Improved design of a falling-film tubular evaporator with a maintenance-friendly novel juice distributor

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Abstract Several variants of falling-film tubular evaporators (FFTE) are in use in the sugarcane industry. Most of these suffer from three main drawbacks: (i) occasional tube chokes due to uneven distribution of juice, (ii) absence of headroom between the top tube sheet and juice distributor necessitating its dismantling for mechanical de-scaling of tubes, and (iii) occasional cracking of austenitic SS tubes fitted in carbon steel calandria caused by thermal stresses due to widely dissimilar expansion at elevated temperature. A new design of juice distributor has been developed. It comprises an inlet weir box and a five-stage cascading system that forms a uniform shower of juice across the entire cross-section. It is installed at 2 m above the top tube sheet to facilitate easy access to various tubes for inspection or mechanical de-scaling without its dismantling. A segmented tray plate bolted to the top tube sheet and having an individual tripod-type umbrella structure located over each tube ensures equal wetting of each and every tube, making the system failsafe. One 3300 m² FFTE unit with this design of distributor is installed at a sugar factory in India. It has successfully completed three harvesting seasons without any tube choke. This plant produces plantation-white sugar by the double sulphitation process and has to carry out mechanical de-scaling during the crop to maintain heat transfer efficiency. Thermal stress analysis of another FFTE unit has been carried out using advanced software to simulate stress, buckling and deflection behaviour at elevated temperature for combination of carbon steel calandria and different grades of SS tubes to develop a structurally strong design with enhanced operational reliability. FFTEs with SS439 material tubes are installed as 2nd-4th effect evaporators at a 24,000 tcd sugar plant of the White Nile Sugar Company, Sudan. In the first crop, there was a problem of tube choking due to intermittent supply of juice arising out of frequent stoppage of milling process. In subsequent crops, the supply of juice to the evaporator station has been largely consistent and hence, the problem of tube choking was not experienced. This plant has completed three more crushing seasons without any tube failure or structural deformity.

Key words Falling-film tubular evaporator, cascade juice distributor, tripod umbrella, thermal-stress analysis

INTRODUCTION

The Indian sugar industry largely produces plantation-white sugar by double sulphitation (DS) process, although a couple of factories produce refined sugar by the defeco-remelt-phospho-flotation (DRP) process. All the falling-film evaporators operating in the Indian sugar industry are of a tubular type and comprise carbon steel calandria fitted with 10 m long SS 304 tubes. Several variants of juice distributors are in use, but most of these are of integral design, such that these are required to be located just above the top tube sheet as mentioned by Rein (2007). Therefore, one must dismantle the distributor for mechanical de-scaling of tubes, making the whole process very cumbersome, time-consuming and impractical to adopt during the crushing season. These falling-film tubular evaporators (FFTE) were initially used as 1st or 2nd effect vessels where the scale, predominantly calcium phosphate and calcium sulphite, is softer and largely removable by chemical cleaning (CIP). In 2007, Shree Renuka Sugars’ Athani unit in Karnataka (India) installed an IPRO design quintuple-effect evaporator set having all the five vessels of the falling-film tubular type fitted with 12 m long SS 304 tubes. This plant produces white sugar by the DRP process and they are reported to be working well.

In 2011, India Cane and Power’s sugar plant in Karnataka (India) installed a BMA design quintuple-effect evaporator set having all the five vessels of the falling-film tubular type fitted with 10 m long SS304 tubes. This plant produces white sugar by the double sulphitation process and these FFTE units work well, except for the difficulty experienced in removing the scale by CIP during the crushing season from the 4th and 5th effect vessels as reported by Lehnberger et al. (2013). Many of the sulphitation factories face severe fouling problems in the later effects where the scale, predominantly silicates and calcium sulphate, is very hard and is difficult to remove by CIP. Almost all sugarcane-processing factories, producing raw or white sugar, have to carry out mechanical de-scaling of evaporator tubes during the off-harvest, while the factories using the DS process often require mechanical de-scaling during the harvesting season.
Mechanical de-scaling is carried out either by using a tool head cutter or a hydro-jet system. In both of these systems, workmen are required to enter the space above the top tube sheet for holding the flexible shaft or the hydro-jet lance and guiding it inside the tubes one by one for mechanical de-scaling. The earlier practice of using tool head cutter is labour intensive and also reduces the life of the tubes. It is being gradually replaced by hydro jet de-scaling system that is much more efficient. However, both systems require sufficient head room and leg space for ease of maneuvering the device. Hence, there has been an urgent need for redesigning the juice distributor to ensure uniform wetting of each and every tube and to provide sufficient head and leg room over the top tube sheet for ease of maintenance without its dismantling.

Isgec Heavy Engineering Ltd, India has developed and supplied an improved design of FFTE, fitted with a novel juice distributor, that is reliable and maintenance friendly. The vessel design has been improved by thermal stress analysis and incorporation of ferritic (SS439) tubes instead of austenitic (SS304) tubes. This paper describes the salient features and advantages of the juice distributor and results of the FEA study for a 3500 m² FFTE unit.

Features of the novel juice distributor

The novel juice distributor is comprised of two main components (Fig. 1). The first component, called the cascade juice distributor, consists of an inlet weir box and a 5-stage cascading system that forms a uniform shower of juice across the entire cross section of the vessel. The second component, called the segmented tray plate, consists of individual tripod umbrellas located over each tube and welded to a tray plate. This tray plate is segmented and bolted to top tube sheet for ease of dismantling (Fig. 1). For better understanding, an exploded view of tripod umbrellas is shown in Figure 2. These prevent short circuiting and also ensure equal and uniform wetting of each and every tube.

The cascade distributor is installed 2 m above the top tube sheet to facilitate easy access to various tubes for inspection or mechanical de-scaling without its dismantling (Fig. 3). Each segment of the tray plate, along with the tripod umbrellas, can be removed and placed along the wall to allow easy access to the tubes during the crushing or after crushing.

The novel juice distributor is simple, yet rugged and reliable. It also ensures uniform wetting of each and every tube of the FFTE. However, the vessel height is increased by about 1.5 m. The cascade juice distributor, once assembled inside the vessel, need not be dismantled even during the off-crush. The 3300 m² FFTE vessel fitted with this distributor, installed at our sister sugar factory in India, has successfully completed three processing seasons without any tube choke. This plant produces plantation-white sugar by the double sulphitation process and is required to carry out mechanical de-scaling after every two cycles of chemical cleaning (CIP) during the crop to maintain heat transfer efficiency. The design wetting rate of this vessel is 20-22 L/(cm h).

Tube de-scaling system

Scaling on the surface of tubes of FFTE occurs overtime, as ingredients of the juice, mainly inorganic materials, become saturated and precipitate, some of which attach to the tube surface causing scaling. It is a normal phenomenon during sugarcane processing, eventually reaching a stage when the evaporation rate drops below acceptable levels. This requires time for shut down of the fouled vessel for tube cleaning. The scale can be removed either by chemical cleaning (CIP) and/or mechanical de-scaling process. However, in a situations when the quality of juice is bad, chemical cleaning does not remove the scale completely, particularly in factories using the DS process. The remaining scale is then removed by tool head cutter to restore the original condition of the tubes.

Srivastava and Goel (2014) have described the advantages of the hydro-jet de-scaling process, comprising a skid-mounted high-pressure water-pumping system, a lance tube and a mixed flow rotating head type nozzle to dislodge the scale from the surface of the tube. The pump, sourced from Gardner Denver System, USA, operated at 1000 bar pressure. This has been successfully used for de-scaling of 10 m long tubes of FFTE in many sugar factories in India and Sudan. There is no need to carry out any caustic soda boiling prior to hydro-jetting. The quality of surface finish is far better than by tool head cutting. Figure 4 shows hydro jet tube cleaning in progress at one of the project sites.
**Fig. 1.** Internal 3D view of the novel juice distributor.

**Fig. 2.** Exploded view of tripod umbrellas fitted on the tray plate.
**Fig. 3.** Mechanical cleaning of tubes in progress.

**Fig. 4.** Hydro-jet cleaning of tubes in progress.
Design optimization of FFTE through thermal-stress analysis

Generally, falling-film tubular evaporators (FFTE) are comprised of carbon steel calandria with tubes of 35-45 mm diameter and 10-12 m long made of SS 304, an austenitic stainless steel. However, the coefficient of linear expansion of SS 304 is 1.43 times that of carbon steel, resulting in higher thermal stresses at elevated temperatures, particularly in evaporators operating at temperatures above 100°C. The sugar industry wants material for tubes that has nearly same coefficient of linear expansion as that of carbon steel. After detailed study we selected SS 439, a ferritic stainless steel that has a coefficient of linear expansion 0.87 times that of carbon steel. Kaul et al. (2015) described the advantages of SS 439 tubes due to their superior yield strength, higher thermal conductivity and better resistance to stress corrosion as compared to SS 304 tubes. Table 1 compares the mechanical and thermal properties of SS 439 tubes, SS 304 tubes and carbon steel shell/tube sheets.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>SS 439 tubes</th>
<th>SS 304 tubes</th>
<th>Carbon steel shell/tube sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabrication procedure</td>
<td></td>
<td>Laser welded</td>
<td>Electric-resistance welded (ERW)</td>
<td>Arc welded</td>
</tr>
<tr>
<td>Type of steel</td>
<td></td>
<td>Ferritic</td>
<td>Austenitic</td>
<td>Ferritic</td>
</tr>
<tr>
<td>Density</td>
<td>kg/dm³</td>
<td>7.75</td>
<td>7.75</td>
<td>7.85</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>MPa</td>
<td>450</td>
<td>586</td>
<td>410</td>
</tr>
<tr>
<td>0.2% (Yield strength)</td>
<td>MPa</td>
<td>370</td>
<td>350</td>
<td>250</td>
</tr>
<tr>
<td>% Elongation</td>
<td>%</td>
<td>45</td>
<td>60</td>
<td>23</td>
</tr>
<tr>
<td>Coefficient of linear expansion</td>
<td>µ/m/K</td>
<td>9.8</td>
<td>16.1</td>
<td>11.3</td>
</tr>
<tr>
<td>Young's modulus</td>
<td>MPa</td>
<td>193,000</td>
<td>193,000</td>
<td>206,000</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>W/m°C</td>
<td>24</td>
<td>16</td>
<td>39</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td></td>
<td>0.31</td>
<td>0.31</td>
<td>0.29</td>
</tr>
<tr>
<td>Stress corrosion resistance</td>
<td>Range</td>
<td>100</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>0-100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Kharbanda et al. (2015) studied the design optimization of sugar plant equipment including tubular juice heaters and vacuum pans using advanced Finite Element Analysis (FEA) software. We have extended this to optimize the design of FFTE assembly made of carbon steel calandria fitted with stainless steel tubes of two different grades, i.e. SS 439 and SS 304. Since the first effect of evaporator set is subjected to the highest thermal and pressure loading, we chose its operating parameters for the thermal stress analysis. Solid works software version 2016 and ANSYS Workbench R15 software were used for the 3D modeling and thermal stress analysis, respectively.

The 3500 m² FFTE fitted with integral entrainment separator, novel juice distributor and 45 mm diameter, 10 m long tubes was selected as a complete assembly for FEA. A 3D model of the assembly is shown in Figure 5. The assembly is constrained (fixed) at bottom support skirt. The pressure and temperature were applied simultaneously in full body.

Three iterations were done, i.e. (1) FFTE assembly at the time of hydro test, (2) FFTE assembly fitted with SS 304 tubes and subjected to operating parameters below, and (3) FFTE assembly fitted with SS 439 tubes and subjected to operating parameters below:

- Tube side pressure and temperature 1.2 bar (g) and 115°C
- Shell side pressure and temperature 1.8 bar (g) and 130°C
- Ambient temperature 30°C
- Material of construction and their properties As in Table 1.
Results of the FEA study

A FEA study was carried out based on above inputs. Figure 6 shows the deflection pattern of the FFTE assembly at the operating parameters. Other important outputs, such as stress pattern in the top tube sheets and stress/deflection pattern in the tubes, are discussed below.

Stress in tube sheets: The von Mises stress patterns for the top tube sheets in respect of three different loading scenarios are shown in Figures 7-9.
Fig. 7. Stress pattern in top tube sheet in cold conditions i.e. at hydrotest.

Fig. 8. Stress pattern in top tube Sheet with SS 304 tubes in hot conditions.
It can be observed from above figures that at hydro-test condition, the stress in the top tube sheet is only 35-40 MPa. However, once the FFTE vessel is subjected to the operating temperature conditions, the stress level in the tube sheets increases substantially due to the difference in the coefficient of linear expansion between the calandria and the tubes. At the operating pressure and temperature conditions, the top tube sheet (assembled with SS 304 tubes) develops a stress level of 130-150 MPa, which decreases to 100-120 MPa for tube sheet (assembled with SS 439 tubes).

**Deflection pattern in the tube bundle:** Figures 10 and 11 show the deflection pattern of the tube bundle at operating pressure and temperature for SS 304 and SS 439 tubes, respectively.

It is clear from Figure 10 that, for the SS 304 tube bundle, all the tubes have buckled-in to cater the relatively lower expansion of carbon steel calandria shell. However, for the SS 439 tube bundle, the tube sheets have sagged inwards marginally and the outer periphery tubes have followed the shell expansion (Fig. 11).

**Stress in tubes:** At the hydro-test condition, the stress in the tubes is only 6-12 MPa. At the operating conditions, SS 304 tubes develop a stress of 65-130 MPa, which decreases to 30-50 MPa if the tubes are SS 439. A summary of stress values for tube sheets and SS tubes is given in Table 2.

**Table 2. Summary of actual stress values in top tube sheet and SS tubes.**

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Iteration-1</th>
<th>Iteration-2</th>
<th>Iteration-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual stress value in top tube sheet</td>
<td>MPa</td>
<td>35-40</td>
<td>130-150</td>
<td>100-120</td>
</tr>
<tr>
<td>Actual stress value in SS tubes</td>
<td>MPa</td>
<td>6-12</td>
<td>65-130</td>
<td>30-50</td>
</tr>
</tbody>
</table>
CONCLUSIONS

The novel juice distributor ensures uniform wetting of each and every tube of the FFTE assembly and also facilitates mechanical de-scaling by a tool head cutter or the hydro-jet system. The cascade juice distributor, once assembled inside the FFTE vessel, need not be disturbed or dismantled even during the off-crush. A 3300 m² FFTE vessel fitted with this juice distributor, installed at our sister sugar factory in India, has successfully completed three crushing seasons without any tube choke.

The tubes, as well as the tube sheets of FFTE unit fitted with SS439 tubes, are subjected to much lower stresses at the operating conditions, thereby improving their life and reliability compared to a FFTE unit fitted with SS 304 tubes. FFTEs with SS439 tubes installed as 2nd to 4th effect evaporators at a 24,000 tcd sugar plant in Sudan have completed four processing seasons without any tube failure or structural deformity.
Amélioration de la conception d’un évaporateur tubulaire à flux tombant avec un nouveau distributeur de jus d’un entretien facile

Résumé. Plusieurs variantes d’évaporateurs tubulaires à flux tombant (FFTE) sont utilisées dans l’industrie de la canne à sucre. La plupart d’entre eux souffre de trois problèmes : (i) blocages des tubes en raison de la répartition inégale des jus, (ii) l’absence d’espace libre entre la plaque des tubes du haut et le distributeur du jus, ce qui nécessite un démantèlement pour le détartrage mécanique des tubes, et (iii) occasionnellement des fissurations de tube en acier inoxydabilité, montés dans la calandre en acier au carbone, et causées par des contraintes thermiques dues aux dilatations très dissemblables à température élevée. Une nouvelle conception du distributeur de jus a été développée. Il est composé d’un déversoir d’entrée et d’un système en cascade de cinq étapes qui forme une douche uniforme de jus dans l’ensemble de la section entière. Il est installé à 2 m au-dessus de la plaque de tubes supérieurs afin de faciliter un accès facile aux différents tubes pour inspection ou détartrage mécanique, sans son démantèlement. Un plateau segmenté boulonné sur la plaque de tubes supérieurs, ayant une structure faîtière en forme de parapluie individuel située sur chaque tube assure une distribution égale pour chaque tube, rendant le système très fiable. Une unité FFTE de 3300 m² avec cette conception du distributeur est installée dans une sucrerie en Inde. Elle a complété avec succès trois campagnes sans aucun tube bloqué. Cette usine de sucre blanc plantation, produit par la double sulfatation, doit effectuer le détartrage mécanique au cours de la récolte pour maintenir l’efficacité du transfert de chaleur. L’analyse des contraintes thermiques d’une autre unité FFTE effectué à l’aide de logiciels pour simuler les comportements de stress, flambage et déflexion à des températures élevées, pour la combinaison de calandre en acier au carbone et différentes qualités de tubes inox, a développé une conception structurellement forte avec une fiabilité opérationnelle accrue. FFTEs avec tubes en matériel SS439 sont installés comme 2e-4e corps dans une usine de sucre de 24 000 tonnes de canne par jour de la Société de Sucre du Nil blanc, au Soudan. Pendant la première campagne, un problème de blocage de tube s’est développé, en raison d’un approvisionnement intermittent du jus, causé par des arrêts fréquents aux moulins. Dans les campagnes suivantes, le débit du jus vers la station d’évaporateur a été largement compatible et, par conséquent, le blocage des tubes n’a pas eu lieu. Cette usine a complété trois nouvelles campagnes sans défaillance de tube ou de déformation structurelle.

Mots-clés: Évaporateur à flux tombant, distributeur de jus en cascade, trépied parapluie, analyse de contraintes thermiques

Diseño mejorado de evaporadores tubulares de película descendente con un nuevo distribuidor de jugo de fácil mantenimiento

Resumen. Muchas variantes de evaporadores tubulares de película descendente (FFTE, por su siglas en inglés) se emplean en la industria azucarera de caña. La mayoría sufren de tres principales “dolencias”: (i) ocasionales estrangulamientos de los tubos como consecuencia de una poco uniforme distribución del fluido, (ii) ausencia de espacio entre la placa superior de los tubos y el distribuidor del jugo, que lo obliga a su desmantelamiento para permitir la desincrustación mecánica de los tubos, (iii) ocasionales fractura de los tubos de acero inoxidable austenítico insertados en una calandría de acero al carbono, en razón de de el estrés térmico debido a expansiones diferentes a elevadas temperaturas. Se ha desarrollado un nuevo diseño de distribuidor de jugo que incluye una caja vertedera de entrada y un sistema de cascada de cinco etapas, que forma una cascada uniforme de jugo a lo largo de toda la sección transversal. Se instala dos metros por encima de la placa superior de los tubos, para facilitar el acceso a varios tubos para inspección o desincrustación sin necesidad de desmantelar. Una bandeja segmentada atornillada a la placa superior de tubos, con una estructura de tipo de sombrilla individual de trípode, localizadas sobre cada tubo, asegura u humedecimiento igual para cada y todos los tubos, haciendo el sistema libre de fallas. En una fábrica de azúcar en la India se ha instalado una unidad de FFTE, de 3300 m² con este diseño de distribuidor, que ha completado tres exitosas zafras sin ninguna interrupción en los tubos. Esta instalación produce azúcar blanco directo, por el método de doble sulfatación y posee un sistema mecánico de desincrustación que asegura mantener la eficiencia de la transferencia de calor durante toda la campaña. Se han realizado análisis de estrés térmico en otras unidades de FFTE, empleando programas computacionales para simular el estrés, el pandeo y la deflexión a temperaturas elevadas, n combinaciones de calandrías de acero al carbono de diferentes grados de molida. Falling-film de tubos, para desarrollar un diseño estructuralmente fuerte, con una superior estabilidad operacional. Equipos FFTE con tubos de acero inoxidable 439 en el 2do. Y 4to efecto del evaporador, están instalados en una planta de azúcar blanco directo, de 24 000 tcd de la White Nile Co. en Sudan; en su primera campaña problemáticas de estrangulamiento de tubos debido a al suministro intermitente de jugo, induciendo frecuentes paradas de la molida, en las zonas subsiguientes el
abastecimiento de jugo en la estación de evaporación ha sido altamente consistente y no han existido dificultades con el estrangulamiento de los tubos. La planta ha completado tres campañas de molida, sin ningún fallo en los tubos ni deformación estructural.

**Palabras clave:** Evaporador tubular de película descendente, distribuidor de jugo de cascada, sombrilla de trípode, análisis de estrés térmico