Black Liquor Evaporators: Design and Operation

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INTRODUCTION

Weak Black Liquor (WBL) from the brown stock washers is typically at 13-18%TS. Most of this water content must be evaporated to produce a material with high enough solids to support effective combustion in the recovery boiler, typically between 65% and 80%TS.

During evaporation to this level of solids, various volatile components (sulfur compounds, methanol, etc.) are released from the liquor and must be separated from the condensate to allow reuse in the fiberline and recausticizing. From this point of view, the evaporation plant actually serves as a "water factory" within the mill.
Black liquor also contains a substantial fraction of inorganic compounds which, during the evaporation process, reach their solubility limit and can deposit as scale on the evaporator heat transfer surfaces greatly limiting the operating capacity of the evaporation plant and of the entire recovery island.

The inherent complex composition of black liquor translates into several interdependent design requirements for the evaporators:

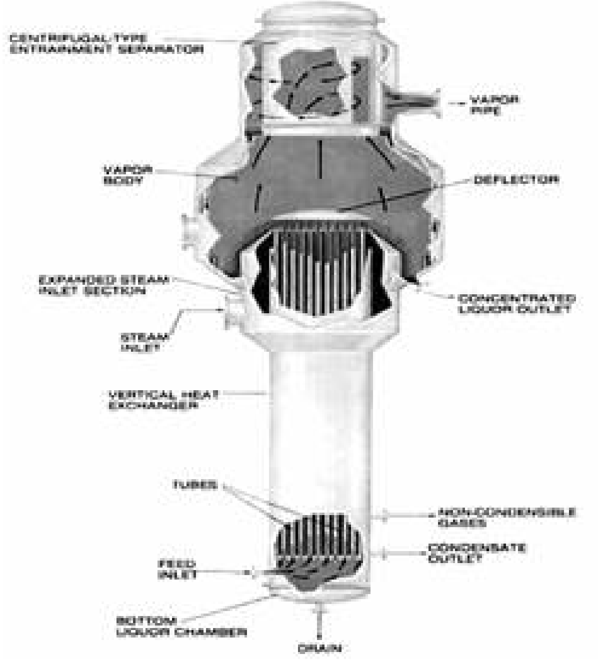
- The evaporation plant must efficiently transfer heat for the evaporation of the black liquor.
- It must do so while avoiding scale formation on the heat transfer surfaces.
- The evaporation plant must also produce sufficiently clean condensate fractions to satisfy the needs of the pulp mill and recausticizing area, thus greatly reducing the fresh water intake of the mill.
- Volatile components and NCGs must be removed and conditioned for safe disposal via incineration.

EVAPORATOR EQUIPMENT

There are two basic types of evaporator equipment in service today for black liquor evaporation:

Rising Film Evaporators

Also referred to as a Long Tube Vertical (LTV) evaporator, this design has dominated the Industry for decades and remains a common sight in older Kraft mill operations.



The heating element is a shell and tube heat exchanger using 2" OD tubes, typically 24ft. to 30 ft. long. Liquor is fed into the bottom liquor chamber and then into the tubes. It is heated with condensing steam on the outside of the tubes. The lower portion of the tubes is used to preheat the liquor to its boiling point. Evaporation then begins at that height within the tubes where the vapor pressure of the feed liquor equals the system pressure.

As the liquor climbs up the inside of the tubes, additional vapors are generated and the velocity of the liquid-vapor mixture increases to a maximum at the tube exit. The outlet mixture impinges upon a deflector, mounted above the top tubesheet of the heat exchanger, where gross, initial separation of the liquid from the vapors occurs.

Additional liquor is separated from the vapor by gravity as the vapors rise in the vapor body. An entrainment separator is installed near the top of the vapor body to remove most of the remaining traces of liquid from the vapors prior to their exiting the vapor body. The concentrated liquor is discharged from a connection near the bottom of the vapor body.

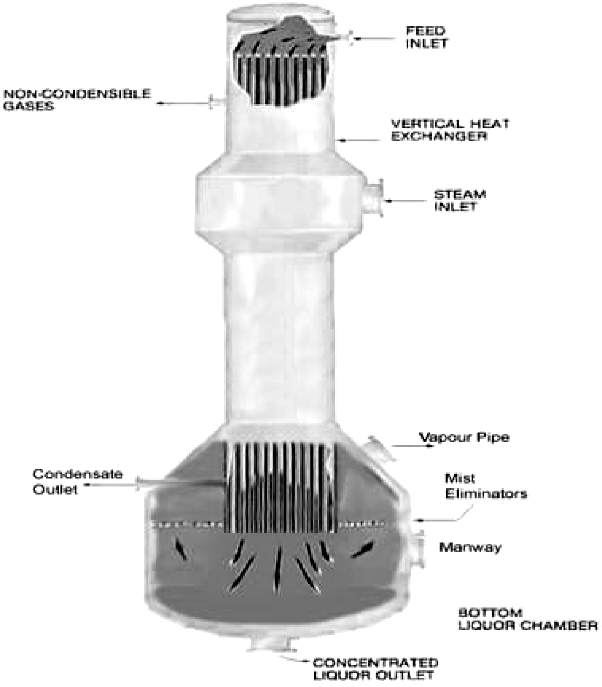
Heat-transfer rates in the preheating section are quite poor due to the slow moving liquor pool inside the tubes, but are several times greater in the boiling section due to the turbulence enhancement provided by nucleate boiling. It is therefore critically important to reduce the non-boiling zone to a minimum.

Different two-phase flow schemes are created in the boiling zone, including *slug flow*, where a slug of liquor is followed by a slug of vapor, similar to the perking in a coffee percolator; *annular flow*, where a ring of liquor encases a center core of vapor and liquid mist; and *mist flow*, where vapor blankets the tube surface.

Mist flow conditions should be avoided because poor heat transfer results when there is not enough liquid present to wet the tube walls. To avoid mist flow, it is sometimes necessary to recycle concentrated product liquor from the vapor body to the bottom liquor chamber so as to supplement the feed liquor.

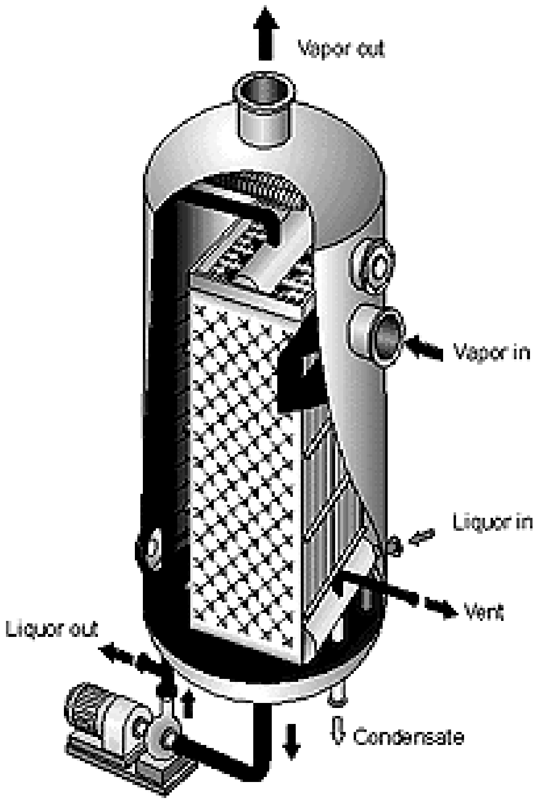
Falling Film (FF) Evaporators

This evaporator design relies either on tubes or plates as heat transfer surfaces. Liquor is processed on the inside of the s in tubular units but on the outside of the heat transfer surface in plate designs.



FF evaporators consist of a liquor sump from which a defined volume of liquor is continuously recirculated to the top of the heating element.

A distribution device, typically a tray or a spray nozzle in some designs, then distributes the flow of liquor over the entire heating surface. Holes in tubular units or slots for plate units are positioned to allow the liquor to fall onto the tubesheet or the plates. Even distribution of liquor is a critical consideration for this type of designs and both the tray and the tubesheet (or plate element) must all be level.



Following the distribution device, a thin film of liquor is established on the heating surfaces and flows downward back to the liquor sump while being partially evaporated. Heat-transfer rates are considerably better, especially at higher concentrations, when using falling film designs over rising film designs since the liquor falls turbulently over the heating surface. Any liquor preheating requirement is also efficiently accomplished in the falling film design.

Concentrators

This terminology refers to a class of evaporator designs specifically engineered to address the two issues associated with the processing of black liquor at high concentrations:

1. Precipitation of supersaturated components from the liquor

At some point, typically around 50-55%TS, water soluble sulfate and carbonate sodium salts exceed their solubility limits and begin to precipitate from the black liquor being evaporated. The double salt burkeite is the first to precipitate in the concentration process while dicarbonate, another sodium double salt, reaches its solubility limit later on, around 60%TS.

Control of this precipitation process is a crystallization problem, and achieving higher concentrations requires that evaporation equipment be designed as crystallizers to allow these salts to form in the bulk of the liquor, and not as scale on the heat transfer surfaces.

2. High liquor viscosity

As its concentration increases, black liquor rheological behavior changes from a Newtonian fluid to a pseudo-plastic fluid extremely viscous. Such high viscosities translate into poor heat transfer in concentrators (low Reynolds number hence low turbulence) but also represent an impediment to crystal growth within the bulk of the liquor. In addition, storage of the concentrated liquor, especially if well above 75%TS, may have to be in a pressurized tank in order to maintain the ability to pump the liquor to the boiler as well as proper spraying patterns.
To address these viscosity issues, black liquor concentrators are typically operated at substantially elevated temperatures and proper control of the liquor temperature under varying operating conditions becomes a critical parameter of the design as a mere 20 °F increase in liquor temperature can translate into a viscosity reduction of 50% in some cases.

Operation at elevated temperatures enhances the breakdown of calcium-organic complexes present in the liquor and, as a result, the risk of precipitation of calcium carbonate on the heat transfer surfaces is substantially increased. Precipitation of other water insoluble compounds, such as silica and oxalate salts if present in the liquor, can also occur at these higher temperatures, increasing the risk of scaling of the concentrator units.

Heat treatment of the liquor prior to the concentrator can permanently reduce the liquor viscosity by thermal-cracking of the long lignin and other organic compounds responsible for the liquor viscosity. Such treatment typically takes place in a continuous reactor operated at high pressure and temperature (above 350 °F). Over 30 min of residence time in the reactor must be provided to achieve maximum viscosity reduction.

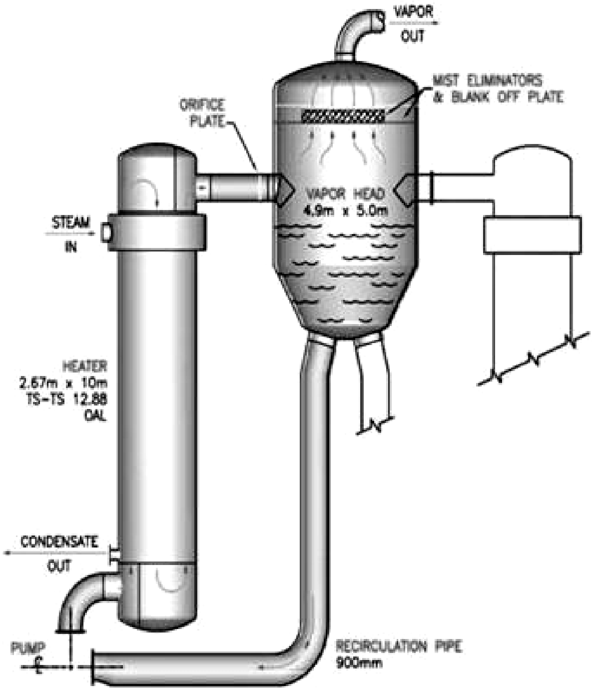
Two types of black liquor concentrators are in use today and those can be broadly classified as Falling Film (FF) and Forced Circulation (FC) designs.

Falling Film Concentrators are really an adaptation for high solids service of the FF evaporator design discussed above. By nature, FF concentrators, where evaporation takes place from a liquor film within the heating element, result in high supersaturation levels being developed within the liquor. This can result in uncontrolled scale formation due to excessive crystal nucleation rather than gentle crystal growth.
Some FF concentrator designs actually do not even attempt to control scale formation on the heating surfaces, but rather provide a mean to remove such scale faster than it forms and before it can negatively impact capacity or lead to plugging. Quick switching designs, commonly used with plate and tubular-element units, rely on this strategy by continuously moving multiple concentrator bodies (or chambers within the same body) between product liquor and washing positions.

Another design approach involves operating the FF concentrator at low heat flux to reduce the amount of supersaturation developed in the liquor during heat transfer. A substantial amount of heat transfer area has to be provided in this case, as well as a commensurate recirculation rate, to reduce both operating ΔT and specific evaporation per unit of heat transfer area.

Forced Circulation concentrators have been around since the 1950's and are well proven in black liquor service.

The design consists of a heat exchanger and a vapor/liquor flash chamber connected to each other through a recirculation loop.



Liquor is heated in the heating element that is back-pressured to prevent boiling within the tubes. Boiling and evaporation occurs away from the heat transfer surface and only when the heated liquor enters the flash chamber and its pressure is reduced. The flash chamber provides ample liquor retention time to allow relieving supersaturation via crystal growth. Liquor is then recirculated back to the heating element for another cycle of heating, flash evaporation and crystal growth.

Spiral inserts are used inside the heater tubes to disrupt the viscous boundary layer against the tube wall and promote mixing within the bulk of the liquor. The use of these inserts allows the design to make efficient use of the recirculation pump horsepower in establishing a high degree of turbulence thus improving heat transfer. High heat transfer is then achieved at relatively low liquor velocities.

As no evaporation takes place within the heat exchanger, the FC design achieves very low developed supersaturation levels that can be fully released in the flash chamber via evaporation and crystal growth.

Liquor viscosity (and its impact on hydraulics) is not as critical as in FF concentrator designs as there are no considerations for liquor distribution and film thickness. This ability to handle higher viscosity liquors while still at reasonable temperatures mitigates the risks of thermal decomposition of the liquor as well as the risk of calcium carbonate scaling.

MULTIPLE EFFECT EVAPORATORS

Black liquor evaporators use indirect contact with condensing steam (or vapors) on one side of a heat transfer surface to evaporate water from the black liquor circulating on the other side. As with all indirect heat exchangers, the overall heat transfer between the condensing steam and the black liquor is governed by the basic relationship:

$$Q = U \times A \times \Delta T$$

In this equation, the heat flow Q represents the amount of heat transfer that can be accomplished. As shown, this heat flow is dependent on the overall heat transfer coefficient U, the amount of heat transfer area A available to condense the incoming vapors and the temperature differential ΔT between the condensing vapors and the black liquor within the evaporator. Any reduction in U, A or ΔT will result directly in a reduction of Q. Evaporation can only take place when heat is added (in the form of condensing steam) to a surface area and a ΔT is established across that surface area.

The heat transfer coefficient U represents the rate at which heat transfer is accomplished across the given surface under the operating conditions of the evaporator. It is a complex number which varies with the material and quality of the heating surface, the temperature, concentration and viscosity of the black liquor and the level of turbulence within the liquor. The heat transfer coefficient is adversely affected by scale and deposits on the heat transfer surface, by low turbulence and also by the finish and thickness of the heat transfer surface.

Multiple effect evaporators (MEEs) are always used in black liquor service. The term *multiple effect* comes from the multiple effective use of energy to perform the evaporation task. In such configuration, live steam is condensed only in the first effect evaporator, generating vapors that are then sent to condense in a second effect where additional evaporation takes place. The process can then be repeated until reaching the last effect evaporator where generated vapors are condensed in a condenser using cooling water.

Steam generation in the Kraft mill is a significant operating expense and every effort must be made to conserve its use. The evaporation plant is by far the major consumer of that steam for the removal of water from the weak black liquor. Economic operation of the evaporator is therefore predicated upon the multiple effective use of the heat available from the steam and therefore on the number of effects in the MEE.

If the heat content of live steam was used only once, 100,000 lbs of steam would evaporate only 100,000 lbs of water from the liquor. By reusing the heat content of the generated vapors, 100,000 lbs of live steam in a 6 effect MEE could theoretically evaporate 600,000 lbs of water from the liquor.

Due to radiation losses and to the change in latent heat of evaporation at various temperatures and pressures, the full theoretical efficiency value cannot be attained and a rough rule of thumb is that the evaporation in each effect will be between 0.7 and 0.9 lbs for each 1.0 lbs of live steam condensed in the first effect of the MEE. The term *steam economy* refers to the number of lbs of water evaporated in the MEE per lbs of steam used.

The operating conditions in the MEE are set by the available live steam pressure at one end (typically 60 psig or less) and the vacuum established in the last effect and condenser at the other end (typically around 25” Hg). These two boundaries define the overall ΔT available to drive the evaporation process. Actual ΔT will actually be much lower due to the increasingly negative impact of the Boiling Point Rise (BPR) of the liquor as its concentration increases across the train.

Rising film evaporators are sensitive to the amount of ΔT available for the heat transfer operation. A ΔT of less than 13-15º F will often cause the unit to “stall” and overall to behave poorly. This ΔT limitation has great repercussions on the entire MEE train as it limits the number of rising film effects that can be operated within the overall ΔT available. This has generally limited system design to 6 effects (however, some 7 effect trains are still in operation) thus limiting the steam economy achievable and preventing operation under substantial turndown conditions.

Because the film of liquor in a falling film evaporator design is established over the heating surface via the use of a mechanical device and not through vapor generation as in a rising film unit, FF evaporators do not require a minimum ΔT to operate properly unlike rising film units as we noted earlier. This feature allows for much higher turndown capabilities and much higher efficiencies achievable from the evaporation plant. Several modern 7 and 8 effect trains operate today in many Kraft mills in North America and worldwide.

Besides the number of effects, other contributors to steam economy in the MEE include feed liquor temperature, condensate flashing, product liquor flashing, as well as actual venting and radiation losses from vessels, piping and tanks.

REFERENCES

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