evaporative HTC when heating takes place in a portion of the Kestner tubes, it is small, of the same order as the accuracy of the design assumptions and can probably be neglected.

Costing procedures

To fully evaluate the cost effectiveness of juice heaters the ideal situation is to produce two full designs, one using heaters and one without, and have both of them costed in detail. There are, however, techniques for more rapid costing, which, although less accurate, should be able to indicate whether there will be a substantial cost advantage for the design which does not use clear juice heaters.

Equipment costs
The cost of individual items of purchased equipment may often be related to equipment size by means of the following exponential relationship:

$$C_E = k \cdot S^n$$

where n is the cost index, S is a characteristic size parameter for the equipment in question and k is a cost constant which is determined using a set of current data for equipment costs.

Various values of n for use in equipment costing are available in the literature. A summary of some of these is presented in Table 3.

Table 3. Factor values for use in the estimation of individual equipment item costs.

Reference	**Cost index (*n*) for shell and tube heat exchangers**	**Note**	**Cost index (*n*) for evaporator vessels**	**Note**
Coulson *et al.* (1983)	0.66	(1)	0.53	(2)
Perry and Green (1984)			0.73	(2)
Peters and Timmerhaus (1991)	0.44	(3)	0.52	(4)
Peters and Timmerhaus (1991)	0.56	(5)		
Peters and Timmerhaus (1991)	0.66	(6)		
Peters and Timmerhaus (1991)	0.71	(7)		
Perry and Green (1999)	0.59	(8)		

Notes:
- Figure for heat exchangers with a carbon steel shell and either carbon steel tubes or stainless steel tubes.
- For carbon steel evaporator vessels with carbon steel tubes.
- For shell and tube heat exchangers with fixed tubeplates, of between 100 and 400 ft^2 in size.
- For vertical tube evaporator vessels.
- For shell and tube heat exchangers with carbon steel shell, fixed tubeplate and carbon steel tubes.
- For shell and tube heat exchangers with carbon steel shell, fixed tubeplate and 304 stainless steel tubes.
- For shell and tube heat exchangers with carbon steel shell, fixed tubeplate and 316 stainless steel tubes.
- For shell and tube heat exchangers of between 1.9 and 1860 m^2 in size.

Installed costs

A rough estimate of the capital cost for a fully installed item of equipment may be made using the factorial method of cost estimation:

$$C_T = f \cdot C_E$$

where C_T is the total fixed capital cost of the installed plant, f is a factor which may depend on a number of variables (for example, the type of process being carried out) and C_E is the delivered cost of the major individual items of equipment making up the plant (such as storage tanks, heat exchangers and reaction vessels).

A number of f factor values for use in plant costing have been reported in the literature. A summary of some of these values is presented in Table 4, where the figures for 'installed cost' include charges for labour, foundations, supports, platforms, construction expenses and other factors directly related to the erection of the purchased equipment.

The figures for the 'total plant cost' incorporate the installed equipment costs, plus charges for insulation, instrumentation and controls, piping, electrical installations, buildings, service facilities and engineering design and supervision.

Table 4. Multiplying factor values for use with the factorial method of cost estimation.

Reference	Installed cost	Note	Total plant cost	Note
Coulson *et al.* (1983)			4.7	(1)
Peters and Timmerhaus (1991)	1.25 to 1.90	(2)		
Peters and Timmerhaus (1991)	1.30 to 1.60	(3)		
Perry and Green (1999)	1.4 to 2.2		3.0 to 3.5 4.0 to 4.9	(1) (1), (4)
Perry and Green (1999)			3.37	(3)

Notes:
- Figure for a predominantly fluids-processing plant.
- For evaporator vessels.
- For shell and tube heat exchangers.
- The higher factor values include an allowance for contractors' fees and contingencies.

Cost comparison for current conditions

By combining some current budget prices for shell and tube clear juice heaters and Kestner evaporators with the costing techniques presented in the previous section, it is possible to make an estimate of whether clear juice heaters would be cost effective equipment for the 'standard' sugar mill considered in this paper.

Based on the data presented in Table 3, it is assumed that a cost index of 0.65 can be used for both heaters and evaporators. Using the current budget prices it is possible to estimate the cost constant, *k*, for the exponential sizing equation as follows:

For shell and tube heaters:

Budget price for 250 m^2 heater – R540 000

The formula for estimating equipment cost is thus:

$$C_{EH} = 14919 \cdot S_H^{0.65}$$

For Kestner evaporators:

Budget price for 5800 m^2 evaporator – R4 900 000

The formula for estimating equipment cost is thus:

$$C_{EE} = 17538 \cdot S_E^{0.65}$$

Using these two formulae it is possible to cost the two design options as follows (rounded to the nearest R1000):

Option 1:

Two by 289 m^2 clear juice heaters :	R1 187 000
One by 6297 m^2 Kestner evaporator:	R5 170 000
Total cost	R6 357 000

Option 2:

One by 7947 m^2 Kestner evaporator:	R6 013 000
Total cost	R6 013 000

These costs indicate that there will be a saving in equipment costs of approximately R340 000 by installing an appropriately sized larger first effect Kestner rather than the conventional combination of clear juice heater and Kestner evaporator. Based on the figures in Table 4, assuming a value of 2.0 for the cost factor, *f*, should provide a very conservative estimate of the total cost. A cost saving of more than R680 000 can thus be expected for the total project cost.

Even larger savings may be possible if it is possible to confirm, and have confidence in, the higher HTC values for juice heating in Kestners that are indicated by some of the available data.

Conclusions

A detailed evaluation of available data indicates that the heat transfer performance of portions of a Kestner evaporator operating in juice heating mode are not nearly as bad as would be assumed by a more cursory appraisal.

Selecting a relatively conservative HTC in the light of this evaluation it is possible to develop a sugar mill design which uses a larger first effect Kestner rather than the conventional combination of clear juice heater and Kestner evaporator.

Using a hypothetical 'standard' sugar mill as an example, budget costings indicate that clear juice heaters are *not* cost effective equipment and that considerable savings can be achieved by 'replacing' them at the design stage with an enlarged first effect evaporator.

A factory design without clear juice heaters has the added benefit of less demanding pumping requirements, and provides the potential for a cheap marginal expansion in evaporator capacity at a later stage by the subsequent installation of clear juice heaters.

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