Learning Objectives

After this lecture the student

• understands the principles of kraft pulp washing simulation
• is able to explain the most important concepts in washing operations (e.g. washing loss, dilution factor)
• can formulate an overall balance for kraft pulp mill washing plant
• can explain the importance of adequate brown stock washing
Kraft pulp mill
Fibre line (Example)
Purpose of pulp washing

- Pulp washing represents the crossroads between the fiberline and the chemical recovery
- The dissolved organic matter from cooking and reacted cooking chemicals forms the *black liquor*, which is pursued to be separated from the fibre material as efficiently and as concentrated as possible
- On the other hand, the post-cooking delignification and bleaching stages imply that cook-based organic matter can be washed away (in order to reduce additional chemical consumption, to maintain fibre strength and pulp yield as well as considering the environmental aspects)
Pulp washing in fibre line

• After delignification (cooking). This is called brown stock washing (BSW).

• After oxygen delignification (O). This is called post oxygen washing (POW).

• Typically after each bleaching stage (D, A, AD, E, EP, EOP, P, PO, Z, Q,...)
Motivation of pulp washing

- Separate fibres and dissolved inorganic and organic material
- Recovery of cooking chemicals for re-use.
- Recovery of dissolved organic material for energy production in a recovery boiler.
- Decrease of bleaching chemical consumption.
- Decrease of environmental discharge.
- Maintain product quality.
Counter-current washing

- Motivation to save water
- The clean wash water is introduced into the last washing stage, from which the filtrate is used as the washing liquid in the previous stage etc.
- The most unclean (highest concentration of the washable material) is withdrawn from the first washing stage. This filtrate is taken to evaporation. Nowadays in the modern cooking methods the first washing stage is arranged inside the cooking process.
Wash water and the connections of washing

- The wash water is commonly **hot water** of 70 – 80 °C and is obtained from the hot water system of the pulp mill. Often also the **secondary condensates** from the evaporation plant are used but they may be unclean (rather high concentration of COD) which needs to be taken into account.

- Some mills are considering the usage of the alkaline filtrates of bleaching as the wash water of pulp washing (due to environmental reason). The COD-content and Cl-content of such filtrates needs to be taken into account, as well.

- Sometimes the washing line has sidestreams: a sidestream of pulp for eg. producing unbleached pulp. Sometimes there may be sidestreams in the filtrate side (eg. leakages of water from the pump seals). In such situations the complete countercurrent connection is disturbed and any calculations imply the use of simulation programs.
Principles of washing

- The most simple pulp washing principle is the dilution of pulp with the washing liquid followed by thickening (consistency increase). Commonly used in the washing of mechanical pulps and in small production pulping lines.

- The most important washing principle is displacement washing (cake washing), where the clean washing liquor displaces the dirtier one from the pulp suspension. Displacement commonly takes place at a consistency of 10 – 12 % which often implies pre-thickening of pulp to the desired consistency ahead of the displacement.

Often an actual washer is combination of above two main basic operations.
Principles of washing
What are the substances to be washed away in pulp washing?

- **The total dissolved material** in black liquor is the main target to be washed away (dissolved solids, DS)

- Often the washing of organic and inorganic matter are kept separate from each other: The organic matter is described with the **Chemical Oxygen Demand (COD)** and the inorganic matter eg. with sodium sulphate (Na$_2$SO$_4$)

- The washing efficiency in terms of the COD correlates with the performance of oxygen delignification and bleaching (1 kg COD corresponds 0,6 – 0,8 kg akt. Cl in bleaching) as well as with the COD- ja AOX- discharges from bleaching

- The Na-washing loss was earlier in the general use because the sodium loss in the washed pulp represented one of the main losses from the chemical circulation
Terminology of pulp washing

- **Washing loss (carry-over):**
  - The amount of washable material entering oxygen delignification or bleaching per ton of pulp
  - Can be expressed as COD-loss (kg COD/ton pulp), dissolved solids loss (kg DS/ton of pulp) or sodium loss (eg. kg Na$_2$SO$_4$/ton pulp)
  - Determination of the washing loss is standardized (eg. according to SCAN or Tappi standards). Many mills have their own ”fast methods” that may give different results from the standard methods.
Washing terminology

- **Dilution factor (DF):**

  - DF = total wash water amount (t/ton pulp) – the water amount in the washed pulp (t/ton pulp)

  - The dilution factor keeps constant in all the equipment in the washing line provided that the filtrates are connected in complete countercurrent (no sidestreams of pulp or the filtrates) and if the washing line is completely in balance

  - The dilution factor is the main control parameter of the pulp washing line
Washing terminology

- **Definitions of the washing efficiency:**

  - **E-factor, Nordén number:** The most widely used parameter for the washing efficiency. It expresses how many ideal mass transfer stages (dilution-thickening stages) there are in the washing system or in a certain washing apparatus.

  - **Displacement ratio, DR:** Traditional measure for washing efficiency. Commonly used in many countries (North America, Asia).

  - **Recovery rate, washing yield:** Expresses the recovery rate of the washable substance in relation to the input from cooking and oxygen delignification.
Washing stage

The principal drawing of a washing stage:

Filtrate $V_1$
Concentration of washable material $y_1$

Wash water $V_2$
Washable material conc. $y_2$

Feed consistency (%) $C_0$
Liquid with pulp $L_0$
Washable material conc. $x_0$

Outlet consistency (%) $C_1$
Liquid with pulp $L_1$
Washable material conc. $x_1$
Balances

All liquid streams $m^3$/ton pulp or t/pulp

All concentrations of the washable material in the same unit (eg. g/l, w-% etc.)

Ton pulp is either ADt or BDt (ODt)

1 ADt is 900 kg fiber (ADt = Air Dry ton)

1 BDt (ODt) is 1000 kg fiber (BDt = Bone Dry ton, ODt = Oven Dry ton)
Balances

\[ L_0 = \frac{(100 - C_0)}{C_0}, \quad L_1 = \frac{(100 - C_1)}{C_1} \quad (t/BDt, \ t/ODt) \]

\[ L_0 = 0.9\frac{(100 - C_0)}{C_0}, \quad L_1 = 0.9\frac{(100 - C_1)}{C_1} \quad (t/ADt) \]

\[ V_1, V_2 \quad (t/ADt, \ t/BDt) \]

\[ L_0 + V_2 = L_1 + V_1 \quad \text{Total liquid balance} \]

\[ x_0 L_0 + y_2 V_2 = x_1 L_1 + y_1 V_1 \quad \text{Balance of the washable material} \]

\[ DF = V_2 - L_1 \quad \text{Dilution factor} \]

\[ DF = V_1 - L_0 \quad \text{Dilution factor} \]
Washing efficiency: Norden E-factor

\[ E = \ln \left[ \frac{L_o (x_o - y_1)}{L_1 (x_1 - y_2)} \right] \]

\[ \ln \left( \frac{V_2}{L_1} \right) \]
Definition of E-number

Norden E-number

Example: $E = 3$

Thickening
Washing efficiency: Measured values does necessary fullfill material balance

\[ L_0 + V_2 = L_1 + V_1 \]

\[ L_0x_0 + V_2y_2 = L_1x_1 + V_1y_1 \]

Inserting DF to solute balance equation one gets

\[ L_0x_0 + (L_1 + DF)y_2 = L_1x_1 + (L_0 + DF)y_1 \]

Solving different parameters from above equation and inserting to E-factor formula one gets different material balance closing methods.
Washing efficiency: Modification of the E-factor, most common

Basic definition (material have to fit!, when apply this):

\[ E = \frac{\ln\left(\frac{L_0(x_0 - y_1)}{L_1(x_1 - y_2)}\right)}{\ln\left(1 + \frac{DF}{L_1}\right)} \]

Correction in the pulp feed (either \(L_0\) or \(x_0\) is calculated):

\[ E = \frac{\ln\left[1 + \frac{DF(y_1 - y_2)}{L_1(x_1 - y_2)}\right]}{\ln\left[1 + \frac{DF}{L_1}\right]} \]
Washing efficiency: Modification of the E-factor (most common)

Correction in DF (DF is calculated):

\[ DF = \frac{L_{0}(x_0 - y_1) + L_{1}(y_2 - x_1)}{(y_1 - y_2)} \]

\[ E = \frac{\ln \left( \frac{L_{0}(x_0 - y_1)}{L_{1}(x_1 - y_2)} \right)}{\ln \left( 1 + \frac{DF}{L_{1}} \right)} \]

Correction in the filtrate \( y_1 \) (\( y_1 \) is calculated):

\[ E = \frac{\ln \left( \frac{L_{0}}{L_{0} + DF} \left( 1 + \frac{DF(x_0 - y_2)}{L_{1}(x_1 - y_2)} \right) \right)}{\ln \left( 1 + \frac{DF}{L_{1}} \right)} \]
Washing efficiency: E-factor values

• E-factor is quite constant regardless of dilution factor
• E-factor is characteristic of each washing equipment type. It can be determined experimentally
• Ideal displacement: E = infinite
• Dilution + thickening: E = 1
• Non-existing displacement: E = 0
• In practice the E-value of industrial washing equipment varies between 2 - 10
Calculating a washing system

\[ L = \text{Liquid flow with pulp, t/f}\]
\[ V = \text{Wash liquid of filtrate flow, t/f}\]
\[ x, y = \text{concentration of dissolved substance, kg/ton}\]
Washing system

\[ E_{tot} \ln \left( \frac{V_{n+1}}{L_n} \right) = \ln \left( \frac{L_0(x_0 - y_1)}{L_n(x_n - y_{n+1})} \right) = \ln \left( \frac{L_0(x_0 - y_1)}{L_1(x_1 - y_2)} \frac{L_1(x_1 - y_2)}{L_2(x_2 - y_3)} \cdots \frac{L_{n-1}(x_{n-1} - y_n)}{L_n(x_n - y_{n+1})} \right) = \]

\[ \ln \left( \frac{L_0(x_0 - y_1)}{L_1(x_1 - y_2)} \right) + \ln \left( \frac{L_1(x_1 - y_2)}{L_2(x_2 - y_3)} \right) + \cdots + \ln \left( \frac{L_{n-1}(x_{n-1} - y_n)}{L_n(x_n - y_{n+1})} \right) = \]

\[ E_1 \ln \left( \frac{V_2}{L_1} \right) + E_2 \ln \left( \frac{V_3}{L_2} \right) + \cdots + E_n \ln \left( \frac{V_{n+1}}{L_n} \right) \]
Calculating the washing system

The total E-value vs. Individual E-values of equipment

\[ E_{tot} \ln R_n = E_1 \ln R_1 + E_2 \ln R_2 + \ldots + E_n \ln R_n \]

\[ R_1 = \frac{V_2}{L_1} \]

\[ R_2 = \frac{V_3}{L_2} \]

\[ \ldots \]

\[ R_n = \frac{V_{n+1}}{L_n} \]

Important special case:

\[ R_1 = R_2 = R_3 = \ldots = R_n \]

\[ E_{tot} = E_1 + E_2 + E_3 + \ldots + E_n \]
Definition of $E_{st}$-factor (st = standard)

$$L_1x_1 + (L_{st} - L_1) = L_{st}x_{1,st}$$
Relation between $E$ and $E_{st}$

\[
E_{st} = E - \frac{\ln \left( \frac{L_0 (x_0 - y_1)}{L_{st} (x_{1, st} - y_2)} \right)}{\ln \left( \frac{V_2 + L_{st} - L_1}{L_{st}} \right)} = \ln \left( \frac{L_0 (x_0 - y_1)}{L_{st} x_{1, st} - L_{st} y_2} \right)
\]

\[
E = \ln \left( \frac{L_0 (x_0 - y_1)}{L_1 (x_1 - y_2)} \right) - \frac{\ln \left( \frac{L_0 (x_0 - y_1)}{L_1 (x_1 - y_2)} \right)}{\ln \left( \frac{V_2}{L_1} \right)} = \ln \left( \frac{L_0 (x_0 - y_1)}{L_1 (x_1 - y_2)} \right)
\]

\[
E_{st} = E - \frac{\ln \left( 1 + \frac{DF}{L_{st}} \right)}{\ln \left( 1 + \frac{DF}{L_{st}} \right)}
\]
Calculating the washing system

E-value in the ”standard consistency”:
- Makes it easier to compare different washing equipment if the discharge consistencies of different equipment vary
- Calculating the total E-value is easy
- The commonly used standard consistency is 10 %

\[ L = \frac{100 - 10}{10} = 9 \text{ m}^3 / BDT \]

\[ E_{10} = \ln \left( \frac{L_0 (x_0 - y_1)}{L_1 (x_1 - y_2)} \right) \]

\[ = \ln \left( 1 + \frac{DF}{9.0} \right) \]

\[ E_{10, total} = E_{10,1} + E_{10,2} + \ldots + E_{10,n} \]
Washing efficiency: Displacement ratio (DR-value)

\[ DR = \frac{x_0 - x_1}{x_0 - y_2} \]

- **Filtrate in** \( V_1 \)
- Concentration of washable material \( y_1 \)
- **Filtrate out**
- **Liquid with pulp** \( L_0 \)
- **Pulp in**
- **Pulp out**
- **Wash water in** \( V_2 \)
- Washable material conc. \( y_2 \)
- **Wash water out**
- **Outlet consistency (%)** \( C_1 \)
- **Liquid with pulp** \( L_1 \)
- **Feed consistency (%)** \( C_0 \)
- Washable material conc. \( x_0 \)
DR-value

- Often used in pulp mills, since it is easy to calculate
- DR-value depends on the feed and discharge consistency of a washer and DF.
- Be careful, when DF is changing.

DR is the volume of actually displaced liquor divided by the volume of the original liquor which is the same as the liquor on the pulp out of the washer.
Model washer
Equivalent DR-values

\[
DR_{C_{0, st}, C_{1, st}} = \frac{x_{0, st} - x_{1, st}}{x_{0, st} - y_2} = 1 - (1 - DR) \frac{L_1}{L_{1, st}} \frac{L_{0, st} (L_0 + DF)}{L_0 (DF + L_{0, st}) - L_1 (L_{0, st} - L_0) (1 - DR)}
\]

Equivalent Displacement Ratio: DR of a filter: \(C_{0, st} = 1\%\) and \(C_{1, st} = 12\%

\[
EDR = DR_{1,12} = 1 - (1 - DR) \frac{L_1}{7.333} \frac{99 (L_0 + DF)}{L_0 (DF + 99) - L_1 (99 - L_0) (1 - DR)}
\]

Equivalent DR-values can be used for comparison of the different washers (same DF)
The Washing yield expresses how big share of the washable material in the inlet flow is recovered in the filtrate:
Washing yields

\[
Y = 1 - \frac{L_1(x_1 - y_2)}{L_0(x_0 - y_2)} \quad Y = \frac{(L_0 + DF)(y_1 - y_2)}{L_0(x_0 - y_2)}
\]

Equivalent wash yield. The constant feed consistency \(C_{0, st}\)

\[
Y_{C_{0, st}} = 1 - \frac{L_1(x_1 - y_2)}{L_0(x_0 - y_1) + L_{0, st}(y_1 - y_2)} \quad Y_{C_{0, st}} = \frac{(L_{0, st} + DF)(y_1 - y_2)}{L_0(x_0 - y_1) + L_{0, st}(y_1 - y_2)}
\]

Example: Standard feed consistency \(C_{0, st} = 10\% \) \( (L_{0, st} = 9.0 \text{ t/BDt}) \)

\[
Y_{10} = 1 - \frac{L_1(x_1 - y_2)}{L_0(x_0 - y_1) + 9.0(y_1 - y_2)} \quad Y_{10} = \frac{(9.0 + DF)(y_1 - y_2)}{L_0(x_0 - y_1) + 9.0(y_1 - y_2)}
\]

Equivalent wash yield can be used for the comparison of the different washers (same DF)
Washing yields (Continue)

Mass balance error is put in the pulp feed flow

\[ Y_{C_{0,st}} = 1 - \frac{L_1(x_1 - y_2)}{L_1(x_1 - y_2) + (L_{0,st} + DF)(y_1 - y_2)} \]

Mass balance error is put in the leaving filtrate flow

\[ Y_{C_{0,st}} = 1 - \frac{(L_0 + DF)L_1(x_1 - y_2)}{(L_{0,st} + DF)L_0(x_0 - y_2) + (L_0 - L_{0,st})L_1(x_1 - y_2)} \]

Example: Standard feed consistency \( C_{0,st} = 10\% \)
Washing yields (Continue)

Example: Standard feed consistency $C_{0,st} = 10\% \ (L_{0,st} = 9.0 \ t/BDt)$

Fixing the material balance

Material balance error is put in the pulp fedd flow

\[
Y_{10} = 1 - \frac{L_1(x_1 - y_2)}{L_1(x_1 - y_2) + (9.0 + DF)(y_1 - y_2)}
\]

Material balance error is put in the leaving filtrate

\[
Y_{10} = 1 - \frac{(L_0 + DF)L_1(x_1 - y_2)}{(9.0 + DF)L_0(x_0 - y_2) + (L_0 - 9.0)L_1(x_1 - y_2)}
\]
Washing yield vs. DF and E-value

Graph showing the relationship between washing yield and dilution factor for different E-values.
Example: Calculating the washing efficiency and other washing parameters

The dilution factor of the system is $DF = 2.5 \text{ m}^3/\text{BDT}$
Example...

- Calculate:
  - Washing loss
  - E-factor with the different material balance closing methods
  - Standard E-value ($E_{10}$)
  - Displacement Ratio (DR), equivalent displacement Ratio (EDR)
  - Washing Yield, equivalent washing yield
Example...

Define first the flows:

\[ L_o = \frac{100 - C_o}{C_o} = \frac{100 - 10}{10} = 9m^3 / BDT \]

\[ L_1 = \frac{100 - C_1}{C_1} = \frac{100 - 12}{12} = 7.33m^3 / BDT \]

\[ DF = V_2 - L_1 \Rightarrow V_2 = DF + L_1 = 2.5 + 7.33 = 9.83m^3 / BDT \]

From the total flow balance:

\[ V_1 = L_o + V_2 - L_1 = 9 + 9.83 - 7.33 = 11.5m^3 / BDT \]
Example...

- **Washing loss:**

\[ \text{Washing loss} = x_1 L_1 \text{ kg COD/BDT pulp} \]

- \( x_1 = 1 \text{ g COD/l} = 1 \text{ kg COD/m}^3 \)
- \( L_1 = 7.33 \text{ m}^3/\text{BDT} \)

=> Washing loss = 7.33 kg COD/BDT
Example...

- E-value according to Nordén definition

\[
E = \ln \left( \frac{L_o (x_o - y_1)}{L_1 (x_1 - y_2)} \right) = \ln \left( \frac{9(220 - 171,5)}{7,33(1-0)} \right) = 13,9
\]

- \( 9 \times 220 + 9.83 \times 0 - 7.33 \times 1 - 11.5 \times 171.5 = 0.42 \)

Balance does not match! (luckily balance error is small)

BE CAREFUL, WHEN APPLYING DIRECTLY E-FORMULA!!
Example...

Balance error is put in the pulp feed flow

\[
E = \frac{\ln \left[ 1 + \frac{DF(y_1 - y_2)}{L_1(x_1 - y_2)} \right]}{\ln \left[ 1 + \frac{DF}{L_1} \right]} = \frac{\ln \left[ 1 + \frac{2.5(171.5 - 0)}{7.33(1 - 0)} \right]}{\ln \left[ 1 + \frac{2.5}{7.33} \right]} = 13.9
\]
Example...

Balance error is put in the leaving filtrate

\[
E = \ln\left(\frac{L_0}{L_0 + DF}\right) \left(1 + \frac{DF(x_0 - y_2)}{L_1(x_1 - y_2)}\right)
\]

\[
= \ln\left(1 + \frac{DF}{L_1}\right) + \ln\left(\frac{9}{9 + 2.5}\right) \left(1 + \frac{2.5(220 - 0)}{7.33(1 - 0)}\right)
\]

\[
= \ln\left(1 + \frac{2.5}{7.33}\right) = 13.9
\]
Example...

Balance error is in DF

\[ DF = \frac{L_0(x_0 - y_1) + L_1(y_2 - x_1)}{(y_1 - y_2)} = \]

\[ (9(220 - 171,5) + 7,33(0 - 1))/(171,5 - 0) = 2,502 \]

\[ E = \frac{\ln\left(\frac{L_0(x_0 - y_1)}{L_1(x_1 - y_2)}\right)}{\ln\left(1 + \frac{DF}{L_1}\right)} = \frac{\ln\left(\frac{9(220 - 171,5)}{7,33(1 - 0)}\right)}{\ln\left(1 + \frac{2,502}{9}\right)} = 13,9 \]
Example…

E-factor -> $E_{10}$-factor ($c_{st}=10\%$)

\[
L_{st} = \frac{100 - c_{st}}{c_{st}} = \frac{100 - 10}{10} = 9
\]

\[
E_{10} = E \cdot \frac{\ln \left( 1 + \frac{DF}{L_1} \right)}{\ln \left( 1 + \frac{DF}{L_{st}} \right)} = 13,9 \cdot \frac{\ln \left( 1 + \frac{2,5}{7,33} \right)}{\ln \left( 1 + \frac{2,5}{9} \right)} = 16,7
\]
E-factor line

Washing efficiency estimation

![Graph showing the relationship between E-value and DF (t/bdt). The graph includes two lines labeled x0, L0 and y1.](image)
$E_{10}$-factor line
Example…

- Standard E-value:

\[
E_{10} = \frac{\ln \left[ 1 + \frac{DF(y_1 - y_2)}{L_1(x_1 - y_2)} \right]}{\ln \left[ 1 + \frac{DF}{9} \right]} = \frac{\ln \left[ 1 + \frac{2.5(171.5 - 0)}{7.33(1 - 0)} \right]}{\ln \left[ 1 + \frac{2.5}{9} \right]} = 16.7
\]
Example...

- **Displacement Ratio, DR:**

\[
DR = \frac{x_o - x_1}{x_o - y_2} = \frac{220 - 1}{220 - 0} = 0.995
\]

- **Equivalent Displacement Ratio, EDR:**

\[
EDR = DR_{1,12} = 1 - (1 - 0.995)*(7.33/7.33)*99*(9 + 2.5)/…
\]
\[
…(9*(2.5 + 99) – 7.33*(99 – 9)*(1 – 0.995)) = 0.994
\]
Example…

Washing yield:

\[ Y = \frac{11.5 \times (171.5 - 0)}{9.0 \times (220.0 - 0)} = 0.996 \]

Material balance error is put in the feed pulp:

\[ Y_{10} = 1 - \frac{7.33 \times (1 - 0)}{7.33 \times (1 - 0) + (9.0 + 2.5) \times (171.5 - 0)} = 0.996 \]

Material balance error is put in the leaving filtrate:

\[ Y_{10} = 1 - \frac{(9.0 + 2.5) \times 7.33 \times (1 - 0)}{(9.0 + 2.5) \times 9.0 \times (220.0 - 0) + (9.0 - 9.0) \times 7.33 \times (1 - 0) + 2.5} = 0.996 \]
Calculating washing systems: Simulation programs

- By means of the above mentioned methods, the washing efficiency and the balances of a washing system can be calculated manually or by using simple Excel-programs if the system is connected completely in the countercurrent way.

- If the washing system is complicated with sidestreams or the oxygen delignification is needed to be calculated accurately, a balance simulation program is needed.

- Such simulation programs are Pulpsim, WinGems, MASBAL etc.
Snapshot from simulation