Transformation of a Dual Stream Low Temperature Digestion Facility

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Abstract

Refineries processing primarily Gibbsitic bauxites require a low temperature digestion circuit to extract the alumina. These circuits typically operate at between 145 °C and 150 °C. Since the 1960's, many of the world's low temperature digestion facilities operated as dual stream circuits with the caustic liquor heated progressively through shell and tube heaters using regenerative flash steam. The liquor and bauxite streams were then mixed at the autoclave or digester vessels. With increasing focus on maximizing energy efficiency, process simplicity and plant utilization, single stream digestion technology has been increasingly the technology selected for refineries around the world. The single stream digestion flowsheet preferentially combines the bauxite and caustic liquor streams together in a single stream prior to regenerative heating. This paper provides a brief overview of the considerations required for the transformation of a dual stream low temperature digestion facility to a single stream operation. A review of process performance parameters and design considerations will be discussed.

Keywords: low temperature digestion; dual stream, single stream.

1. Introduction

Alumina refineries use primarily the "Bayer" process to extract alumina from Gibbsitic, Boehmitic or Diasporic bauxites. Refineries processing Gibbsitic bauxites require a low temperature digestion circuit to extract the alumina. These circuits typically operate at between 145 °C and 150 °C.

The conventional low temperature digestion flowsheet of Figure 1 employs a "split" or "dual" stream system whereby the liquor and bauxite streams are combined at the digester or autoclave. The liquor is directed through typically three or four stages of regenerative heaters for energy recovery prior to being mixed with the bauxite slurry.

Despite the relative simplicity of the dual stream flowsheet, there has been a growing interest in the merits of the single stream flowsheet and its application to the low temperature digestion circuit. As for the high temperature digestion flowsheet, the benefits of single streaming for a refinery processing a Gibbsitic bauxite may be generally summarized as:

- it provides the best thermal match between heat source (flash tank train) and heat sink (heaters). No 'export' of recuperative flash tank energy is required,
- the endothermic heat of reaction through the heating circuit acts as a "free" heat sink, reducing recuperative heat transfer areas,
- as a result of the gibbsite dissolution towards the equilibrium A/C, the driving force for desilication reduces reducing De-Silication Product (DSP) formation on the heat transfer surfaces; this therefore reduces condenser tube cleaning frequencies,
- with gibbsite dissolution through the heating circuit, the alumina dissolution passivates the steel reducing the 'free' caustic and allowing (typically) the use of standard grades of

carbon steel for the recuperative and live steam heater materials depending on caustic concentrations,
- it potentially unlocks yield constraints without requiring exotic materials for heater tubes and wetted surfaces.

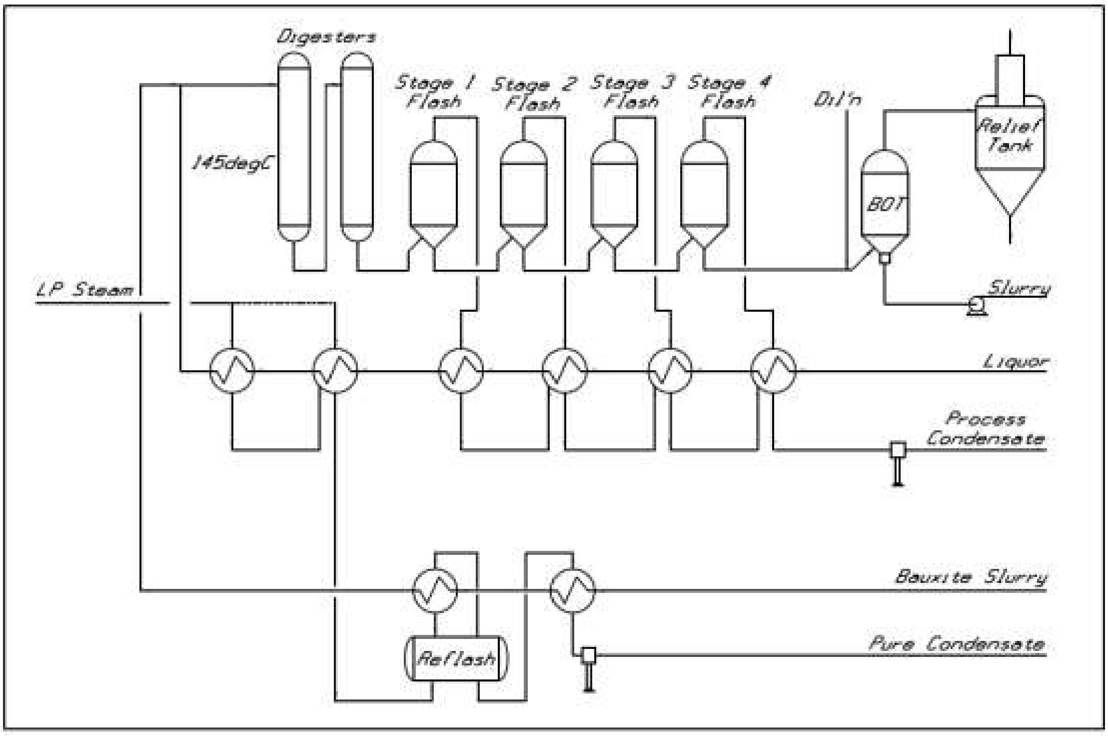

Figure 1. Dual stream low temperature digestion flowsheet.

For an existing dual stream operation to extract the benefits listed above and convert to a single stream operation, a thorough transformation process is required commencing with the mass and energy balance.

2. The Transformation Process

A flowchart of the main elements of a low temperature digestion single stream transformation process is shown in Figure 2 below. Each of the main elements of this flowchart are further discussed below.

2.1. Design Criteria

The Design Criteria defines the salient process performance targets for the new facility with key inputs that will be used in the mass and energy balance. For the single stream digestion conversion, this may include:

- the annualized refinery production target and refinery operating factor,
- the new single stream digestion facility operating factor,
- the digestion temperature and digestion energy consumption target,
- mass flows of input streams (bauxite slurry feed, liquor etc.),
- steam supply pressure and temperature at a nominated battery limit,
- chemical reactions and conversion extents, heats of reaction,
- heater stage heat losses,

- condenser heat transfer coefficients (HTC's),
- expected heater train campaign life and cleaning frequencies,
- digestion flash vessel condensate conductivity target.

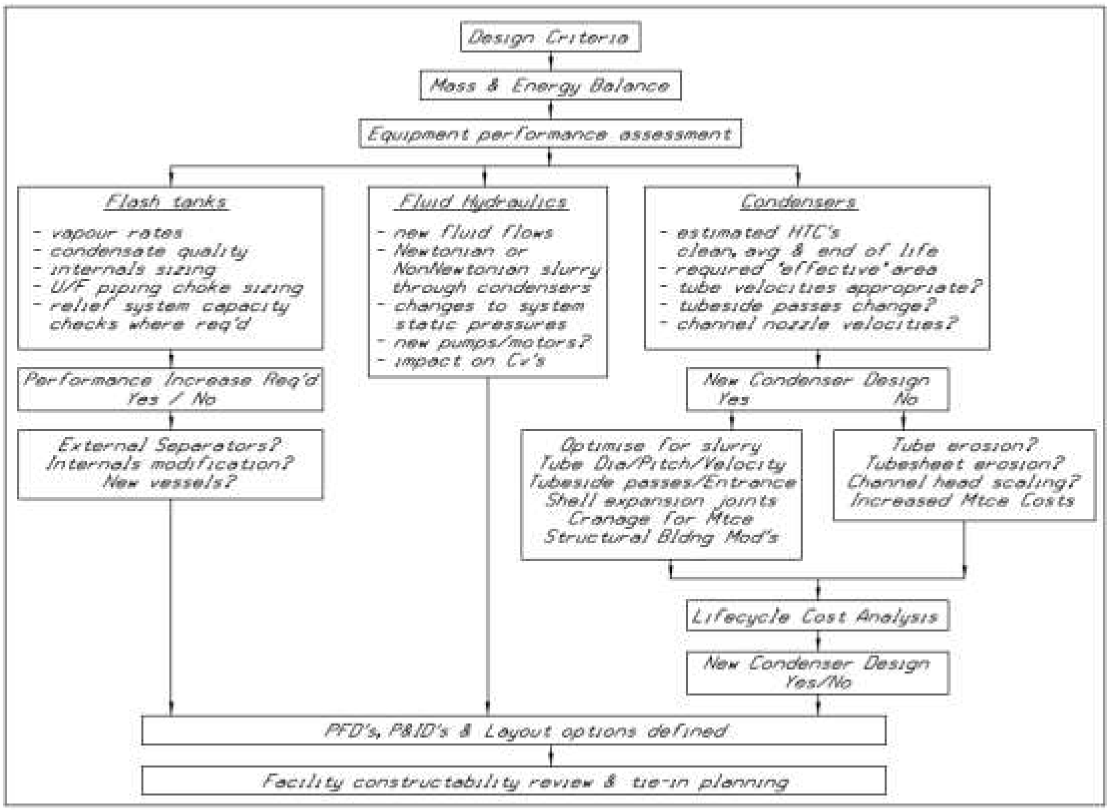

Figure 2. Single stream transformation process flowchart.

2.2. Mass and Energy Balance

The single stream transformation flowsheet is illustrated in Figure 3. For the same input mass flows and condenser areas, the conversion of a dual stream flowsheet (with indirect live steam heating) to a single stream flowsheet will alter the mass and energy balance as follows:

- the heat sink in the condensers from the new mass flow, fluid heat capacities and gibbsite heat of reaction will increase, affecting flash vapor rates and reducing digestion energy consumption,
- condenser overall heat transfer coefficients may change as a result of new tube-side fluid thermophysical property data (thermal conductivity, heat capacity, viscosity, slurry density); elevated tube-side velocities may offset higher fluid viscosities,
- the fluid temperature exiting the live steam condensers will reduce based on an approach margin to the digestion temperature rather than an elevated liquor temperature,
- as a result of the improved thermodynamic balance between heat sink and heat source, atmospheric "blow off" vapor is reduced, reducing water losses,
- free caustics through the condenser tube-side will reduce, increasing the materials of construction resilience to caustic erosion/corrosion mechanisms,
- as the gibbsite in the bauxite dissolves toward the equilibrium A/C, the equilibrium liquor silica concentration (SiO_2 (g/L)) will increase, reducing the differential between the liquor silica concentration and the liquor equilibrium silica concentration,

- this reducing silica differential is reflected in a reduced rate of desilication product formation (DSP). As a result, the condenser tube-side fouling rates will decline. DSP formation also preferentially precipitates on the slurry particles in lieu of the condenser tube surface, reducing cleaning frequencies and associated costs.

The effect of reduced DSP formation is presented in Figure 4. Assuming an equilibrium silica concentration independent of temperature [1], a single stream flowsheet operating at a digestion temperature of 150 °C has a desilication rate constant approximately one third that of a dual stream flowsheet requiring a liquor temperature exiting the live steam heaters of 170 °C.

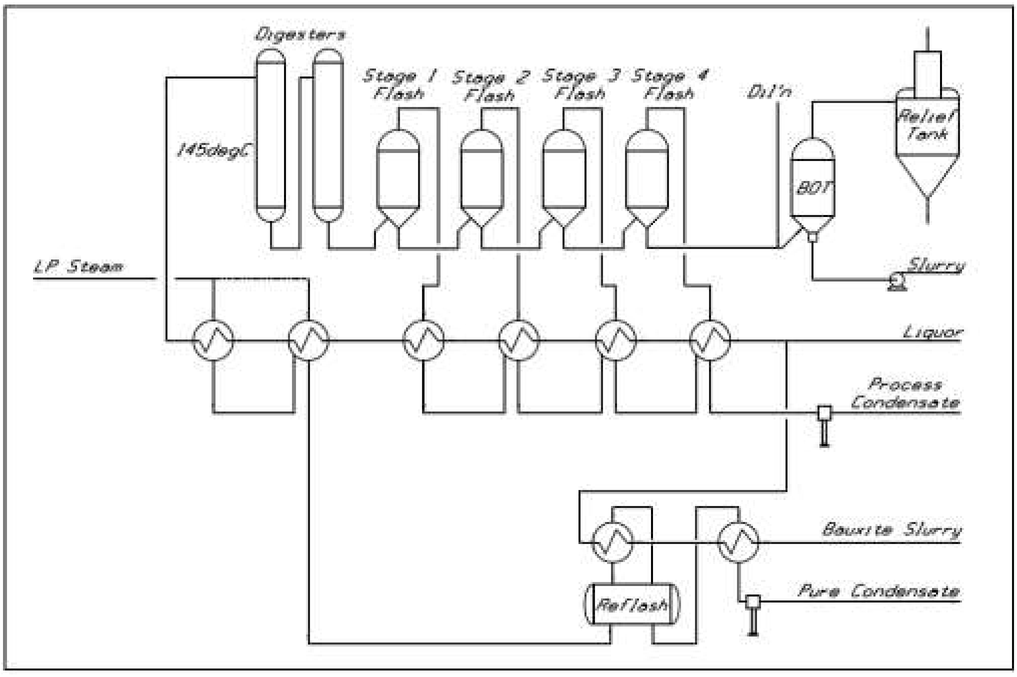

Figure 3. Single stream low temperature digestion flowsheet.

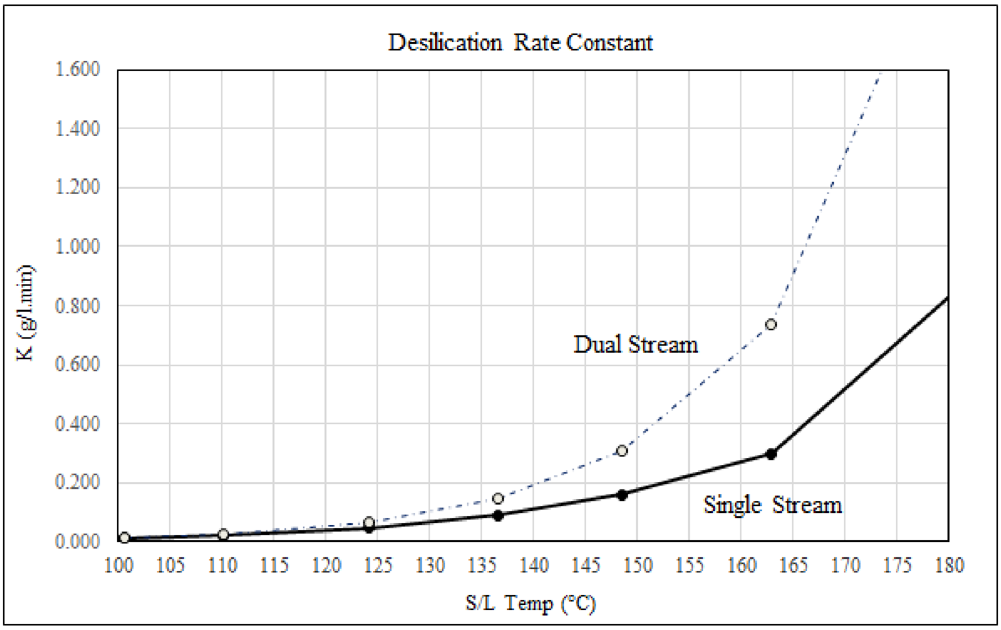

Figure 4. Single stream vs. dual stream – effect on DSP rate constant.

2.3. Equipment Performance Assessment

2.3.1. Condenser Design

2.3.1.1. Thermal Design Considerations

For most Bayer digestion facilities, the thermal design of the condenser is concerned with the efficient transfer of the latent heat of vaporization into the tube-side fluid. This requires determination of the overall heat transfer coefficient including an assessment of the clean, average and fouled conditions of the condenser. The estimated tube-side scaling rate (which generally presents non-linear characteristics with temperature) will then determine the operational cycle time between cleaning campaigns to attain the average heat transfer coefficient. The heat transfer relationships of relevance to the condenser are depicted in Figure 5 below.

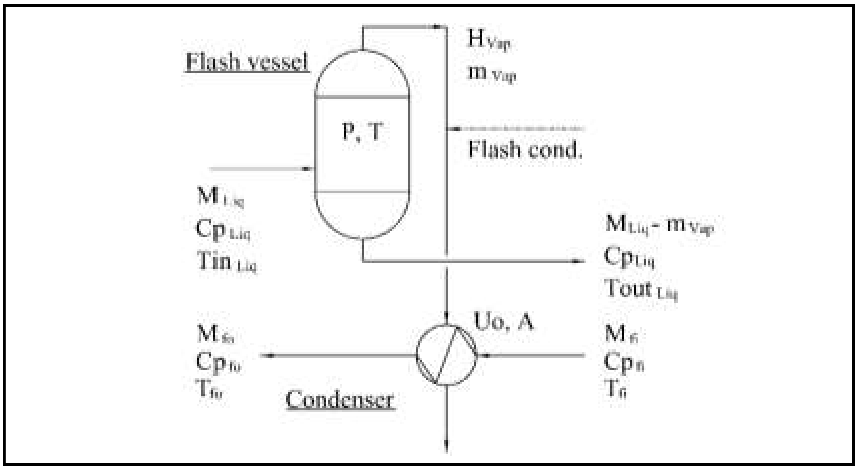

Figure 5. Single effect flash tank and condenser.

For the heat transferred by the condenser, we may use the energy equation for an adiabatic system as:

$$E_{(Accumulation)} = 0 = E_{(Input)} - E_{(Output)} + E_{(Generation)} - E_{(Consumption)},$$

where $E_{(Generation)}$ and $E_{(Consumption)}$ refer to the heats of reaction for exothermic and endothermic systems respectively. Expressing the above energy equation algebraically:

$$\Delta H = 0 = \frac{n \cdot \Delta \widehat{H}°r}{v} + \sum_{out} n_i \cdot \widehat{H}_i - \sum_{in} n_i \cdot \widehat{H}_i$$

where:
n is the moles of a reactant or product consumed or produced,
v is the stoichiometric coefficient of the reactant or product,
$\Delta\widehat{H}°_r$ is the heat of reaction at the reference temperature,
$\widehat{H}_i$ is the enthalpy of component i with respect to the reference temperature.

For the dual stream flowsheet, there is no heat of reaction involved throughout the condenser train. Consequently, the average heat transfer coefficient coincident with the effective heat transfer area is used to attain the digestion energy consumption target. To determine the effective heat transfer area, the actual area provided by the tube surface area must be discounted by the tube sheet thickness (2 off), as well as the tube-side baffles (typically 5 – 10 off). For the single stream flowsheet, the endothermic heat of reaction must be incorporated as a function of the gibbsite equilibrium solubility.

On the shell-side, minimizing frictional losses will maximize the saturation temperature of the steam available for heat transfer as each pipe and fitting loss due to friction is an irreversible loss of available saturation temperature and therefore loss of log mean temperature differential. Reducing shell-side entrance zone effects may, for example, require the use of vapor expansion belts on the shell or enlarged tube bundle clearances.

For vertically oriented condensers (as preferred in a single stream application) the vapor/steam inlet nozzle should be preferentially located as close as possible to the top of the condenser to promote contact with the condenser tube bundle full surface area. Where vapor belts are used, the fabrication detail should preferentially avoid sharp transitions to ensure residual stresses from welding are minimized regardless of the inclusion of stress relieving (e.g. curved knuckles are preferred to conical joints). In addition, any internal vapor baffling used to direct the vapor to the top of the tube bundle should not impede thorough drainage of condensate (or contaminant fluid) from the shell entrance zone. The effective heat transfer area of the condenser must be further discounted (incrementally) by the elevation of the condensate outlet nozzle, as this presents an artificial flooding of the condenser tubes.

To extend the condenser operational cycle, designs that promote a uniform tube-side fluid flow distribution into the tube sheet will reduce the likelihood of tube blockages and excessive slurry velocity through the remaining tubes. In lieu of more traditional condenser design parameters, this may require review of:

- the optimal tube diameter (e.g. $1^1/_2$", $1^3/_4$" or 2 "),
- the tube pitch (e.g. 1.25 or other),
- the number of tube side passes (one or two pass preferred for single stream),
- the channel inlet geometry to minimize eddy generation and tube flow mal-distribution.

2.3.1.2. Mechanical Design Considerations

As with the dual stream flowsheet, the condenser for a single stream application may be one of the many standard TEMA (Tubular Exchanger Manufacturers Association) configurations employing fixed tube-sheets (e.g. AEM or BEM type), floating heads, removable tube bundles and so on.

These standard TEMA designs are ideally suited to heat transfer fluids that do not contain particulate solids. The presence of solids exacerbates the impact of irregularities in the fluid flow streamlines that might otherwise not be observable in a liquid heat transfer fluid. The effect of these irregularities may be one of, or a combination of the items below:

- tube blockages,
- channel end scale accumulation,
- tube end erosion,
- channel end erosion,
- localized tube erosion throughout the tube length resulting from internal scale nodules,
- wire gauging of the tube sheet surface around the tube penetration,
- erosion of channel pass partition plates,
- erosion at partition plate gasket locations.

The result of these items may be a significant maintenance regime required to sustain the condenser performance. Alternative mechanical designs that optimize the fluid flow will present a preferable solution for a single stream flowsheet.

An example of optimizing the tube layout to normalize the tube fluid flow distribution in the inlet pass of a two tube pass heat exchanger is presented in Figure 6, Figure 7 and Figure 8 below.

The tube layouts of Figure 6 show a circular bundle geometry and a more traditional semi-circular distribution. Fluid flow streamlines using Computational Fluid Dynamics (CFD) are illustrated in Figure 7. The resultant individual tube mass flows from the CFD analysis are indicated in Figure 8. These results indicate the improvement in normalizing the fluid flows achieved by minimizing the geometric disturbance from the fluid external piping into the exchanger inlet channel and into the tube sheet.

Hence, vertical condenser designs that minimize the tube-side passes are preferred for the single stream application. In normalizing the fluid distribution into the tube sheet, the likelihood of tube blockages is naturally reduced. As the likely incidence of tube blockages is reduced, the consequent generation of excessive slurry velocities through the remaining tubes is also mitigated.

The long-term maintainability of the single stream exchanger installation may also be improved with designs that facilitate the complete condenser removal from the structural building for on-site or off-site refurbishment, re-tubing or mechanical cleaning. Splitting a single large condenser into individual tube passes is one way to reduce the weight of individual units for extraction by an overhead gantry or mobile cranage.

Whilst not particular to the single stream flowsheet, the fixed tube sheet condenser design may require consideration of the use of shell expansion joints. For the fixed tube sheet exchanger where the tubes are effectively anchored at both ends, thermal growth of the tube is constrained. The thermal expansion stress in the tube is independent of the tube length and can be expressed as:

$$\sigma_{dt} = \alpha . E . dT$$

where:
σ_{dt} is the expansion stress (N/m^2),
α is the coefficient of thermal expansion for the material (m/m°C),
E is the modulus of elasticity of the material (N/m^2),
dT is the temperature difference (°C).

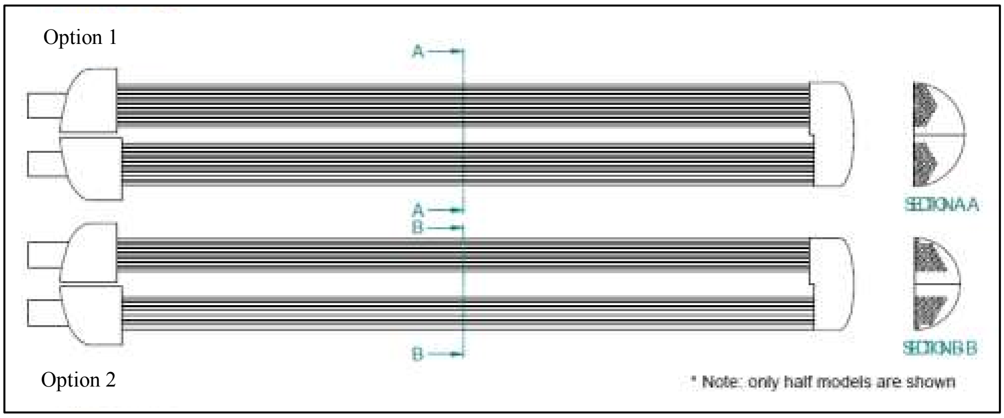

Figure 6. Tube distribution layouts.

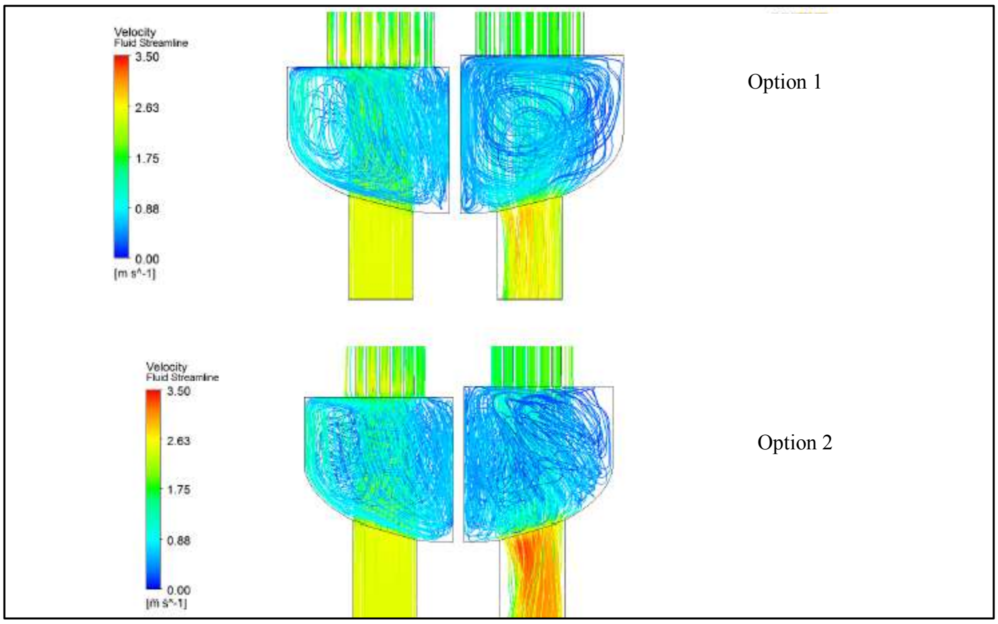

Figure 7. Fluid flow streamlines.

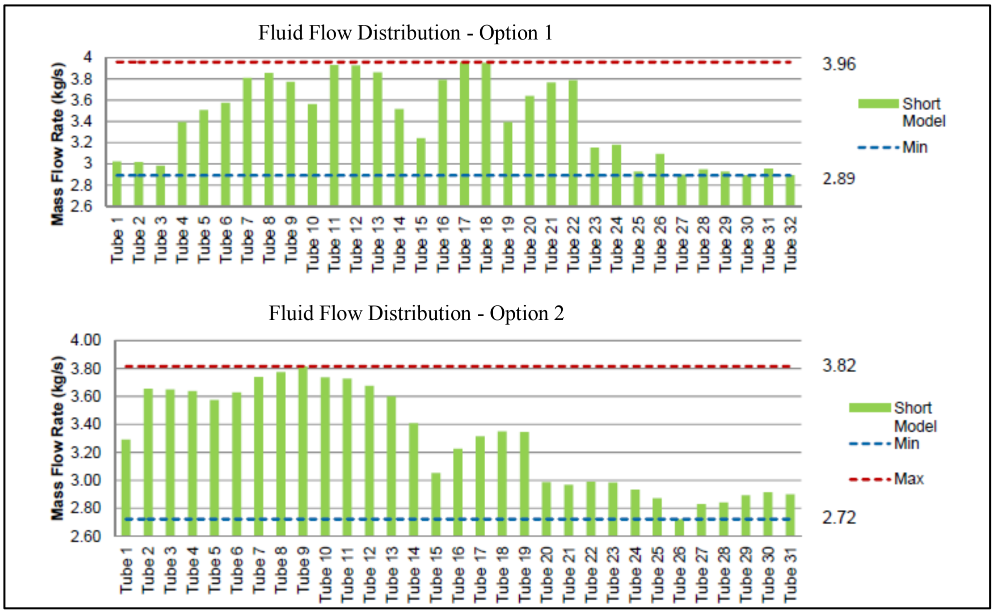

Figure 8. Tube flow distribution.

For the fixed tube sheet condenser, design temperature differentials of typically 70 – 80 °C in the mean metal wall temperature between shell and tube will typically limit thermal expansion stresses to the allowable material stress. Under these temperature differential constraints, the use of shell expansion joints may not be required simplifying the exchanger fabrication, cost and support detail. In determining the maximum mean metal temperature differential between shell and tube, the hot tube – cold shell case is often the determining condition.

The bypassing of flash vessel stages where the vapor is isolated on the condenser shell, may elevate the design temperature differential and this condition coincident with the hot tube – cold shell case, may in fact set the criteria for shell-side expansion joint consideration.

2.3.2. Flash Tanks

2.3.2.1. Vapor Quality

As outlined in Section 2.2, the endothermic heat of dissolution of the gibbsite through the regenerative heaters represents an additional heat sink improving overall energy recovery. As a result of this added heat sink and altered thermophysical properties of the slurry relative to the liquor, then for the same heat transfer area and HTC's, the single stream flow sheet will result in:

1. an additional 5 – 10 % vapor load on the vessel train and condensate recovery system,
2. lower flash tank pressure states and altered inter-tank pressure differentials,
3. a vapor load redistribution through the vessel train,
4. some incremental elevation in overall condensate conductivity as a result of the improvement in energy recovery.

These impacts require assessment of existing flash vessel performance in delivering a target condensate quality for re-use in the refinery. Where necessary, existing performance may be supplemented by the incorporation of external separators and/or optimization of the vessel dis-entrainment performance. As example, for existing flash vessels designed with a side or top entry discharge, conversion to a bottom entry configuration has been shown to provide at least a two to three-fold improvement in condensate quality.

In sizing the flash tank to avoid excessive vapor contamination, upward vapor rise rates are restricted to less than the estimated terminal settling velocity of entrained caustic soda of a maximum drop size. A common approach to sizing utilizes the Souders-Brown equation. This incorporates a vapor quality factor and takes the form of:

$$V_g = K.\sqrt{\left(\frac{\rho_l - \rho_g}{\rho_g}\right)}$$

where:
V_g is the maximum allowable gas velocity (m/s)
K is a vapor quality factor
ρ_l is the liquid density (kg/m^3)
ρ_g is the gas/vapor density (kg/m^3)

Generic values for the quality factor can be found in published texts however, in practice, factors developed from refinery site operational data are often employed in proprietary algorithms to optimally size this equipment. Further integrity in condensate quality may be provided with the incorporation of entrainment separators. However, as the vapor is superheated by the boiling point elevation of the fluid, internal separators such as Chevron style corrugated plates, tend to suffer from scale accretion and blockage and are generally avoided in this duty. External centrifugal separators are favored when incorporating additional vapor cleaning systems.

Where condensate quality targets cannot be attained with retrofits to existing vessels and the incorporation of external separators, new flash vessels may need to be considered for installation.

2.3.2.2. Internal Diffusers

Where existing vessel are equipped with internal diffusers, these should be reviewed for the new single stream flowsheet three phase system velocities and diffuser head reaction loads resulting from the new fluid mass flows and velocity conditions. These internal diffusers may require re-sizing to ensure satisfactory dis-engagement of the vapor from the boiling slurry is retained.

2.3.2.3. Natural Frequency

Separate to the pressure stress resultant from the internal operating pressure, the flash tanks are subject to vibratory forces resulting from the boiling fluid discharge flows and physical arrangement. The mechanical integrity of both pressure and non-pressure welds will be enhanced where the vessels' natural frequency is separated from the excitation frequency imparted by these external forces.

As the single stream flowsheet conditions will alter the process conditions through the vessel train, the new excitation frequencies should be reviewed against the existing vessel natural frequency.

2.3.2.4. Stress Analysis

In addition to reviewing new loads imparted to existing internal diffusers, ultimately these result in new forces and moments being imparted to the vessel wall via the internal supports. These new forces and moments should be reviewed for both weld integrity of the connecting struts/supports as well as local stresses imparted to the vessel wall such that any new stress condition is kept within allowable stress limits.

Modern analysis techniques incorporating Finite Element Analysis are often employed to examine localized stress at internal connections to the vessel shell.

2.3.2.5. Chokes

The chokes installed in the flash tank interconnecting piping are designed to impart a backpressure (or hydraulic resistance) such that:

1. a liquid seal is retained in the upstream vessel, mitigating vapor bypassing through to the underflow piping and its associated loss of energy recovery to the regenerative condensers,
2. three phase flow generation in the interconnecting pipework is delayed as far as practicable, minimizing the piping and fittings exposed to the erosive effects of the accelerating three phase flashing fluid flow,
3. vessel dis-entrainment performance is optimized.

The choke diameter must be sized to accommodate the design flow conditions whilst not restricting the passage of flow at the expected minimum three phase pressure differential operating between flash tank stages. The choke thickness must accommodate the maximum possible operating pressure differential.

As outlined above, independent of any mass flow change, the single stream flowsheet will alter the operating pressure between flash tank stages resulting from an improved energy recovery condition. Installed choke sizes must be reviewed for these new process conditions.

2.3.2.6. Passive Overpressure Protection Capacity Checks

The salient ways the single stream flowsheet transformation may impact the integrity of the passive relief system are as follows:

1. new pumping systems to deliver the slurry through the condenser circuit may provide added static pressure capacity above equipment ratings,
2. relief valves provided to protect the condenser tube-side from hydraulic expansion will now be exposed to a slurry service in lieu of liquor and may require periodic inspection campaigns to ensure inlet passages are not scaled or restricted,
3. lower flash tank pressure states will improve the degree of sub-cooling at flash tank relief stations however any upward re-sizing of interconnecting chokes will reduce the impedance of transient flows between vessels.

2.3.3. Hydraulic Systems

Independent of flowsheet capacity changes, the main hydraulic systems impacted by the single stream transformation process will be:

1. Digestion feed slurry. The dual stream digestion feed system utilizing spent liquor pumps to deliver liquor through the regenerative and live steam liquor heaters must be assessed for the new backpressure resulting from slurry flow through the condenser circuit. For slurry feed compositions in the range 8 – 15 % w/w, Newtonian fluid flow characteristics are expected. As for the liquor delivery system, a critical aspect of the hydraulic design for the single stream system is the estimation of the fouled state condition of the condenser circuit and the dynamic losses to account for this condition. Optimally, the digestion circuit operates thermally constrained, not hydraulically constrained, such that operational life of the condenser train is limited by the available saturation temperature of the delivery steam in lieu of liquor and slurry feed pump capacity.
2. Steam Delivery. A single stream flowsheet utilizing indirect live steam condensers will reduce the saturation pressure of steam required to meet the same digestion temperature. Subject to flowsheet conditions, this may require additional throttling of the steam control station. Valve performance should be reviewed for altered duty conditions.
3. Back Pressure Station. The backpressure station control valve or choke may have a new hydraulic duty imposed resulting from a reduced first flash tank pressure and/or altered mass flows.

2.4. Other Considerations

2.4.1. Layout

Where new or modified equipment is needed to accommodate the transformation process, layout optimization studies will be required to assess the capital and operational cost trade-off between re-use of existing facilities against the cost of new process buildings. New building installations will have the advantage of mitigating interruption to existing operations coincident with minimizing tie-ins and production losses.

Innovative use of equipment layouts (such as offsetting individual condenser units and/or piping systems) may provide opportunities to minimize new building sizes and maximize the opportunity to seamlessly integrate into the existing operations, reducing production downtime.

2.4.2. Structural Loadings

Where new condensers are to be incorporated into existing structural buildings, the condenser weights may impart new loads on existing structures and concrete foundations. To limit plant downtime the constructability sequence may further require a staggered implementation, meaning loads from new condensers may be additive to the existing equipment during the transformation. These new loads must be checked such that the structural building and foundation integrity is not compromised.

2.4.3. Constructability

Once the scope of transformation process has been defined, the implementation process will require a construction execution plan, detailed process and utility tie-in list and detailed project schedule. Stage or sequencing P&ID's may, for example, need to be developed to accommodate certain tie-ins.

3. Conclusions

This paper outlines the salient elements of the flowsheet transformation for a low temperature dual stream digestion facility to a single stream facility, including the strategic process benefits and key design parameters. A generic transformation flowchart has been presented that outlines the major process and mechanical considerations to be assessed such that critical equipment availability is sustained and operational life is maximized.

4. Acknowledgements

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5. References

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