



ProSim

PROSIMPLUS APPLICATION EXAMPLE

BIOETHANOL PRODUCTION PLANT

EXAMPLE PURPOSE

In this example, a bioethanol production unit is represented. Ethanol is produced from biomass by hydrolysis and sugar fermentation. First, the biomass is pre-treated with acid and enzyme to produce sugar. The sugar is then fermented into ethanol. The ethanol produced still contains a significant amount of water, which is removed by using fractional distillation.

This example illustrates how to add new components to the database and how to use multiple complex reaction sets in ProSimPlus.

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|-------------------------------|--|
| CORRESPONDING PROSIMPLUS FILE | E10_BioethanolPlant.pmp3 |
|-------------------------------|--|

Reader is reminded that this use case is only an example and should not be used for other purposes. Although this example is based on actual case it may not be considered as typical nor are the data used always the most accurate available. ProSim shall have no responsibility or liability for damages arising out of or related to the use of the results of calculations based on this example.

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1. INTRODUCTION

There are two types of ethanol industrially produced: synthetic ethanol and fermentation ethanol. Fermentation ethanol (or bioethanol) can be produced from biomass materials containing sugars, starches or cellulose (starch and cellulose are more complex forms of sugar). All these production processes require a fermentation step to convert the sugar into ethanol, as well as a more or less advanced distillation step to separate the alcohol from the water.

Ethanol is a widely used biofuel. In addition to being renewable, ethanol has a major advantage in that it can be easily blended with gasoline. In some cases ethanol is first converted to its ether form (ETBE), obtained in reaction with refinery isobutene. When small amounts of ethanol are added to gasoline, there are many advantages, in particular the reduction of carbon monoxide and other toxic pollution from exhaust gases of vehicles. Because ethanol is made from crops that absorb carbon dioxide and give off oxygen, it helps reduce greenhouse gas emissions. Ethanol is also added to gasoline as an octane enhancer.

For all these reasons many ethanol producers or engineering firms are today focusing on designing and building-up new plants as rapidly as possible in order to satisfy a growing demand. In parallel, rigorous process simulation (as it can be performed with ProSimPlus) is today increasingly used to design and optimize the bioethanol production processes.

2. PROCESS MODELING

2.1. Process description

The feedstock used in this process is corn stover. The main compounds are (on dry basis, wt.) cellulose (37.4%), hemicellulose (21.1%) and lignin (18.0%). The modeling starts just after the washing of the feedstock which step induces an increase of the feedstock moisture. Three reaction steps follow:

1. Hydrolysis (reactor R101): the feedstock is heating (190°C) at high pressure (12.1 atm) with an acid catalyst (H_2SO_4). Most of the hemicellulose is converted to xylose.
2. Saccharification (reactor R102): this is an enzymatic reaction that converts the cellulose into glucose.
3. Fermentation (reactor R103): most of the glucose and xylose are converted to ethanol and carbon dioxide.

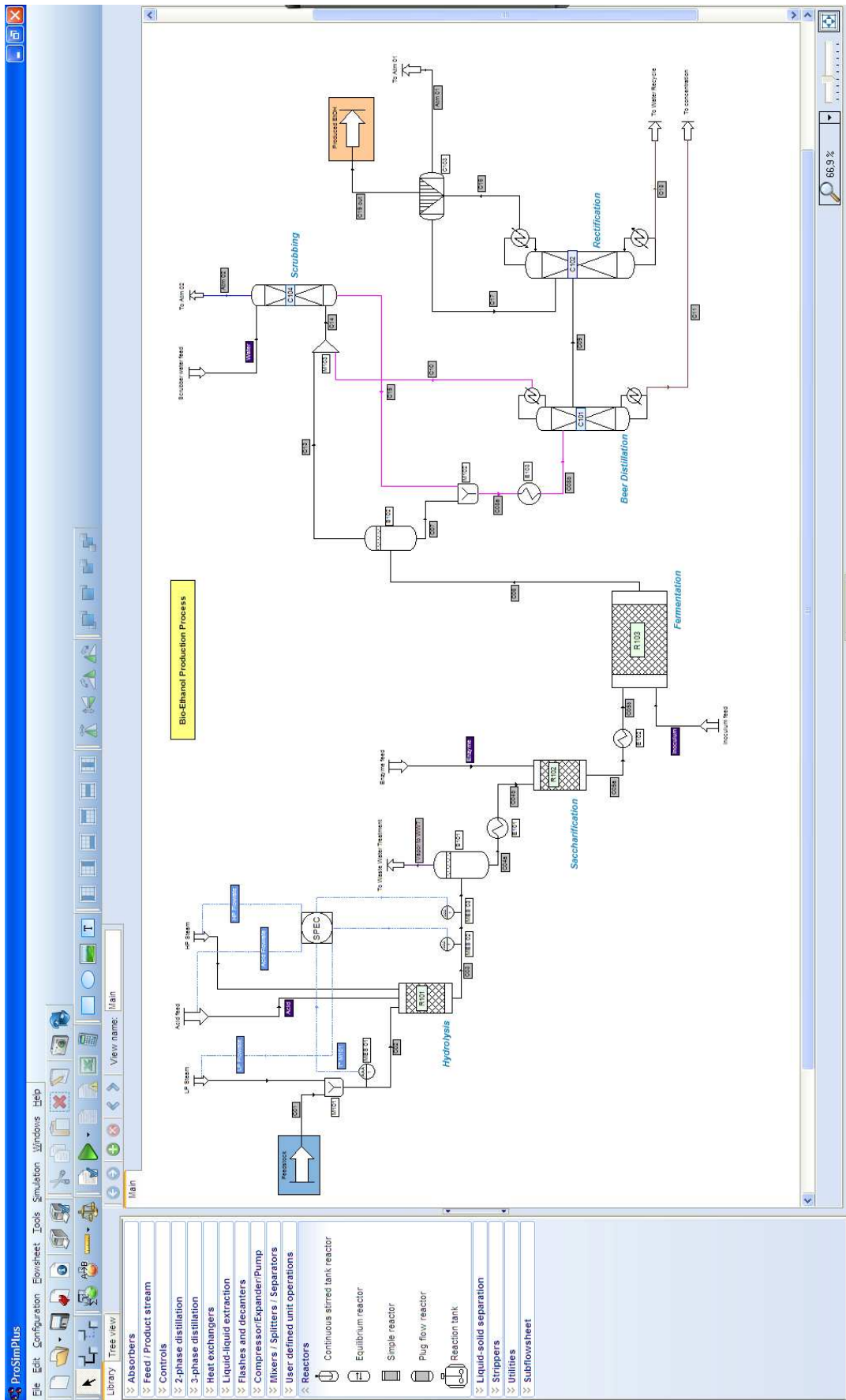
A flash separation (S101) at atmospheric pressure is present between the hydrolysis reactor and the saccharification reactor to evacuate part of the water and some by-products. Another flash (S102) is used after the fermentation reactor (R103) to separate the incondensable (CO_2).

The first distillation column (C101) separates the rest of the incondensable (CO_2), which is recovered at the vapor distillate (stream C10). The water, sugars and the un-reacted part of the feedstock are produced at the bottom (stream C11) and the ethanol ($\approx 40\%$ mass) is withdrawn at a side-stream (stream C09). This side-stream goes to a second distillation column (C102). The ethanol ($\approx 92\%$ mass), is recovered at the vapor distillate (stream C16). At the bottom, water is recovered and recycled in the process (stream C18). The ethanol is dried in a molecular sieve adsorption unit (C103). This part of the process is modeled by a component splitter.

A scrubber (C104) separates ethanol and water contained in the gas stream coming from the flash separator (S102) after the fermentation reactor and the vapor distillate of the first distillation column (C101).

This example is taken from a publication [1].

2.2. Process flowsheet



Bioethanol plant process flowsheet

2.3. Specifications

The main specifications imposed on the process are:

- ✓ A temperature of 100°C after mixer *M101* by acting on the *LP Steam* flowrate
- ✓ A temperature of 190°C at the outlet of hydrolysis reactor *R101* by acting on the *HP Steam* flowrate
- ✓ A H₂SO₄ mass fraction of 1.1% at the outlet of hydrolysis reactor *R101* by acting of the total flowrate of the *Acid* stream.

2.4. Components

The components used in this example are listed in the following table.

| Name | Chemical formula | CAS Number | Use in the process |
|----------------------------|---|------------|--|
| Acetate | C ₂ H ₄ O ₂ | - | Acetate groups present in the hemicellulose polymer |
| Acetic acid | C ₂ H ₄ O ₂ | 64-19-7 | Coming from acetate hydrolysis and fermentation by-product |
| Carbon dioxide | CO ₂ | 124-38-9 | Fermentation product |
| Cellobiose | C ₁₂ H ₂₂ O ₁₁ | - | Coming from cellulose hydrolysis and saccharification |
| Cellulose | C ₅ H ₁₀ O ₅ | - | Feedstock |
| Corn steep liquor (CSL) | Unkown (modeled as water) | - | Bacteria feed nitrogen source |
| Diammonium phosphate (DAP) | (NH ₄) ₂ HPO ₄ | 7783-28-0 | Bacteria feed nitrogen source |
| Enzyme | CH _{1.57} N _{0.29} O _{0.31} S _{0.007} | - | Saccharification enzyme |
| Ethanol | C ₂ H ₆ O | 64-17-5 | Desired product |
| Furfural | C ₅ H ₄ O ₂ | 98-01-1 | Hemicellulose hydrolysis by-product |
| Glucose | C ₆ H ₁₂ O ₆ | 50-99-7 | Coming from cellulose hydrolysis and saccharification |
| Glycerol | C ₃ H ₈ O ₃ | 56-81-5 | Fermentation by-product |
| Hemicellulose | C ₅ H ₈ O ₄ | - | Feedstock |
| Lactic acid | C ₃ H ₆ O ₃ | 598-82-3 | Fermentation by-product |
| Lignin | C ₁₀ H _{13.9} O _{1.3} | - | Feedstock |
| Oxygen | O ₂ | 7782-44-7 | Fermentation product |
| Succinic acid | C ₄ H ₆ O ₄ | 110-15-6 | Fermentation by-product |
| Sulfuric acid | H ₂ SO ₄ | 7664-93-9 | Acid catalyst |
| Water | H ₂ O | 7732-18-5 | Product moisture, washing and |

| | | | |
|------------|--------------------------|---|---|
| | | | reaction product |
| Xylitol | $C_5H_{12}O_5$ | - | Fermentation by-product |
| Xylose | $C_5H_{10}O_5$ | - | Coming from hydrolysis and saccharification |
| Z. mobilis | $CH_{1.8}O_{0.5}N_{0.2}$ | - | Fermentation bacteria |

Some of these compounds are not included in the ProSim standard database provided with ProSimPlus. Consequently, some components have been represented with similar components and some properties have been estimated as detailed in the following table.

| Component | Properties |
|---------------|---|
| Acetate | Modeled as Acetic acid. |
| Cellobiose | Modeled as Glucose. Modification: molecular weight ^(E) |
| Cellulose | Modeled as Glucose. Modification: molecular weight ^(E) , ideal gas heat of formation ^(E) , liquid molar volume ^(E) , liquid heat capacity ^(E) |
| CSL | Modeled as Water. Modification: glucose vapor pressure |
| Enzyme | Modeled as Glucose. |
| Hemicellulose | Modeled as Glucose. Modification: molecular weight ^(E) , ideal gas heat of formation ^(E) , liquid molar volume ^(E) , liquid heat capacity ^(E) |
| Lignin | Modeled as Glucose. Modification: molecular weight ^(E) , liquid molar volume ^(E) , liquid heat capacity ^(E) |
| Xylitol | Modeled as Hemicellulose. Modification: molecular weight ^(E) |
| Xylose | Modeled as Glucose. Modification: molecular weight ^(E) , critical temperature ^(E) , critical pressure ^(E) , critical volume ^(E) , acentric factor ^(E) , ideal gas heat of formation ^(E) , liquid molar volume ^(E) , liquid heat capacity ^(E) |
| Z. mobilis | Modeled as Glucose. Modification: ideal gas heat of formation ^(E) , liquid molar volume ^(E) , liquid heat capacity ^(E) |

Note: (E) estimated property.

2.5. Thermodynamic model

This system contains polar compounds (like water and ethanol), which induce strong interactions in the liquid phase. The working pressure being weak (from 1 to 5 atm), the vapor phase behavior can be assimilated to that of an ideal gas. Consequently the NRTL model has been selected. The required binary interaction parameters that were not available in ProSimPlus database were estimated with a predictive model, using the dedicated functionality offered by Simulis Thermodynamics.

The following table shows the binary interaction parameters taken into account.

| Component | | c_{12}^0 | c_{21}^0 | a_{12}^0 | $c_{12}(T)$ | $c_{21}(T)$ | $a_{12}(T)$ | Note |
|-----------------|-----------------|------------|------------|------------|-------------|-------------|-------------|------|
| 1 | 2 | | | | | | | |
| Water | CO ₂ | 922.65 | 2256.3 | 0.3 | 7.1259 | -5.548 | 0 | A |
| Water | Ethanol | 1616.81 | -635.56 | 0.1448 | 2.0177 | 0.9907 | 0 | B |
| Water | Furfural | 2602.6374 | 436.9686 | 0.3958 | 0 | 0 | 0 | C |
| CO ₂ | Ethanol | 2.0708 | -3.5177 | 0.3 | 927.13 | -18.62 | 0 | A |

Note A: The binary interaction parameters model are estimated from activity coefficients at infinite dilution calculated with UNIFAC-PSRK model.

Note B: These binary interaction parameters are available in ProSim’s software binary interaction parameters database.

Note C: From [2]

2.6. Chemical reactions

Three chemical reaction sets are defined.

For all the chemical reactions, heats of reaction are calculated from standard enthalpies of formation at 298.15 K.

✓ Pretreatment hydrolyser reactions:

| Reactions | Reactant | Fraction converted to product |
|---|---------------|-------------------------------|
| Cellulose + H ₂ O → Glucose | Cellulose | 0.077 |
| Cellulose + 0.5 H ₂ O → 0.5 Cellobiose | Cellulose | 0.007 |
| Hemicellulose + H ₂ O → Xylose | Hemicellulose | 0.925 |
| Hemicellulose → Furfural + 2 H ₂ O | Hemicellulose | 0.05 |
| Acetate → Acetic acid | Acetate | 1 |

✓ Saccharification reactions:

| Reactions | Reactant | Fraction converted to product |
|---|------------|-------------------------------|
| Cellulose + H ₂ O → Glucose | Cellulose | 0.94 |
| Cellulose + 0.5 H ₂ O → 0.5 Cellobiose | Cellulose | 0.012 |
| Cellobiose + H ₂ O → 2 Glucose | Cellobiose | 1 |

✓ Fermentation reactions:

| Reactions | Reactant | Fraction converted to product |
|--|----------|-------------------------------|
| Glucose → 2 Ethanol + 2 CO ₂ | Glucose | 0.95 |
| Glucose + CSL + 0.018 DAP → 6 Z.mobilis + 2.4 H ₂ O + 0.3 O ₂ | Glucose | 0.02 |
| Glucose + 2 H ₂ O → 2 Glycerol + O ₂ | Glucose | 0.004 |
| Glucose + 2 CO ₂ → 2 Succinic acid + O ₂ | Glucose | 0.006 |
| Glucose → 3 Acetic acid | Glucose | 0.015 |
| Glucose → 2 Lactic acid | Glucose | 0.002 |
| 3 Xylose → 5 Ethanol + 5 CO ₂ | Xylose | 0.85 |
| Xylose + 0.0835 CSL + 0.015 DAP → 5 Z.mobilis + 2 H ₂ O + 0.25 O ₂ | Xylose | 0.019 |
| Xylose + 5 H ₂ O → 5 Glycerol + 2.5 O ₂ | Xylose | 0.003 |
| Xylose + H ₂ O → Xylitol + 0.5 O ₂ | Xylose | 0.046 |
| 3 Xylose + 5 CO ₂ → 5 Succinic acid + 2.5 O ₂ | Xylose | 0.009 |
| 2 Xylose → 5 Acetic acid | Xylose | 0.014 |
| 3 Xylose → 5 Lactic acid | Xylose | 0.002 |

2.7. Operating conditions

✓ Process feed

| | Feed |
|----------------------|--------|
| Eau (kg/h) | 45 007 |
| Cellulose (kg/h) | 31 178 |
| Hemicellulose (kg/h) | 22 924 |
| Lignin (kg/h) | 15 002 |
| Acetate (kg/h) | 2 435 |
| Temperature (°C) | 45 |
| Pressure (atm) | 1 |

✓ Steam inlet

| | LP Steam | HP Steam |
|------------------|----------|----------|
| Water (kg/h) | 11 500 | 10 000 |
| Temperature (°C) | 164 | 268 |

| | | |
|----------------|------|----|
| Pressure (atm) | 4.42 | 13 |
|----------------|------|----|

✓ Catalyst feed

| | <i>Catalyst Acid feed</i> |
|----------------------|---------------------------|
| Water (kg/h) | 98 256 |
| Sulfuric acid (kg/h) | 2 104 |
| Temperature (°C) | 745 |
| Pressure (atm) | 4 |

✓ Scrubber feed

| | <i>Scrubber Water feed</i> |
|------------------|----------------------------|
| Water (kg/h) | 36 000 |
| Temperature (°C) | 26 |
| Pressure (atm) | 1 |

✓ Reactors inlet

| <i>Characteristics</i> | <i>Saccharification enzyme inlet Enzyme</i> | <i>Fermentation bacteria inlet Inoculum</i> |
|-----------------------------|---|---|
| Water (kg/h) | 6 255 | 33 881 |
| Enzyme (kg/h) | 568 | |
| Z. mobilis (kg/h) | | 193 |
| Diammonium Phosphate (kg/h) | | 136 |
| Corn Steep Liquor (kg/h) | | 1 087 |
| Temperature (°C) | 20 | 41 |
| Pressure (atm) | 1 | 1 |

✓ Reactors

| <i>Operating parameters</i> | <i>Hydrolysis reactor R101</i> | <i>Saccharification reactor R102</i> | <i>Fermentation reactor R103</i> |
|-----------------------------|------------------------------------|--|--------------------------------------|
| Type of reactor | Simple | Simple | Simple |
| Reaction set | Hydrolysis | Saccharification | Fermentation |
| Temperature outlet (°C) | Adiabatic | 65 | 41 |
| Pressure outlet (atm) | 12,1 | 1 | 1 |

✓ Separators

| <i>Operating parameters</i> | <i>S101 Water evaporation</i> | <i>S102 Reactor R102 vent</i> |
|-----------------------------|-----------------------------------|-----------------------------------|
| Separator type | Liquid-Vapor separator | Liquid-Vapor separator |
| Temperature (°C) | Adiabatic | Inlet temperature |
| Pressure (atm) | 1 | Inlet pressure |

✓ Heat exchangers

| <i>Name</i> | <i>Type</i> | <i>Output temperature (°C)</i> |
|-------------|-----------------|--------------------------------|
| E101 | Cooler / Heater | 65 |
| E102 | Cooler / Heater | 41 |
| E103 | Cooler / Heater | 100 |

✓ Columns

| <i>Operating parameters</i> | <i>C101</i> | <i>C102</i> | <i>C104</i> |
|----------------------------------|-------------------------------|---|-------------|
| Column type | Two-phase distillation column | Two-phase distillation column | Absorber |
| Number of stages | 34 | 62 | 4 |
| Feed stage | 5 | Scrubber bottom: 20 C101 side stream: 45 | - |
| <i>Side streams</i> | | | |
| Stage | 9 | - | - |
| Flowrate (kmol/h) | 2472,5 | | |
| Sate | Vapor | | |
| Vapor distillate flowrate (kg/h) | 491 | 30 740 | - |
| Molar reflux ratio | 3 | 3.2 | |
| <i>Pressure</i> | | | |
| Overhead (atm) | 1.86 | 1.7 | 1 |
| Side stream (atm) | 1.91 | - | - |
| Bottom (atm) | 2.1 | | |
| Tray efficiency | 0.48 | 0.57 | 1 |

Additional column C104 specification:

| Specification | <i>Product type</i> | <i>Compounds</i> | <i>Value</i> | <i>Phase</i> | <i>Type</i> | <i>Action</i> |
|-------------------|---------------------|------------------|--------------|--------------|-------------|----------------------|
| 1: Recovery ratio | Vapor distillate | CO ₂ | 0.998 | Vapor | Mass | Water inlet flowrate |

- ✓ Molecular sieve adsorption unit C103 (modeled as a component splitter)

| <i>Operating parameters</i> | <i>Overhead product</i> | <i>Bottom product</i> | <i>Other product</i> |
|-----------------------------|--------------------------------|-----------------------|------------------------------|
| Temperature (°C) | Inlet temperature | 70 | Bubble point temperature |
| Pressure (atm) | Inlet pressure | 1.53 | Inlet pressure |
| Recovery ratio | Carbon dioxide: 1 Oxygen: 1 | | Water: 0.05 Ethanol: 0.80 |

- ✓ Mixer M102

| | <i>Operating parameter</i> |
|-----------------------|----------------------------|
| Outlet pressure (atm) | 4.76 |

3. RESULTS

3.1. Comments on results

The calculation sequence (order of calculation of the unit operations) is automatically generated. No initialization is required to converge the flowsheet (no tear stream initialized). Although there are two recycle streams and three specifications, convergence of the flowsheet is easily reached.

Three input flowrates are adjusted in order to reach the right operating conditions for the hydrolysis reactions. 6,7 T/h of LP Steam and 38,2 T/h of HP Steam are needed to reach the working temperature level in the hydrolysis reactor. 2,9 T/h of pure H₂SO₄ is needed to reach the working acid mass fraction in the hydrolysis reactor.

To have a recovery ratio de 99.8% of CO₂ in the scrubber, a water flowrate of 41,7 T/h is required.

The production is about 22,8 T/h of ethanol on dry basis (99.8% mass) for a feedstock of 71,6 T/h on dry basis (39% mass moisture).

3.2. Mass and energy balances

This document presents only the most relevant stream results. In ProSimPlus, mass and energy balances are provided for every stream. Results are also available at the unit operation level (result tab in the configuration window).

Main inlet streams

| Streams | C01 | Acid | Inoculum | Enzyme | |
|----------------------|-----------|-----------|---------------|-------------|------|
| From | Feedstock | Acid feed | Inoculum feed | Enzyme feed | |
| To | M101 | R101 | R103 | R102 | |
| Partial flows | t/h | t/h | t/h | t/h | |
| WATER | 45,00 | 98,25 | 33,88 | 6,25 | |
| CARBON DIOXIDE | 0 | 0 | 0 | 0 | |
| ETHANOL | 0 | 0 | 0 | 0 | |
| SULFURIC ACID | 0 | 2,88 | 0 | 0 | |
| GLUCOSE | 0 | 0 | 0 | 0 | |
| XYLOSE | 0 | 0 | 0 | 0 | |
| CELLULOSE | 31,18 | 0 | 0 | 0 | |
| HEMICELLULOSE | 22,92 | 0 | 0 | 0 | |
| LIGNIN | 15,00 | 0 | 0 | 0 | |
| FURFURAL | 0 | 0 | 0 | 0 | |
| CELLOBIOSE | 0 | 0 | 0 | 0 | |
| ENZYME | 0 | 0 | 0 | 0,56 | |
| Z. MOBILIS | 0 | 0 | 0,19 | 0 | |
| DIAMMONIUM PHOSPHATE | 0 | 0 | 0,13 | 0 | |
| OXYGEN | 0 | 0 | 0 | 0 | |
| CSL | 0 | 0 | 1,08 | 0 | |
| GLYCEROL | 0 | 0 | 0 | 0 | |
| SUCCINIC ACID | 0 | 0 | 0 | 0 | |
| ACETIC ACID | 0 | 0 | 0 | 0 | |
| LACTIC ACID | 0 | 0 | 0 | 0 | |
| XYLITOL | 0 | 0 | 0 | 0 | |
| ACETATE | 2,43 | 0 | 0 | 0 | |
| Total flow | kg/h | 116,55 | 101,14 | 35,29 | 6,82 |

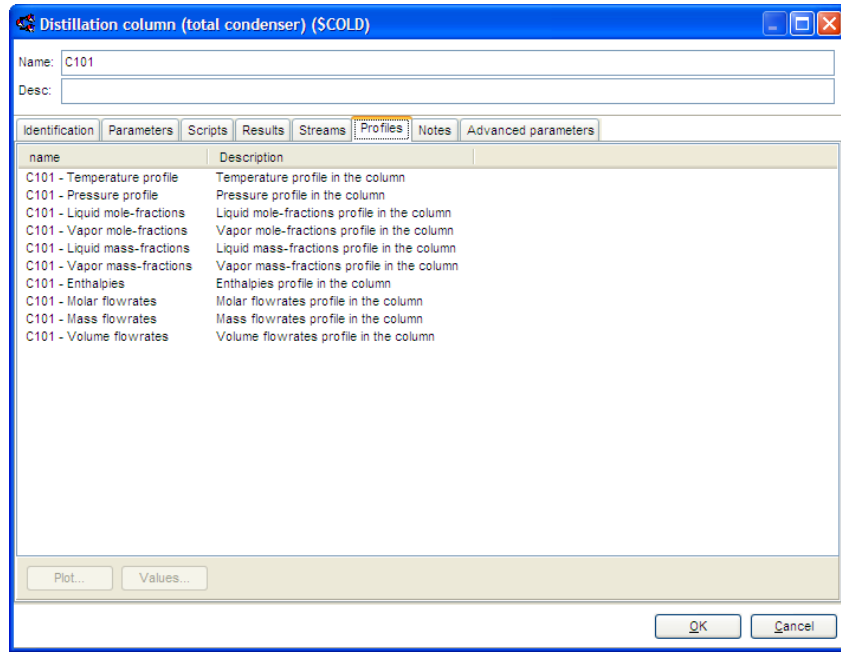
| | | | | | |
|----------------|--------|-------------|-------------|-----------|-------------|
| Physical state | | Liquide | Liquide | Liquide | Liquide |
| Temperature | °C | 45 | 74 | 41 | 20 |
| Pressure | atm | 0,99 | 3,99 | 0,99 | 0,99 |
| Enthalpy | kcal/h | -36684723,5 | -52927597,9 | -19943770 | -3846201,37 |
| Vapor fraction | | 0 | 0 | 0 | 0 |

Other streams

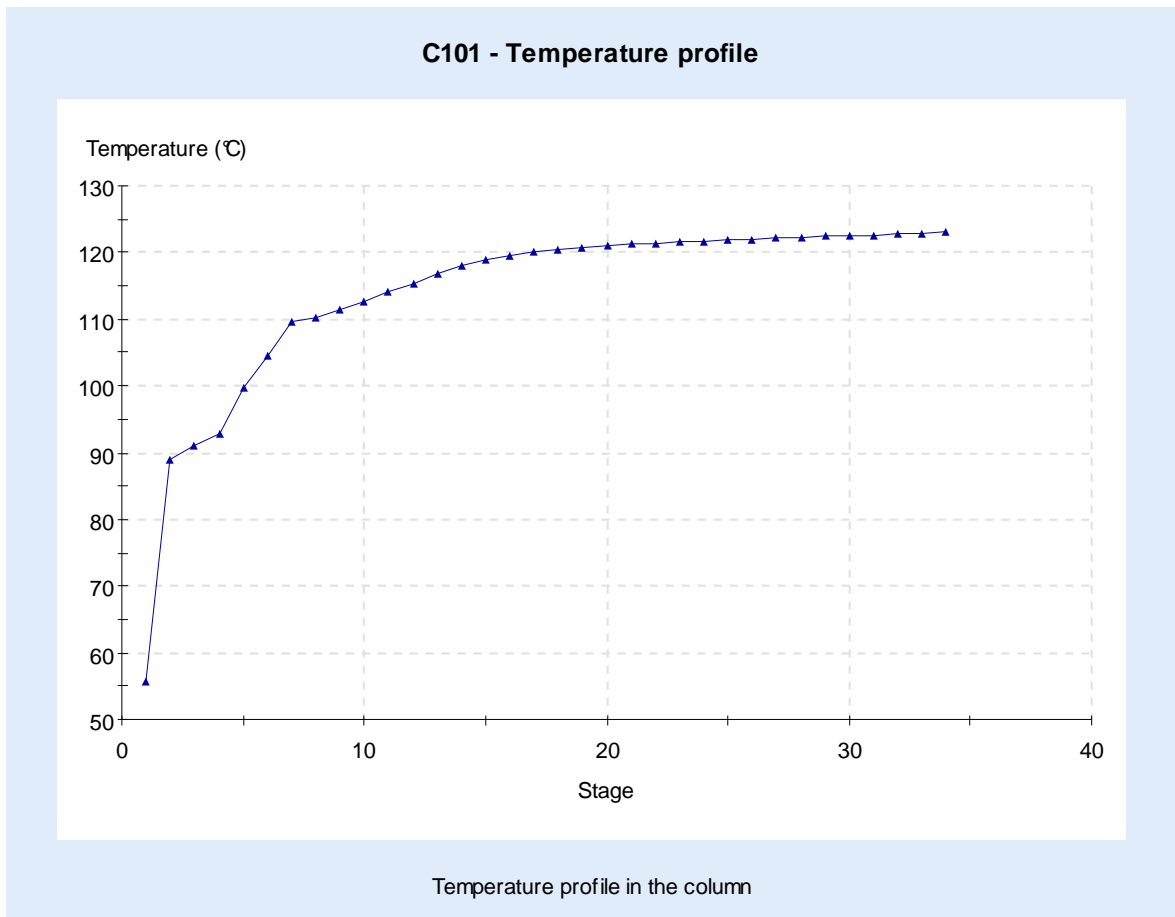
| Streams | | C02 | C05a | C06 | C09 | C19 out |
|----------------------|--------|-----------|-------------|---------------|------------|---------------|
| From | | MES 01 | R102 | R103 | C101 | C103 |
| To | | R101 | E102 | S102 | C102 | Produced EtOH |
| Partial flows | | t/h | t/h | t/h | t/h | t/h |
| WATER | | 51,73 | 152,81 | 186,79 | 34,09 | 0,12 |
| CARBON DIOXIDE | | 0 | 0 | 25,00 | 002 | 0 |
| ETHANOL | | 0 | 0 | 26,39 | 26,38 | 22,75 |
| SULFURIC ACID | | 0 | 2,88 | 2,89 | 6,10E-05 | 0 |
| GLUCOSE | | 0 | 32,74 | 0,10 | 0 | 0 |
| XYLOSE | | 0 | 24,09 | 1,37 | 0 | 0 |
| CELLULOSE | | 31,18 | 1,37 | 1,37 | 0 | 0 |
| HEMICELLULOSE | | 22,92 | 0,57 | 0,57 | 0 | 0 |
| LIGNIN | | 15,00 | 15,00 | 15,00 | 1,14E-07 | 0 |
| FURFURAL | | 0 | 0,46 | 0,47 | 0,32 | 0 |
| CELLOBIOSE | | 0 | 0,36 | 0,36 | 0 | 0 |
| ENZYME | | 0 | 0,56 | 0,57 | 0 | 0 |
| Z. MOBILIS | | 0 | 0 | 1,11 | 8,40E-09 | 0 |
| DIAMMONIUM PHOSPHATE | | 0 | 0 | 0,12 | 0 | 0 |
| OXYGEN | | 0 | 0 | 0,29 | 7,45E-08 | 0 |
| CSL | | 0 | 0 | 0,98 | 7,41E-09 | 0 |
| GLYCEROL | | 0 | 0 | 0,21 | 1,09E-05 | 0 |
| SUCCINIC ACID | | 0 | 0 | 0,54 | 3,76E-06 | 0 |
| ACETIC ACID | | 0 | 2,15 | 2,98 | 0,225972 | 0 |
| LACTIC ACID | | 0 | 0 | 0,11 | 9,61E-05 | 0 |
| XYLITOL | | 0 | 0 | 1,12 | 0 | 0 |
| ACETATE | | 2,43 | 0 | 0 | 0 | 0 |
| Total flow | kg/h | 123,28 | 233,04 | 268,34 | 61,03 | 22,87 |
| Physical state | | Liquide | Liquide | Liq./Vap. | Vapeur | Liquide |
| Temperature | °C | 100 | 65 | 41,00 | 111,40 | 92,08 |
| Pressure | atm | 0,99 | 0,99 | 1,00 | 1,90 | 1,70 |
| Enthalpy | kcal/h | -36310578 | -96472244,9 | -115966771,74 | 2188935,52 | -3952048,52 |
| Vapor fraction | | 0 | 0 | 0,05 | 1 | 0 |

3.3. Column profiles

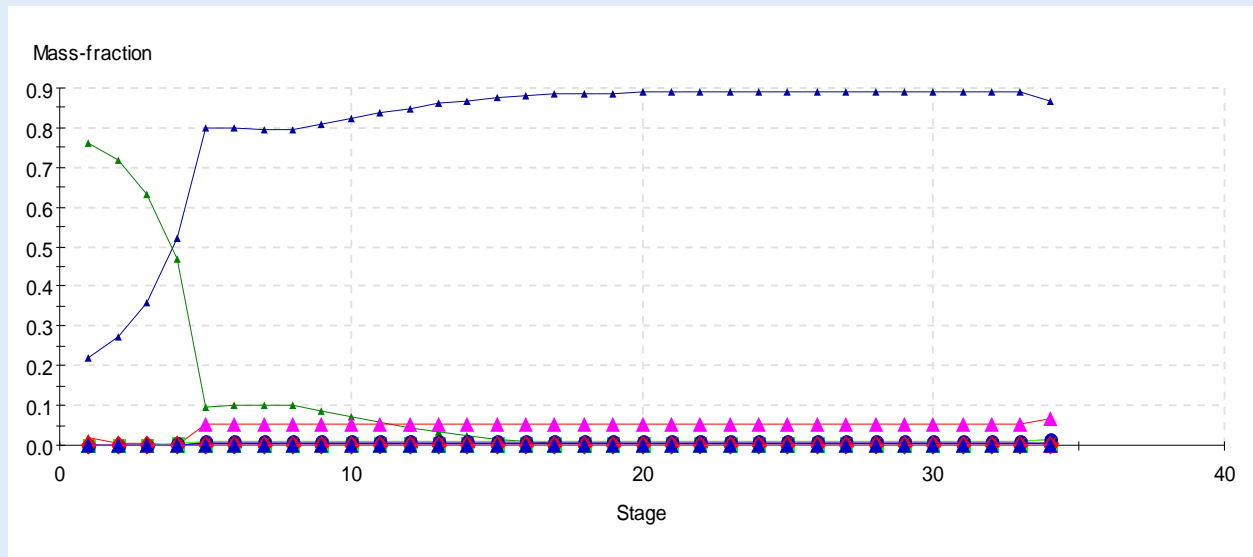
Composition profiles can be accessed after the simulation in each column configuration window, in the "Profiles" tab. Double clicking on the profile will generate the corresponding graph. Here, only the liquid-mole fraction is shown for the three columns. It is important to note that, in ProSimPlus, first stage correspond to condenser and last stage to reboiler (numbering from top to bottom)



Column C101



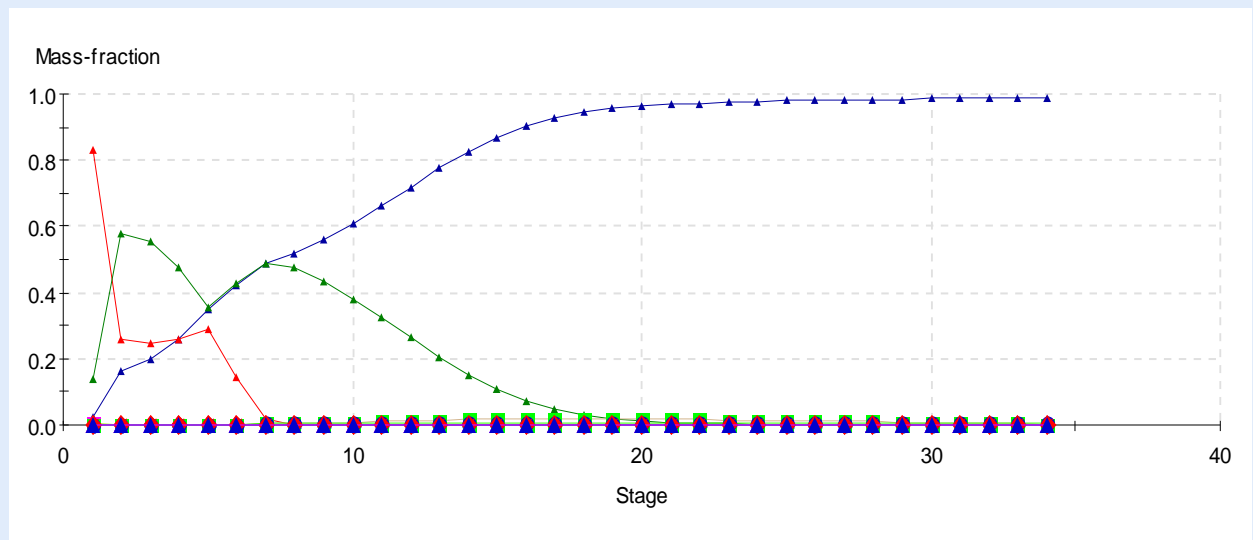
C101 - Liquid mass-fractions



- | | | | |
|----------------|----------------------|-----------------|-------------------|
| —▲— WATER | —▲— CARBON DIOXIDE | —▲— ETHANOL | —▲— SULFURIC ACID |
| —▲— GLUCOSE | —▲— XYLOSE | —▲— CELLULOSE | —▲— HEMICELLULOSE |
| —▲— LIGNIN | —▲— FURFURAL | —▲— CELLOBIOSE | —▲— ENZYME |
| —▲— Z. MOBILIS | —▲— DIAMMONIUM PHOSP | —▲— OXY GEN | —▲— CSL |
| —▲— GLYCEROL | —▲— SUCCINIC ACID | —▲— ACETIC ACID | —▲— LACTIC ACID |
| —▲— XYLITOL | —▲— ACETATE | | |

Liquid mass-fractions profile in the column

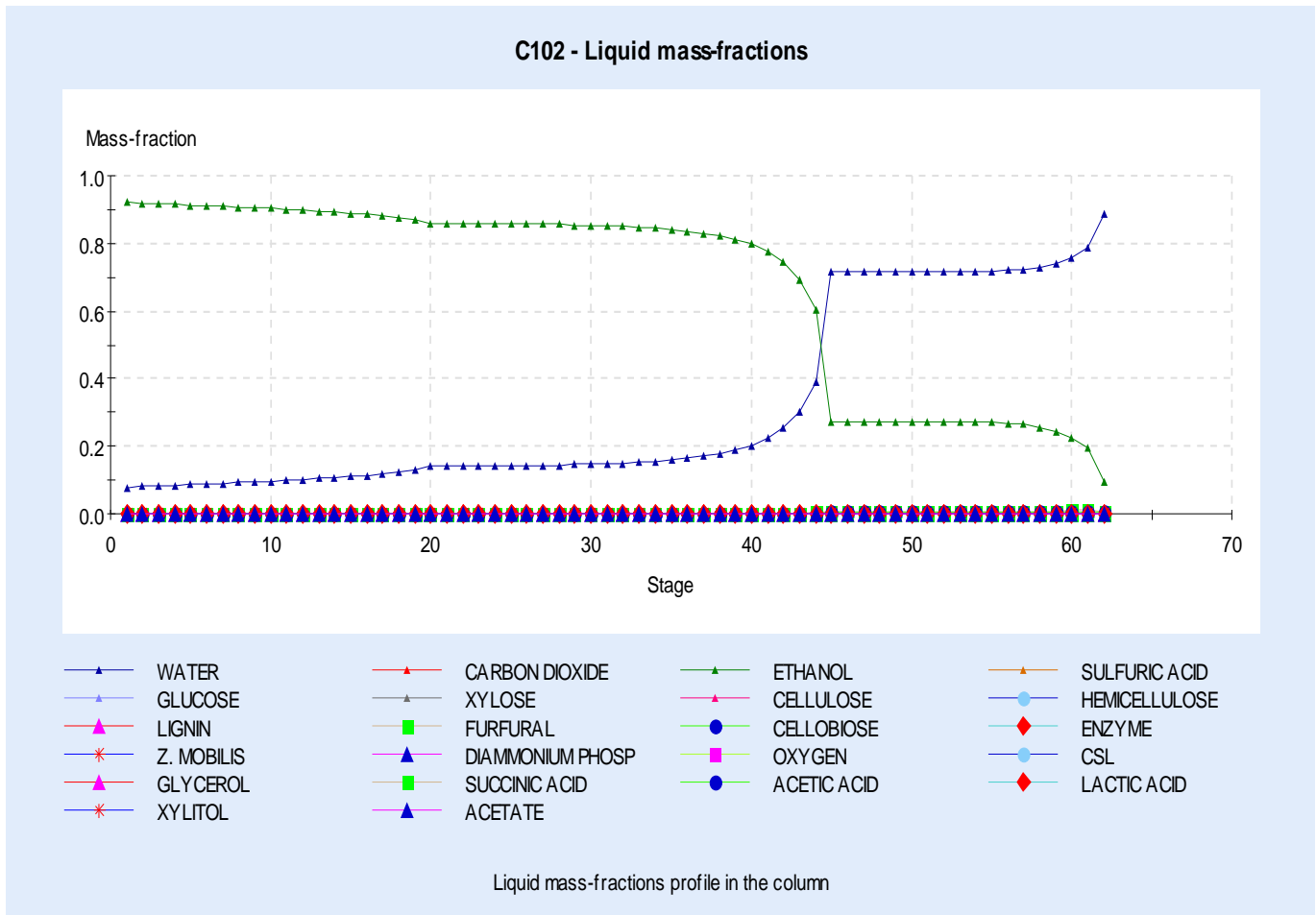
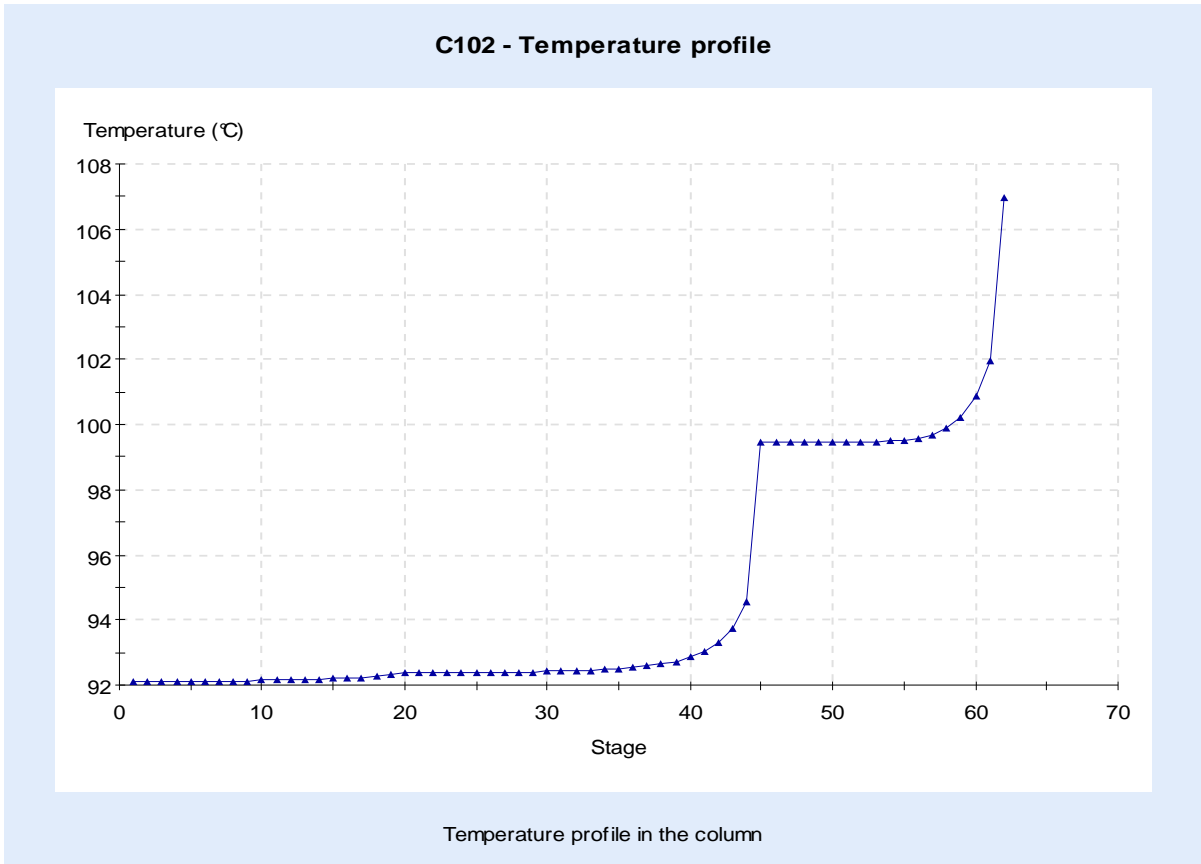
C101 - Vapor mass-fractions



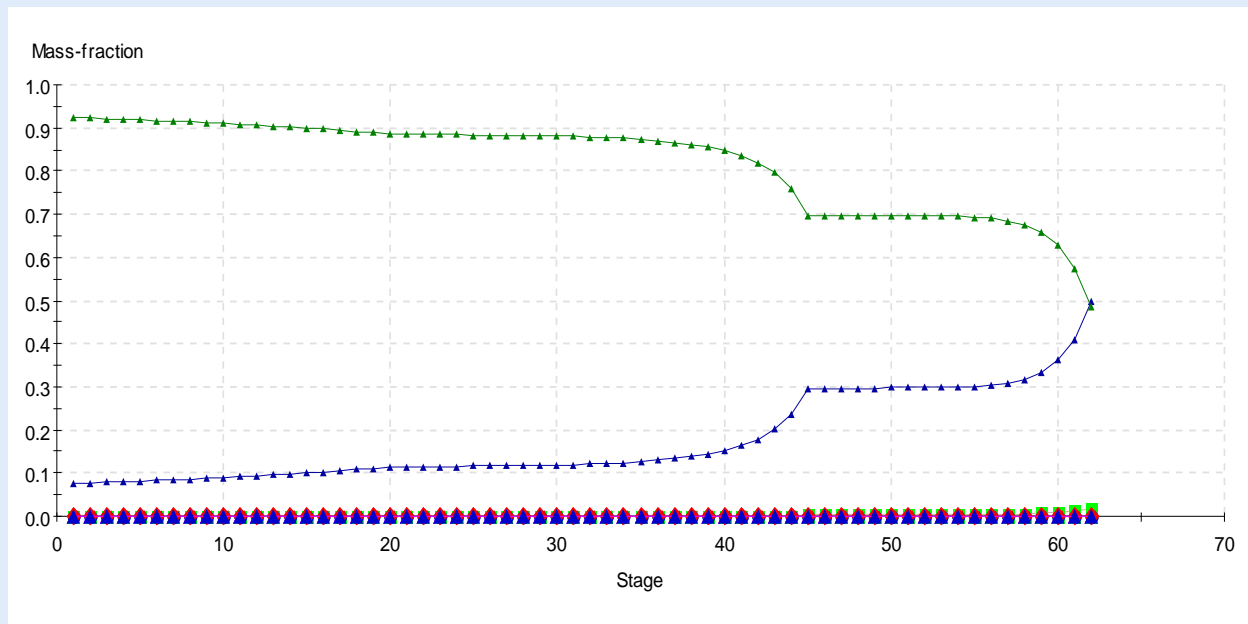
- | | | |
|-------------------|----------------------|-------------------|
| —▲— WATER | —▲— CARBON DIOXIDE | —▲— ETHANOL |
| —▲— SULFURIC ACID | —▲— GLUCOSE | —▲— XYLOSE |
| —▲— CELLULOSE | —▲— HEMICELLULOSE | —▲— LIGNIN |
| —▲— FURFURAL | —▲— CELLOBIOSE | —▲— ENZYME |
| —▲— Z. MOBILIS | —▲— DIAMMONIUM PHOSP | —▲— OXY GEN |
| —▲— CSL | —▲— GLYCEROL | —▲— SUCCINIC ACID |
| —▲— ACETIC ACID | —▲— LACTIC ACID | —▲— XYLITOL |
| —▲— ACETATE | | |

Vapor mass-fractions profile in the column

Column C102



C102 - Vapor mass-fractions

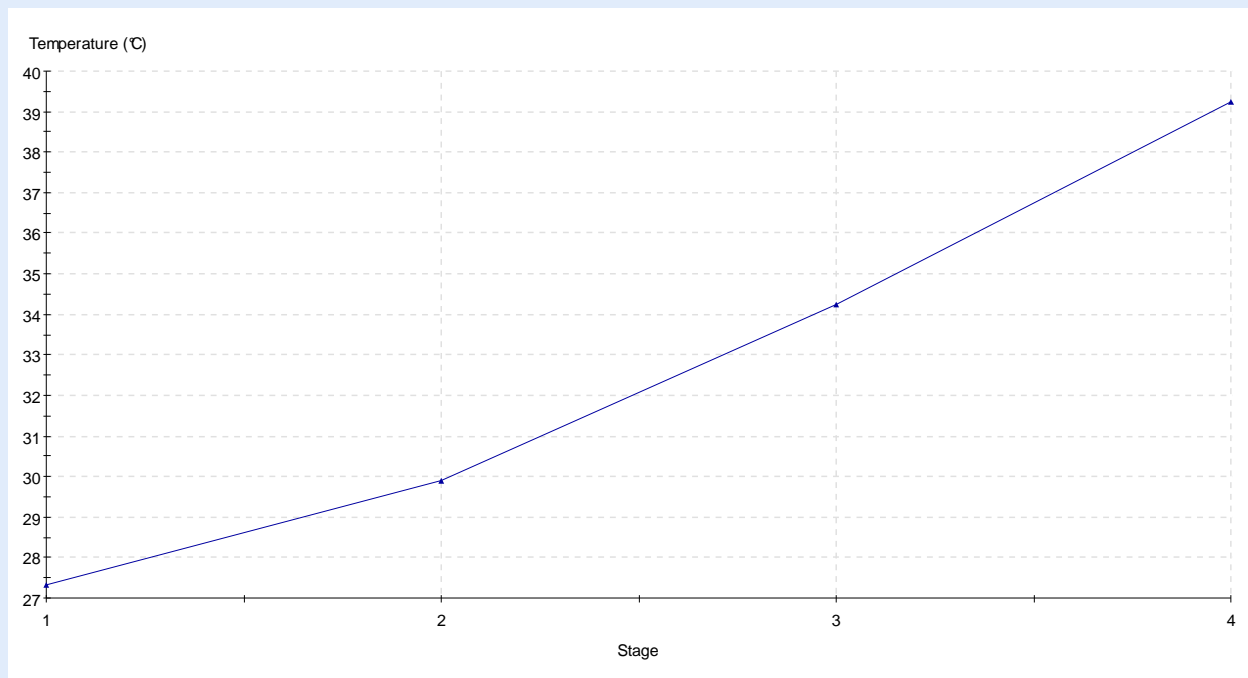


- | | | | |
|----------------|----------------------|-----------------|-------------------|
| —▲— WATER | —▲— CARBON DIOXIDE | —▲— ETHANOL | —▲— SULFURIC ACID |
| —▲— GLUCOSE | —▲— XYLOSE | —▲— CELLULOSE | —▲— HEMICELLULOSE |
| —▲— LIGNIN | —■— FURFURAL | —●— CELLOBIOSE | —▲— ENZYME |
| —*— Z. MOBILIS | —▲— DIAMMONIUM PHOSP | —■— OXYGEN | —▲— CSL |
| —▲— GLYCEROL | —■— SUCCINIC ACID | —●— ACETIC ACID | —▲— LACTIC ACID |
| —*— XYLITOL | —▲— ACETATE | | |

Vapor mass-fractions profile in the column

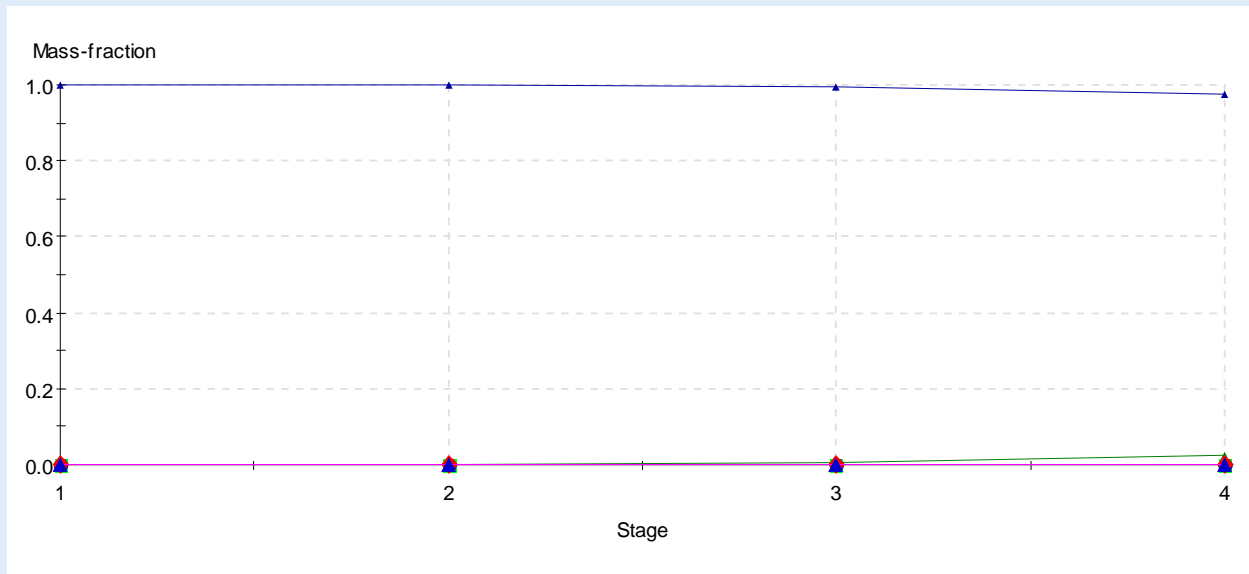
Column C104

C104 - Temperature profile



Temperature profile in the column

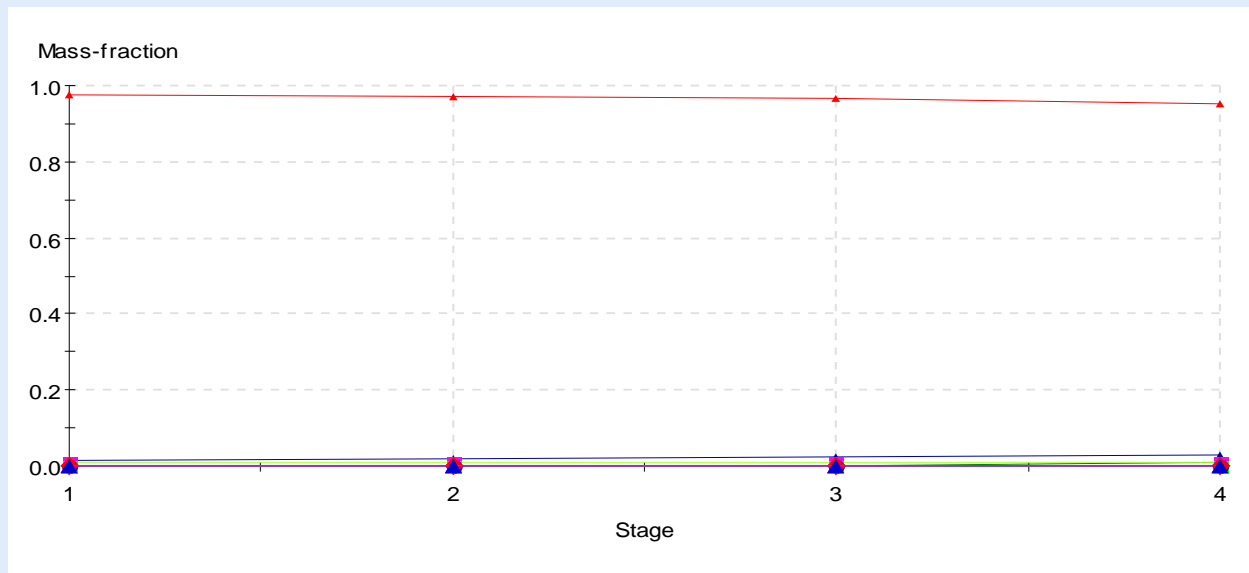
C104 - Liquid mass-fractions



- | | | | |
|----------------|----------------------|-----------------|-------------------|
| —▲— WATER | —▲— CARBON DIOXIDE | —▲— ETHANOL | —▲— SULFURIC ACID |
| —▲— GLUCOSE | —▲— XYLOSE | —▲— CELLULOSE | —▲— HEMICELLULOSE |
| —▲— LIGNIN | —▲— FURFURAL | —▲— CELLOBIOSE | —▲— ENZYME |
| —▲— Z. MOBILIS | —▲— DIAMMONIUM PHOSP | —▲— OXYGEN | —▲— CSL |
| —▲— GLYCEROL | —▲— SUCCINIC ACID | —▲— ACETIC ACID | —▲— LACTIC ACID |
| —▲— XYLITOL | —▲— ACETATE | | |

Liquid mass-fractions profile in the column

C104 - Vapor mass-fractions



- | | | |
|-------------------|----------------------|-------------------|
| —▲— WATER | —▲— CARBON DIOXIDE | —▲— ETHANOL |
| —▲— SULFURIC ACID | —▲— GLUCOSE | —▲— XYLOSE |
| —▲— CELLULOSE | —▲— HEMICELLULOSE | —▲— LIGNIN |
| —▲— FURFURAL | —▲— CELLOBIOSE | —▲— ENZYME |
| —▲— Z. MOBILIS | —▲— DIAMMONIUM PHOSP | —▲— OXYGEN |
| —▲— CSL | —▲— GLYCEROL | —▲— SUCCINIC ACID |
| —▲— ACETIC ACID | —▲— LACTIC ACID | —▲— XYLITOL |
| —▲— ACETATE | | |

Vapor mass-fractions profile in the column

4. REFERENCES

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