IMPROVING ROBERT EVAPORATOR VESSEL DESIGNS

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ABSTRACT

This paper examines the shortcomings in the performance of many existing Robert calandria evaporator designs and proposes design principles that correct these shortcomings. It makes a number of suggestions for improving the performance of existing Robert designs.

It then describes the radial flow Robert (RFR) design specified to address many of the shortcomings of existing designs. Its general performance and heat transfer results have been very favourable. The new design, with variations in the arrangement of its bottom shape, is recommended as a basis for future development of the Robert-type evaporator in the sugar industry.

INTRODUCTION

It remains current practice in the world raw sugar industry for the concentration of clear juice to use standard Robert calandria evaporators with tube diameters of 38 to 51 mm and tube lengths of 1.5 to 3.0 m. Robert vessels are relatively cheap and easy to manufacture in sizes up to ~6000 m^2 in heat transfer area. Traditional designs have some disadvantages however, relative to the 'new technology' plate and falling film types, in their higher juice residence time characteristics, possibly lower heat transfer performance and lack of ability to work efficiently with low differential temperatures across their heating surfaces.

A great deal of experience with evaporator performance matching simulation runs has found that the heat transfer performance of many Robert evaporator vessels in Colombia and India are 60 to 80% of that typical of Australian multi-effect evaporator installations operating with the same exit juice conditions. A close examination of the physical differences in design practice was carried out to see where these departed from established design principles to give improved circulation patterns and improved heat transfer performance. This led to suggestions for practical modifications of the design, and these were incorporated in a new design of a large evaporator for Ingenio San Antonio, Nicaragua (ISA) in 2001. The new design was successful, and the design and its performance were presented in a paper to the ATAGUA Congress in Guatemala (*Wright and Silva*, 2001).

The design considerations were outlined there under the headings:

- The juice feed entry systems,
- Juice removal systems and level control,
- The vapour entry to and vapour flow through the calandria,
- Condensate removal,
- Venting the calandria on non-condensable gases, and
- Steam lanes in the calandria.

DESIGN FEATURES OF ROBERTS EVAPORATOR VESSELS

The short tube calandria

The traditional Robert design uses a tightly packed calandria with vertical tubes, with tube lengths of 1.5 to 3.0 m. The usual tube outside diameter ranges from 38 to 51 mm, and the usual tube material in recent times is stainless steel types 304 or 316, though copper and brass are sometimes preferred. The tubes are expanded into a heavy mild steel tube plate and the usual design code specifies a minimum tube plate ligament of 0.25 of the hole diameter. The codes usually require that a small number of mild steel stay bars be welded into the calandria, as the codes ignore the strengthening effect of the expanded tubes.

Uncertainty remains as to the optimum tube size and length configuration in the calandria, so it seems best to stay with the usual SS or brass/copper tubes and the minimum allowable tube pitch. However, one improvement can be suggested with regards to the stay bars in the calandria. In Australian designs since 1984 a small number of 150 mm heavy mild steel downcomer tubes, about one for each 400 stainless steel heating tubes, are provided (Quinan *et al*., 1985). These serve a double duty, firstly to provide a recirculation return path for the juice and secondly as calandria support stay bars.

Juice feed entry systems

Hugot (1986) gave a full discussion of practical alternatives for feeding juice to Robert evaporator vessels. He noted several methods of feeding juice to the successive vessels.

Australian research based on computational fluid dynamics modelling (*Steindl*, 2003) has shown that substantial improvements to the juice flow pattern could be made by peripheral feeding. This would achieve a better approach to an ideal flow pattern *viz* plug flow of juice, with a steady rise in juice concentration from inlet to outlet. This is particularly important in the later stages of the set where the rise in the concentration of the juice is larger, and hence variations in heat transfer rate due to concentration changes are more significant.

Present Australian practice is to have the feed introduced through three to eight inlets on a pitch circle diameter about 2/3rd of the outer diameter of the calandria. The juice outlet is usually close to the bottom centreline of the vessel.

Experience has shown that when feeding juice which is coming from a previous evaporator stage and hence superheated relative to the boiling point of the receiving vessel, the extra boiling action due to the flash must be managed to aid the circulation of the juice upwards through the calandria and to avoid entrainment or erosion problems.

Improvements in juice entry systems to conventional evaporators are possible if the principle is followed that the feed should be introduced evenly under the calandria and as close as possible to the outer wall of the vessel body. In the newer Radial-Flow systems:

- The juice enters through multiple small inlet pipes or holes close to the periphery of the body of the vessel beneath the calandria.
- There are multiple small (~150 mm) mini-downtakes in the calandria one for each ~10 000 m of tube length.
- Outlet juice is taken from the centre of the vessel:
- Either using a centre well for collection, augmented if necessary with bypass juice taken from the centre under the bottom tube plate, or
- Taken exclusively from the bottom of the vessel as in the conventional Australian system.

New RFR designs have featured an external feed ring with multiple entries into the vessel bottom, about 300 – 400 mm in from the maximum diameter of the calandria. The correct sizing of the inlet pipes to achieve a pressure drop that gives an even feed distribution while not being excessive is a critical aspect of the design. It is possible to arrange that the feed pipes can be cleaned if necessary using a removable-plugged pipe coupling welded on the opposite side of the feed ring in line with the inlet pipes.[1]

In the case of the pre-evaporator or the #1 stage evaporator, where the temperature of the clear juice feed is below that of the body juice, there is an argument that the feed entry should be positioned above the calandria. This has not usually been done.

Trials by *Broadfoot* & *Tan*, 2005 concluded that the SRI-specified radial flow Robert evaporator on #1 stage at Broadwater factory provides substantially improved separation between the inlet and outlet juice than did a conventional Robert design. This is attributed to the combination in the RFR design of peripheral feed and preferred juice outflow into a central downtake. The authors argued that measures to reduce the brix

[1] A modification which was available as an option in RFR designs was to have a circumferential feed ring welded to the outside of the body near its junction with the bottom, and separated slightly from the circumferential vapour belt. The ring is fed at one or two points, and its cross-sectional area is 1.5 to 2 times that of the total cross sectional area of the feed pipes. A large number of small holes are provided to enable the juice to enter from the feed ring into the under-calandria region of the vessel. Unfortunately the small holes were prone to plugging with rust scale and this design idea has been discarded.

above the top tube plate of the calandria near the periphery would result in improvements. The above-calandria feed ring could be a solution, and could be provided as an option to future designs.

The choice of feed system modifications depends on the cost and practicality of the modifications involved in each system, as well as on considerations of the preferred juice removal system.

Juice removal systems and level control

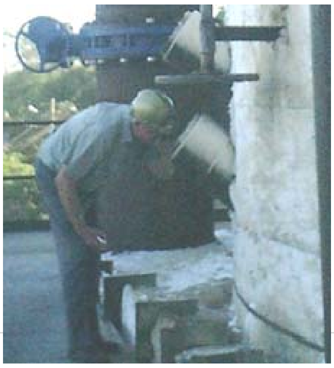
The Chapman removal system positions a cone in a small central downtake of the calandria with the juice takeoff pipe fed directly from this cone. Sometimes the cone is sealed to fix the operating level conditions at the point where just sufficient juice boils over into the downtake. Again, sometimes a gap is arranged around the cone so that the vertical placement of the cone controls the operating juice level. Automatic level control loops have often been added to these designs, but sometimes the effectiveness of these has been constrained by conflicts with the self-levelling arrangements, especially with the sealed downtake.

The Australian system has no central downtake and uses mini-downcomer tubes in the calandria to aid circulation as well as suffice as strengthening staybars. It has 'bottom feed with bottom removal' and has conventional automatic control of juice level using a dP sensor in the bottom of the vessel. Some recent installations have ultrasonic level sensors installed on large stand pipes connected to the body above and below the calandria.

The downtake/cone system probably has a slight advantage in that it tends to prevent the short-circuiting of juice from inlet to outlet as observed by *Jones and Pozzetti* (2000) in the Australian system, and it taps into the region of higher concentration above the tubeplate. However, the automatic level control would be the preferred method, as it allows the optimum juice level for maximising heat transfer to be selected.

Investigations have established that for Robert type evaporators the heat transfer performance (heat transfer coefficient, HTC) varies with the static juice level in the tubes. At too low a level the juice 'dries out' and fails to circulate to the top of the calandria. At too high a level extra hydrostatic head is created, and this suppresses the boiling action. The optimum juice level setting is that which gives just sufficient froth level above the tube plate to enable juice movement across it.

A level optimising system, used at Ingenio San Antonio, is to have a TV camera to enable the evaporator control operator to observe the juice level and boiling action in the vessel. The camera is positioned on a sight glass mounted on a special ~305 mm pipe protruding through the side of the vessel and angle to give a clear view of the boiling surface in the centre of the vessel (See photo).



Manual adjustments are made to the level control set point to keep the boiling surface at the desired condition.

The vapour entry to and vapour flow through the calandria

The pressure loss in the vapour entry to the calandria of some Robert vessels can be substantial. There can be a problem where an inadequate transfer section fails to diffuse the vapour into a wide area of the external tubes. Traditional Robert designs often use steam lanes in an attempt to channel the vapour flow (from one or two entry points) evenly across the tube bundles. The arrangement and size of the tube-free lanes appears to be an inexact science, resulting in many variations of doubtful efficiency. Steam lanes can result in a considerable loss of tubed area, and they often complicate the determination of appropriate locations of gassing points.

A main improvement is to use a circumferential vapour entry belt around the entire calandria, a characteristic of new RFR designs. The vapour is distributed evenly from the belt into the calandria wall without incurring appreciable pressure drop. A small gap is allowed between the calandria wall and the outer heating tubes. No calandria steam lanes are necessary. In very large calandrias constructed in half or quarter sections special precautions have to be taken to prevent vapour bypass through the tube gaps necessitated by the tube plate welds. In RFR vessels using the closest allowable pitch of the heating tubes, the pressure drop of the vapour flow from the outer ring to the inner central space is less than 0.1 kPa per metre of radial path for a #1 stage vessel, rising to double this value for a final stage vessel.

Condensate removal, and venting of noncondensable gases from the calandria

Perry (1999) states “A positive vapour-flow from inlet to outlet should be provided, and the path should preferably be tapered to avoid pockets of low velocity where noncondensables can be trapped. In any event the noncondensable gases should be vented well before their concentration reaches 10 %. The usual practice is to over-vent, even though this means that appreciable amounts of vapour can be lost”.

In traditional Robert evaporators the positioning of spears to remove noncondensable gas (sometimes termed "air” or "ammonia" or “noxious gas”) accumulation in the calandria has been rather arbitrary. If we accept that the removal points should be at the extreme end of the steam path, at both the top and the bottom of the calandria, the methods of air removal from the evaporator calandrias have often not been at all logical. Vents are usually located around the outside edge of the steam space, and it is considered that vent points should be provided at both the top and bottom tube plates. There are obvious deficiencies in the original gas venting arrangements, as there are regions in the calandria that would be subject to gas accumulation. This could be alleviated somewhat by adding extra gas spears, though this strategy can incur extra vapor loss.

Condensate is traditionally taken from the bottom of the calandria and it was convenient to locate it at the periphery of the calandria at a protruding “condensate box” structure. Less commonly condensate is also taken from near the centre well using a pipe connection though the bottom of the vessel. Ideally, removal should be co-current with the vapour flow, and the accumulation of condensate minimised. It is logical that the condensate removal should also be at points remote from the vapour entry. When the condensate box is used, it is logical and convenient to locate a vent outlet at the top of the box and to have a second vent point just under the top tube plate of the calandria in line with the box.

With the new RFR design the condensate is discharged through slots in the centre tube just above the bottom tube plate, and the vapour and condensate flows are radially through the calandria, with the noncondensable gases being swept to enter the centre chamber through special vent holes. These gases can be removed through one or more gas spears and either taken upward through the downcomer to exit to the gas removal line at the body wall. The downwards removal option has the advantage that there are no pipe connections (which might be subject to vibration and breakage) above the tube plate inside the vessel.

General discussion on improvements of the Robert design

The observations on traditional Robert designs prompted a re-examination of the flow patterns of juice, vapour gases and condensate to make them comply better with principles of good design. It was seen that it would be beneficial to have all the flows to be well-defined, moving from inlet to outlet in plug flow. It was reasoned that plug flow would be of particular benefit on the juice side, where the effective average juice concentration in the calandria would be substantially lower than that of the outlet juice and therefore the heat transfer coefficients would be higher.

The concept of "Radial Flow" was envisaged, where all the flows were made to move radially from the outside of the calandria to the inside. Design sketches were made to see how this could be implemented in practice, and the arrangements appeared to be feasible. The general principles of the RFR design are illustrated in Figure 1. Almost all the uncertainties in the placement of steam lanes, condensate outlets and vent positions were eliminated, with little or no increase in the cost or complexity. Several options were available in the RFR design with regards to the entry arrangements for the juice (circumferential belt, under-calandria feed ring, or over-calandria circumferential belt), the use of the centre well as the main source of the exit juice, the double inverted cone bottom, the over calandria or under calandria location of the gas removal pipes, and the use of the dropped centre chamber as a convenient level-controlled sealed collection vessel for the condensate.

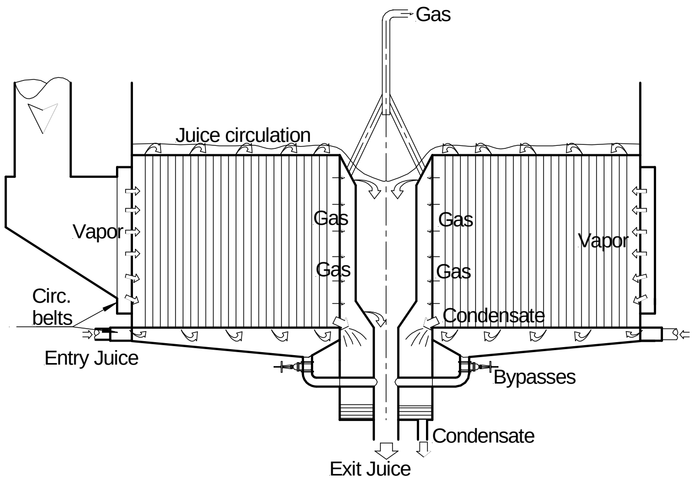


Figure 1 General layout for a radial flow evaporator

An enhancement of the RFR design is to have the centre well extended downwards below the vessel to form a chamber which can be level controlled on its outlet valve to act as a steam trap. A further enhancement is to have a second flash chamber below the first one. This chamber can act as a flash vessel if it is fed by the first condensate valve and vented to the vapour space of the vessel. The condensate then leaves the system at the saturation temperature of the vapour in the body of the vessel, leading to higher thermal efficiency.

An emphasis in later variations of the design is to reduce the residence time of juice in the vessels, particularly in the #1 and #2 vessels, by using the double cone bottom and a relatively low bottom angle. The operating juice volume in the vessel can be reduced by at least 10% in these designs. The double inverted cone bottom, which ties the bottom to the heavy centre well cylinder of the calandria, reduces unsupported distances in the bottom and lessens the amount of support bracing required. This feature is particularly important as it facilitates installations of very large heating surface area.

Experience with the improved design

The prototype Radial Flow vessel of 5300 m^2 heating surface area was constructed in the Ingenio San Antonio workshops in the second half of 2000. It had a sealed centre well for the exit juice, a single cone bottom, and over-calandria gas removal. This vessel was initially set up in series with the existing vessels of the #2 evaporator stage and received #1 vapour at ~70 kPag Vapour from the new vessel was passed to the vacuum pan stage and juice heaters, as well as to the #3 stages of the sets.

In the initial design a large centre well was provided, with a sealed pipe outlet for the juice through the bottom cone. The use of the ‘central downtake with inherent juice exit’ feature was an option and at that time was not considered essential to the radial flow design. Arrangements were made for the controlled bypass of juice from the lowest point in the vessel to the outlet pipe, as this feature was required for the purposes of level control. The installation of three small valved bypass pipes allowed a more flexible level control to be operated.

The performance of the prototype radial flow vessel was tested as described by *Wright*, *Silva* and *Pennisi* (2003). The heat transfer coefficient (HTC) and the 'heat transfer performance relative to standard Robert HTC values at the same conditions' (HTR), results were determined. The standard Robert HTC values were calculated by the 'Australian typical' formula of the form:

$$\text{'Typical' HTC} = 0.01694\, \boldsymbol{T_j}^{1.0174}\, (\boldsymbol{B_j}/(86-\boldsymbol{B_j}))^{-0.2695}$$

where $\boldsymbol{T_j}$ denotes the exit temperature and $\boldsymbol{B_j}$ denotes the exit brix of the juice leaving the evaporator stage.

The measured performance of the vessel over a 21-day period, shown in Table 1, was substantially above the heat transfer coefficient typically achieved in Australian evaporator bodies under the same juice brix and temperature conditions, and was all the more remarkable because it was achieved at relatively low evaporation loadings and on sulphited juice.

Table 1 Operational heat transfer performance of the prototype evaporator at San Antonio, Nicaragua (March 3 - 14, 2001)

Test	Heat transfer coefft. overall, W/m^2.K	Standard Robert heat transfer coefft. W/m^2.K	Calc. heat transfer ratio (HTR)	Inlet juice brix	Outlet juice brix	Calandria pressure kPa abs	Head space pressure kPa abs	Pressure difference kPa	Satn. temp. difference °C	Evap. load kg/h.m^2
Av.	3014	2185	1.38	24.4	37.95	172.1	141.2	30.95	6.00	22.0

In later seasons the function of the prototype unit at ISA was changed to be the only #2 stage vessel, a duplicate vessel was added as the #3 stage, and the entire raw factory pan stage supplied with #3 vapour. In the years of operation since 2001 factory mass/energy balance matches have consistently shown a HTR performance of around 1.3 for the two radial flow vessels. Later a third 5300 m^2 radial flow vessel was added, and a 8760 m^2 (94250 sq.ft) vessel was added to boost the #1 stage and cope with increased crushing rates. The largest vessel design differed from the prototype design in its bottom shape and its condensate collection arrangements.

It was observed that the pressure difference and the saturation temperature difference between the vapour in the calandria and vapour in the vapour space of the vessel are relatively small. Temperature differences below 5 K were recorded, which indicate a good turn-down characteristic for the design. The best operation was associated with a juice level that allowed just enough juice to flow over into the central downtake, occasionally showing bare tube plate for a few seconds between cyclic surges.

A number of radial flow design vessels have been installed in Australia since 2002. SRI (Australia) provided specifications for several of these, including the 4000 m^2

#1 stage unit at Broadwater Mill. *Moller* et al (2003) reported that the effective temperature difference between the condensing vapour and the boiling juice was ~6 K, which was considered excellent given its use of sub-heated clear juice feed. Other variations were installed at Millaquin and Rocky Point Mills in 2002 and both have been reported to be operating well. Approximate HTR estimates on the 2500 m^2 #1 stage unit at Rocky Point have been in excess of 1.2. Other installations have been installed in India, Philippines, Mexico and other countries.

After observing the behaviour and noting the heat transfer performance results, some ideas for future design modifications were formulated, mainly concerned with the reduction in juice volume beneath the calandria, and in isolating the condensate removal line from the juice space. These have been explored in later variations of the basic design. The author has developed a spreadsheet design program which allows the rapid formulation of RFR designs to meet factory preferences for duty, tube specification, and other features.

Summary

Shortcomings in the performance of many Robert evaporator designs have been studied, and design principles that correct these have been proposed. Suggestions to improve existing Robert designs have been made.

A novel radial flow Robert (RFR) design has been formulated to address many of the shortcomings of traditional Robert designs. Its general performance and heat transfer results have been very encouraging. The RFR design, with variations in the arrangement of its bottom shape, is recommended as a basis for future development of the Robert-type evaporator in the sugar industry.

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