

- 1. Introduction
- 2. Kraft Pulp and Black Liquor Production Worldwide
- 3. Properties Relevant to Evaporation
  - 3.1 Introduction to Black Liquor Properties
  - 3.2 Chemical Composition of Black Liquor
    - 3.2.1 Black Liquor Composition
    - 3.2.2 Molecular Size and Conformation of Kraft Lignin and Polysaccharides
    - 3.2.3 Extractives
    - 3.2.4 Terpenes
  - 3.3 Thermal and Transport Properties
    - 3.3.1 Viscosity
      - 3.3.1.1 Newtonian Behavior
      - 3.3.1.2 Impact of Temperature and Dry Solids Content on the Viscosity of Black Liquor
      - 3.3.1.3 Impact of Pulping Conditions
      - 3.3.1.4 Comparison of the Viscosity of Black Liquors from Pulping of Northern Hemisphere Woods and Eucalyptus
      - 3.2.4.1 Viscosity of Black Liquor from Pulping of Agricultural Residues and Other Nonwood Raw Materials
      - 3.3.1.6 Impact of Lignin Removal
      - 3.3.1.7 Non-Newtonian Behavior
      - 3.3.1.8 Reduction of Black Liquor Viscosity by Thermal Treatment
      - 3.3.1.9 Controlling Black Liquor Viscosity in the Mill Environment
    - 3.3.2 Boiling Point Rise
    - 3.3.3 Solubility Limit
    - 3.3.4 Density
    - 3.3.5 Enthalpy and Heat Capacity
      - 3.3.5.1 Heat Capacity
      - 3.3.5.2 Heat of Dilution
      - 3.3.5.3 Enthalpy
    - 3.3.6 Surface Tension
    - 3.3.7Thermal Conductivity
  - 3.4 Summary
  - 3.5 Nomenclature

### 4. Evaporation Fundamentals

- 4.1 Evaporator Hardware
  - 4.1.1
- 4.2 Evaporator Equipment 4.2.1 Long Tube Vertical (LTV) Evaporators

- 4.2.2 Falling Film Evaporators, Tube-Type Falling Film Evaporators
- 4.2.3 Falling Film Evaporators with Lamella-Type Heating Surfaces
- 4.3 Concentrator Equipment
  - 4.3.1 Lamella-Type Falling Film Concentrators
  - 4.3.2 Falling Film Concentrators with Tubular Heating Surfaces
  - 4.3.3 Black Liquor Inside Tubes
- 4.4 Forced Circulation Concentrators
  - 4.5 Direct-Contact Evaporation
  - 4.6 Multiple-Effect Evaporator Concepts and Evaporator Configurations
    - 4.6.1 Steam Consumption
  - 4.7 Vapor Compression Evaporation

#### 5. Design Principles and Analysis for Black Liquor Evaporation

- 5.1 Black Liquor Evaporator Mass & Energy Balances
  - 5.1.1 Mass and Energy Balance Calculation Procedure
    - 5.1.1.1 Introduction
    - 5.1.1.2 Mass and Energy Effect Balances for Single Effect
    - 5.1.1.3 Mass and Energy Balance Coupling Between Effects
    - 5.1.1.4 Optimizing Operation
    - 5.1.1.5 Complete Mass and Energy Balance for an LTV Evaporator Set
- 5.2 Evaporator Capacity and Steam Economy
- 5.3 Flow Characteristics in Evaporators and Concentrators
- 5.4 Descriptions of Flow Patterns in Vertical, Co-Current Vapor-Liquid Flow
  - 5.4.1 Rising Film LTV Evaporators
  - 5.4.2 Vertical Downflow Inside Tubes
  - 5.4.3 Vertical Downflow Over Tube Heating Elements
  - 5.4.4 Vertical Downflow Over Plate Heating Elements
  - 5.4.5 Design Procedure
    - 5.4.5.1 Design Basis and Input Variables
    - 5.4.5.2 Calculation of the Required Heat transfer Area
    - 5.4.5.3 Liquor Recirculation Rate
    - 5.4.5.4 Flow Distribution
  - 5.4.6 Flow Distributors in Black Liquor Falling Film Evaporators
- 5.5 Heat Transfer in Black Liquor Evaporators
  - 5.5.1 Evaluating  $\triangle T$  for Individual Evaporator Effects
  - 5.5.2 Estimating Heat Transfer Coefficients for Black Liquor Evaporators
  - 5.5.3 Terminology for Dimensionless Heat Transfer Correlations
  - 5.5.4 Convective Heat Transfer Correlations for Black Liquor
  - 5.5.5 Subcooled Flow Boiling Heat Transfer
  - 5.5.6 Determination of Flow Quality
  - 5.5.7 Nucleate Boiling Heat Transfer
  - 5.5.8 Falling Film Heat Transfer, Black Liquor on Outside of Tubes

5.5.9 Wetting of Heat Transfer Surfaces by Falling Black Liquor Films [10] 5.5.10 Nucleation Film Destruction

5.6 Evaporator and Concentrator Design Considerations for Troubleshooting

- 5.6.1 Design of Evaporation Systems
- 5.6.2 Troubleshooting Evaporation Systems
- 5.6.3 Design Principles for Troubleshooting Evaporation Systems
  - 5.6.3.1 Principle 1
  - 5.6.3.2 Principle 2
  - 5.6.3.3 Principle 3
  - 5.6.3.4 Principle 4
  - 5.6.3.5 Principle 5
  - 5.6.3.6 Practical Considerations
- 5.6.4 Industry Examples
  - 5.6.4.1 Example 1 Surface Condenser Fouling
  - 5.6.4.2 Example 2 Vacuum System Leak
  - 5.6.4.3 Example 3 Lower Concentrator Product Solids
  - 5.6.4.4 Additional Examples
- 5.6.5 Conclusions

#### 6. Auxiliary Processes

- 6.1 Tall Oil Soap Recovery
  - 6.1.1 Soap Quantities and Characteristics
  - 6.1.2 Solubility of Soap
  - 6.1.3 Physicochemical Characteristics of Soap
  - 6.1.4 Why Should the Tall Oil Soap Be Removed?
  - 6.1.5 How Soap Hurts Black Liquor Evaporators
  - 6.1.6 How Much Tall Oil Soap Is Present and Recoverable?
  - 6.1.7 Soap Recovery
  - 6.1.8 Foam Control
    - 6.1.8.1 Foam in First Filtrate Tank
    - 6.1.8.2 Soap Accumulation on Weak Liquor in Storage
    - 6.1.8.3 Removal of Soap in the Evaporators
    - 6.1.8.4 European Soap Recovery Practice
    - 6.1.8.5 Black Liquor Entrained in Soap
- 6.2 Fiber Removal
  - 6.2.1 Drum Filters
    - 6.2.1.1 Working Principle
  - 6.2.2 Design
  - 6.2.3 Basket Fiber Filters
  - 6.2.4 Who Should Have Responsibility for Operating the Fiber Filters?
- 6.3 Condensate Segregation
  - 6.3.1 Principles of Condensate Segregation
  - 6.3.2 Evaporator Condensate Segregation
  - 6.3.3 Digester Condensate Segregation

6.3.4 Kraft Mill Condensates

- 6.4 The Basics and Practice of Foul Condensate Stripping
  - 6.4.1 Why Strip Foul Condensates?
  - 6.4.2 What Condensates are Stripped?
    - 6.4.2.1 Batch Digester Blow Steam Condensate
    - 6.4.2.2 Batch Digester Relief Steam
    - 6.4.2.3 Continuous Digester Flash Steam
    - 6.4.2.4 Turpentine Decanter Underflow
    - 6.4.2.5 Evaporator Condensates
    - 6.4.2.6 Noncondensible Gas System Condensates
  - 6.4.3 Methods of Stripping
    - 6.4.3.1 Air Stripping for Total Reduced Sulfur
    - 6.4.3.2 Air Stripping for BOD
    - 6.4.3.3 Steam Stripping for Total Reduced Sulfur
    - 6.4.3.4 Steam Stripping for BOD
  - 6.4.4 Types of Columns
  - 6.4.5 Integrated Columns
    - 6.4.5.1 Fully Integrated
    - 6.4.5.2 Partially Integrated
  - 6.4.6 Column Operation
    - 6.4.6.1 Foaming
    - 6.4.6.2 Unstable Operation
    - 6.4.6.3 Steam Collapse
    - 6.4.6.4 Control of Contaminant Removal
    - 6.4.6.5 Fiber
    - 6.4.6.6 Plugging of Heat Exchangers
    - 6.4.6.7 Turpentine in Storage Tank
  - 6.4.7 Reflux Control
  - 6.4.8 Transport and Disposal of Contaminants
  - 6.4.9 Proper Operation Procedures
  - 6.4.10 Conclusion
  - 6.4.11 Acknowledgement
- 6.5 Methanol Purification
  - 6.5.1 Methanol Formation
  - 6.5.2 Methanol Capture
  - 6.5.3 Process Overview
  - 6.5.4 Modular Construction
  - 6.5.5 Process Description
    - 6.5.5.1 Topping System
    - 6.5.5.2 Red Oils Decanting
    - 6.5.5.3 Rectification System
    - 6.5.5.4 Methanol Product
- 6.6 Collecting and Burning Noncondensible Gases
  - 6.6.1 Composition of Noncondensible Gases
  - 6.6.2 Properties of Noncondensible Gases

- 6.6.2.1 Corrosivity
- 6.6.6.2 Toxicity
- 6.6.6.3 Explosivity
- 6.6.3 Ignition Sources
- 6.6.4 Concentrated Noncondensible Gas (Low Volume High Concentration) Systems
- 6.6.5 Piping Design and Layout
- 6.6.6 Scrubbing Noncondensible Gases
- 6.6.7 Dilute Noncondensible Gas (High Volume, Low Concentration) Systems
- 6.6.8 Chip Bin Gas Systems
- 6.6.9 Stripper Off Gas Systems
- 6.610 Burning Noncondensible Gases
  - 6.6.10.1 Lime Kiln
  - 6.6.10.2 Power Boilers
  - 6.6.10.3 Recovery Boilers
  - 6.6.10.4 Incinerators
  - 6.6.10.5 Waste Heat Boiler
  - 6.6.10.6 Incinerator Flue Gas Conditioning
  - 6.6.10.7 Regenerative Thermal Oxidizers
  - 6.6.10.8 Other Considerations
- 6.6.11 Impact
- 6.6.12 Conclusion
- 6.6.13 Acknowledgements

# 7. Scaling and Fouling in Black LiqUOr Evaporators

- 7.1 Introduction
- 7.2 Sodium Carbonate-Sodium Sulfate Scales in Black Liquor Evaporators and Concentrators
  - 7.2.1 Influence of Composition on the Sodium-Carbonate-Sulfate Crystals Formed in Black Liquor
  - 7.2.2 Solubility of Sodium Salts in Black Liquor
  - 7.2.3 Crystallization in Black Liquor Concentrators
  - 7.2.4 Critical Solids Content
  - 7.2.5 Stable Operation of Crystallizing Evaporators
  - 7.2.6 Design Considerations for Black Liquor Concentrators
  - 7.2.7 Controlling Dicarbonate Crystal Populations
  - 7.2.8 Small ΔTs Avoid Dicarbonate Scaling
  - 7.2.9 Washing Soluble Scales
- 7.3 Sodium Oxalate Scaling
- 7.4 Calcium Carbonate and Pirssonite Scales
  - 7.4.1 Where Calcium-Based Scales are a Problem
  - 7.4.2 Chemical Processes in Calcium-Based Scaling
  - 7.4.3 What is Soluble Calcium?
  - 7.4.4 Impact of Process Conditions on Calcium Carbonate Fouling Rate
  - 7.4.5.1 Modified Kraft Pulping Processes
  - 7.4.5.2 How to Control Calcium Carbonate Scaling

#### 7.5 Organic Foulants

#### 7.6 Aluminosilicate Scales

- 7.6.1 Aluminosilicate Chemistry
- 7.6.2 Solubility and Precipitation Regions for Aluminisilicates
- 7.6.3 Removing Aluminosilicate Scales

## 8. Research Needs in Black Liquor Evaporation

- 8.1 Opportunities for Technology Enhancement
- 8.2 Lower Cost Water Removal Methods
- 8.3 Increasing Evaporation Rates with Existing Evaporators

#### 9. TERMINOLOGY