Technical University of Denmark
Chemical & Biochemical Engineering
Pilot Plant

Stelar July 2026

Overview of the Pilot Plant units at DTUs Chemical & Biochemical Engineering dep.

This overview shows most of the Pilot Plant units used for practical unit operations exercises in the following courses:

28121, 28125:	Chemical Unit Operations Laboratory
28123:	Large Scale Exercises in Process Technology and Chemical Unit Operations - 4 weeks Summer University for International Students
28344:	Biotechnology and Process Design
28932:	Process Engineering Laboratory (only for PhDs)

The exercise units and the unit operations they represent are divided into three general groups:

1. Basic Transport Phenomena
2. Traditional Technical Chemical Unit Operations
3. Biotechnical Chemical Unit Operations

The Pilot Plant Center of the DTU Chemical & Biochemical Engineering Department has at our disposal six large pilot halls, totaling 900 m^2, along with several modern laboratories equipped with all modern standard lab instruments. We have more than 40 different pilot-scale units within a digitally integrated environment, covering nearly all commercially used unit operations in the chemical, biochemical, food and pharmaceutical industries.

As one of the very few university units in Denmark with a GMO Class 1 large-scale facility, we offer upstream unit operations, bioreactors ranging in size from 2 to 200 liters, and a variety of downstream separation and concentration equipment.

While most of our units are designed for educational purposes, many in this overview, along with additional units not mentioned here, are also well-suited for research and commercial collaborations.

Technical University of Denmark
Chemical & Biochemical Engineering
Pilot Plant

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List of practical unit operations exercises offered by the Pilot Plant of the DTU Chemical Engineering.

Exercise			**Unit operation type c):**			**Duration**
#	Code	Name	1	2	3	H/F a)
1	1A	Liquid flow in pipes	X			H
2	1B	Pump systems	X			H
3	1C	Agitation in a stirred tank	X			H
4	1D	Aeration in a stirred tank	X			F
5	1E	Gas flow in pipes	X			H
6	1F	Bubble column aeration	X			F
7	2A	Filtration in a plate and frame filter press		X		H
8	2B	Rotary vacuum drum (RDV) filtration		X		F
9	2C	Flow in packed columns		X		H
10	3B	Pneumatic transport and separation of solids		X		F
11	4A	Heat transfer	X			H
12	5A	Distillation in a bubble cap column		X		F
13	5B	Batch distillation		X		H
14	6A	Absorption of packed column		X		H
15	7A	Drying in a tunnel dryer	X			H
16	7B	Spray drying		X		F
17	7C	Fluid bed drying		X		H
18	8B	Hydrocyclone separation		X		H
19	8C	Liquid – liquid extraction		X		F
20	8D	Solid – liquid extraction		X		F
21	8E	Centrifugation			X	H
22	9A	Crystallization of citric acid			X	F
23	9B	Falling film evaporation			X	F
24	10A	Ultrafiltration			X	F
25	10B	Desalination by Reverse Osmosis			X	H
26	10C	Ultrafiltration by a vibration membrane unit			X	F
27	11B	Fluid bed reactor - Ion exchange		X		F
28	12A	Process control – 2 tank	X			H
29	13A	Organic synthesis		X		F
30	13C	High temperature processes		X		F
31	13D	Cleaning in Place (CIP)			X	F
32	14A	Fermentation			X	2 x F b)
33	15A	High pressure homogenization - Cell rupture			X	F

a) Half day (H) or full day (F) exercise
b) Two full days of exercise
c) See front page

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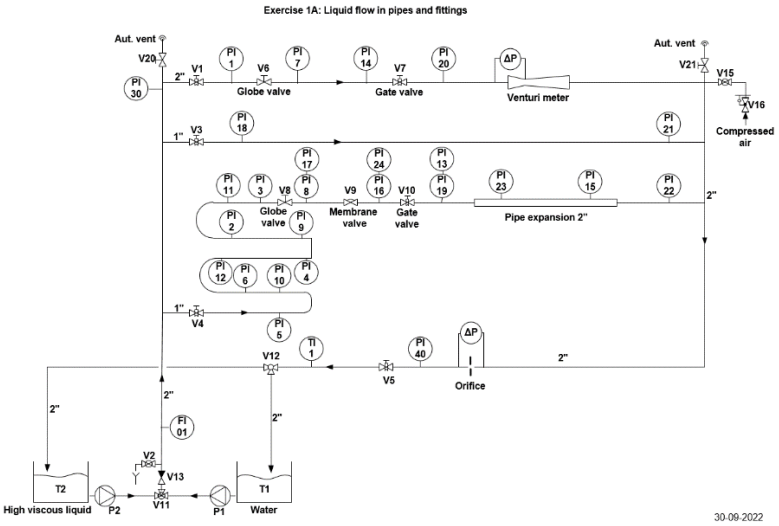
Exercise: 1A	**Liquid flow in pipes**
Half-day	Type: Basic transport phenomena

Purpose:

The pressure drops in piping systems and various components (different types of valves and pipe-bends), under different flow rates are experimentally determined using both a Newtonian liquid (water) and a non-Newtonian liquid (CMC or Xanthan solution). The results are then compared with standard data from the literature. Additionally, various flow measurement techniques, including orifice, venturi, and manual bucket methods, are examined, along with the pressure drops across different components and fittings, assessing their accuracies.



Exercise unit:

Two tanks and their respective pumps supply low viscosity and high-viscosity liquid to the piping system. The system consists of three parallel pipelines, each with different dimensions and equipped with various typical industrial fittings and components. Pressure transmitters, positioned between all components and fittings, provide pressure measurements visible on a panel.
A laboratory exercise is also included to determine the viscosity of the high-viscosity liquid.

User interface:

Manual control and data collection.

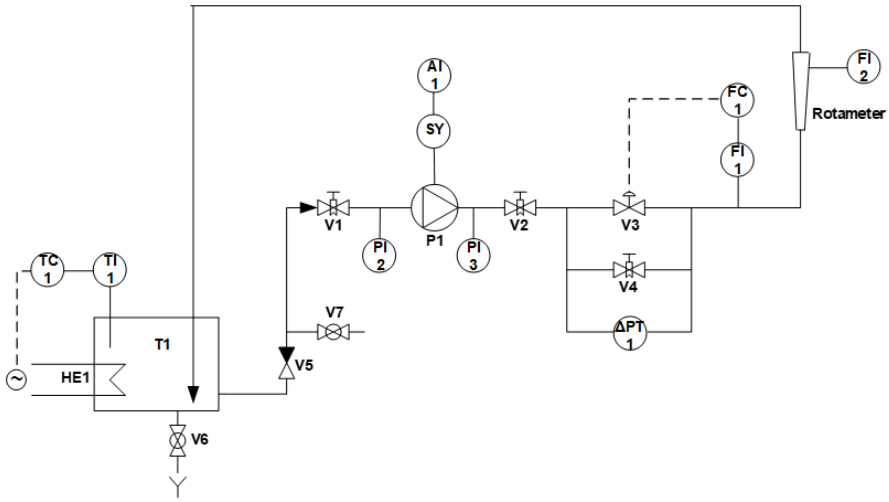
Main reporting subjects:

Flow and pressure drop calculations for both liquids and for all different components.
Reynolds numbers and a complete pressure drop overview of the exercise unit are done using Fanning's factor of friction.
Pressure loss coefficients K for all components are calculated and compared to literature values.
Shear rate calculations, and theoretical viscosity calculations are compared to experimental viscosity determinations.

Exercise: 1B	**Pump system**
Half-day	Type: Basic transport phenomena

Purpose:

The behavior of a piping system with a two-stage, adjustable-speed centrifugal pump and an adjustable control valve is investigated in terms of pressure and flow at different pump speeds and control valve openings. The system includes various fittings, valves, and flow meters.



Exercise unit:

Water is circulated in a pipe loop by a single-stage centrifugal pump, whose speed can be controlled using a handheld remote. The pipe loop contains various components, including an automatic control valve of the globe valve type, several shut-off gate valves, pressure indicators, a magnetic flow meter that also functions as a flow controller, and a variable-area rotameter.

Pump speed and control valve openings can be adjusted, while pressure, flow, pump speed, and power consumption can be monitored.

User interface:

Manual control and data collection.

Main reporting subjects:

Preparation of pump and system curves (Head, flow, efficiency) at the measured conditions.

NPSH calculations and theoretical conditions for pump cavitation as well as pump performance related to fluid properties are determined.

The affinity laws (flow, head, power) for centrifugal pumps are investigated.

The characteristics of the control valve are investigated including its valve constant Kv.

A static pressure profile of the pipe system is calculated and illustrated using the Bernoulli equation and the components friction factors.

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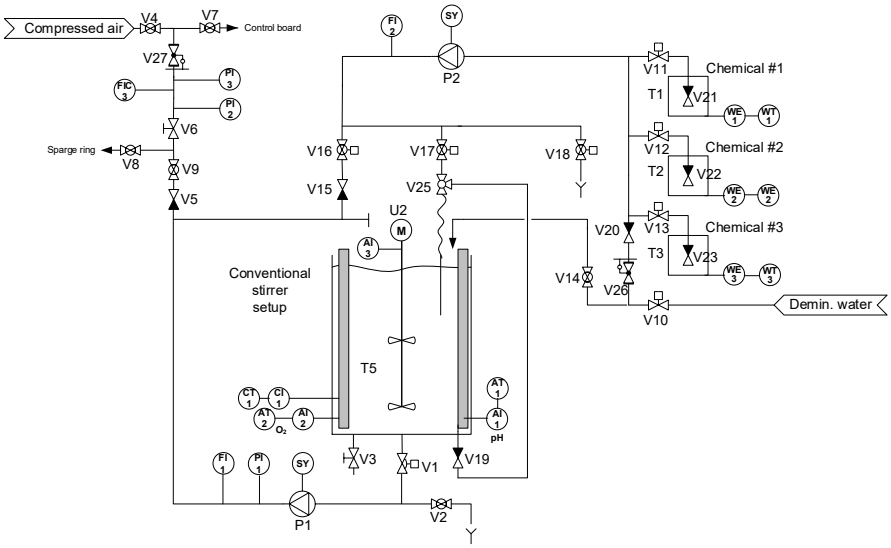
Exercise: 1C	**Agitation in a stirred tank**
Half-day	Type: Basic transport phenomena

Purpose:

Mixing efficiency is evaluated during the agitation process of a low-viscosity Newtonian aqueous solution (water) in a pilot-scale vessel. Mixing time is defined as the duration required to reach a predefined level of homogeneity after introducing a tracer chemical into the mixing vessel.

Experimental results using various types of impellers at different rotational speeds are compared with theoretical expectations. These results can also be used for scaling up from pilot-plant size to industrial scale.



Exercise unit:

The unit consists of a mixing tank made of clear PVC. The vessel can be equipped with different types of mixing devices; conventional impellers and a rotating fluid-driven jet nozzle (RJH = Rotary Jet Head).

The impellers are mounted on a vertical agitator shaft, and up to four baffles can be placed inside the vessel.

The rotational speed of the impellers and the pumping speed of the RJH can be adjusted. During mixing, a small amount of acid or base is dosed into the tank, and the response time, measured through changes in pH or conductivity, serves as an indicator of mixing efficiency.

User interface:

Web-based user interface via a tablet, supervisory control and data acquisition (SCADA) system.

Main reporting subjects:

Experimental and theoretical blending times, power consumption, torque and blending numbers against Re for the different impellor and mixing conditions, are measured and compared.

Comparison of data between different impeller types and the RJH.

Determination of the mixing constant for a selected experiment.

Upscaling of a stirred tank based on experimental data.

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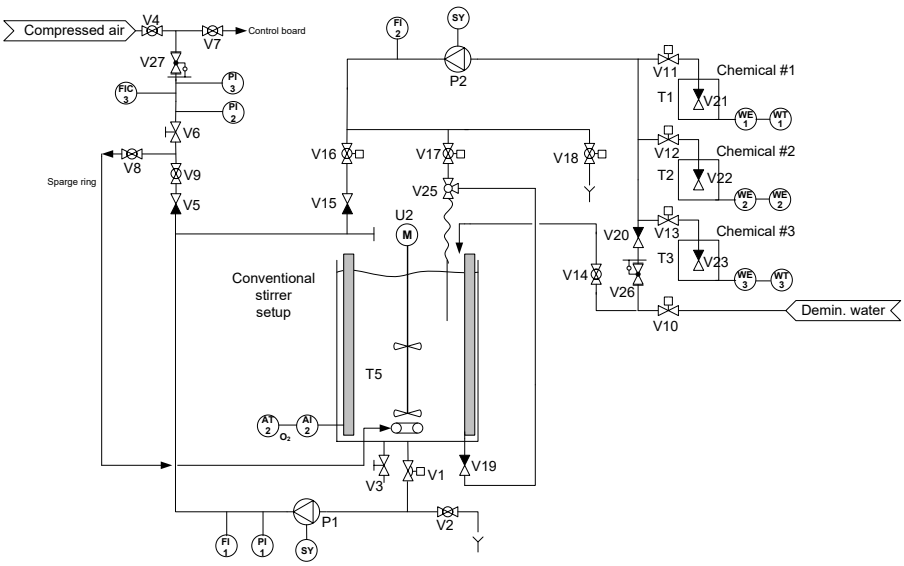
Exercise: 1D	**Aeration in a stirred tank**
Full day	Type: Basic transport phenomena

Purpose:

In a mixing tank with impellors and air injection via a ring sparger, the objective is to investigate the mass transfer of oxygen from the liquid phase to the gas phase (in reverse) by measuring the Kl·a values, mixing times, and gas hold-up under different conditions.



Exercise unit:

The unit consists of a mixing tank made of clear PVC. The vessel can be equipped with different types of mixing devices; conventional impellers and a rotating fluid-driven jet nozzle (RJH = Rotary Jet Head). Air is injected into the vessel through a sparge ring located below the impeller. The rotational speed of the impellers and the pumping speed of the RJH can be adjusted.

An antioxidant enzyme is added to the reactor, and during the experiment a hydrogen peroxide solution is added into the reactor. The enzyme decomposes the hydrogen peroxide, and the resulting supersaturation of oxygen in the liquid can be measured using an oxygen sensor, providing an indirect value for the oxygen transfer under the test conditions.

User interface:

Local PLC control of certain key parameters. Manual valve adjustment and local PC based data collection.

Main reporting subjects:

Calculation of the expected $K_l a$ and OTR values and the theoretical power consumption for un-gassed and gassed condition for the different process situations.

Calculation of the air hold-up, the initial and maximum bubble diameter and the interfacial mass transfer area per volume reactor.

Exercise: 1E	**Gas flow in pipes**
Half-day	Type: Basic transport phenomena

Purpose:

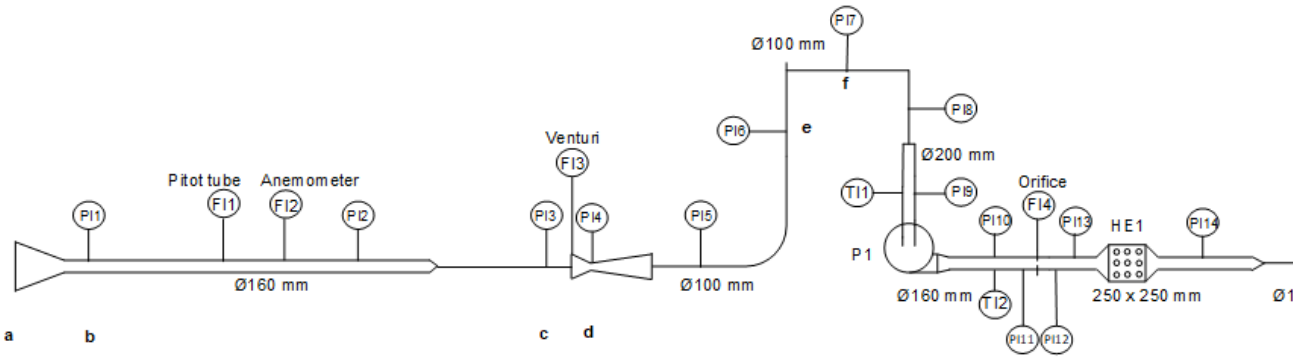
The objective is to explore various methods for measuring gas flow and gas flow profiles in pipes. The measured pressure drops across fittings and components are compared with theoretical predictions. The validity of Bernoulli's equation and theoretical velocity profiles is assessed, while the fan's properties, including its characteristic curve, temperature increase, energy consumption, and efficiency, are also studied.

Exercise unit:

The system consists of a fan, a duct with varying dimensions and obstacles, and various air flow measurement devices, including a Pitot tube, a Venturi meter, an orifice meter, and a digital anemometer. Pressure readings are provided for each instrument.

The system also includes several components such as duct bends, a T-piece, duct contractions and expansions, and two types of removable tube bank bundles designed to simulate heat exchanger pipes.

The fan speed can be adjusted to modify the airflow, and a manually operated valve at the duct outlet allows for pressure adjustments within the system.



User interface:

Manual control and data collection.

Main reporting subjects:

Determination of fan curve characteristics, power consumption and efficiency for different speeds. Comparison to affinity laws. Comparison of flow measurement methods.

Bernoulli's equation is used to calculate static pressure, velocity pressure and height pressure for different conditions.

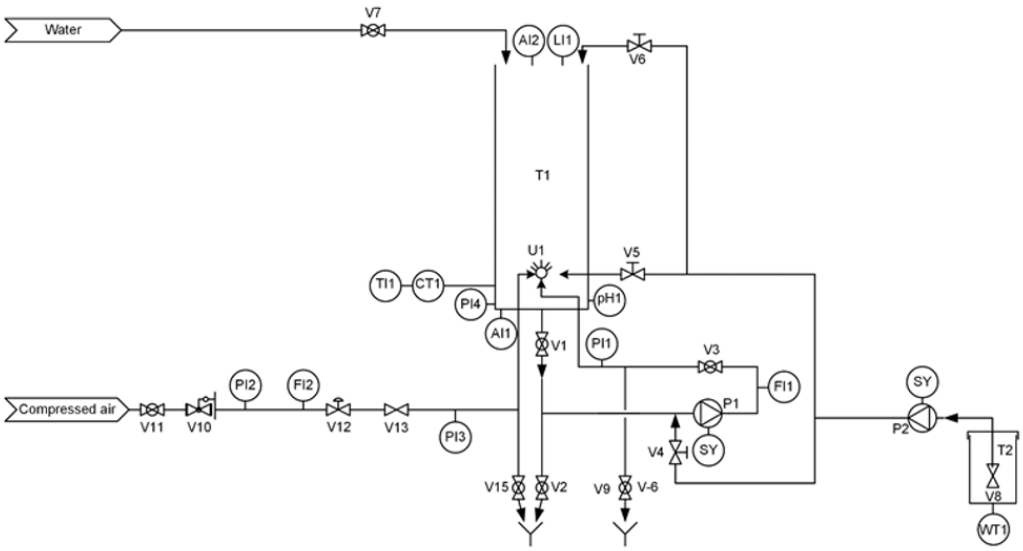
Friction factors and the loss coefficients are calculated for the various fittings and components and compared with literature values. A static pressure diagram for the system is constructed.

Use of a P-h diagram for enthalpy and entropy changes.

Exercise: 1F	**Bubble column aeration**
Full day	Type: Basic transport phenomena

Purpose:

In a cylindrical vertical tank with air injection at the bottom and the ability to recirculate the liquid content, various experiments are conducted using different air flow rates, water circulation flows, and salt additions. The objective is to investigate the mass transfer of oxygen from the liquid phase to the gas phase (in reverse) by measuring the Kl·a values, mixing times, and gas hold-up under different conditions.



Exercise unit:

The unit consists of a 3-meter-tall cylindrical reactor made of transparent acrylic plastic. It is open at the top to the atmosphere. At the bottom, there is a nozzle for liquid and air injection, as well as various instruments.

An antioxidant enzyme is added to the reactor, and during the experiment, a hydrogen peroxide solution is pumped into the reactor. The enzyme decomposes hydrogen peroxide, and the resulting supersaturation of oxygen in the liquid can be measured using oxygen sensors, providing an indirect value for the oxygen transfer under the test conditions.

User interface:

Web-based user interface via a tablet, supervisory control and data acquisition (SCADA) system.

A video presentation of the exercise and its details is available as a supplement to the written manual.

Main reporting subjects:

Experimental and theoretical gas (air) hold-up, gas residence time and mixing time.

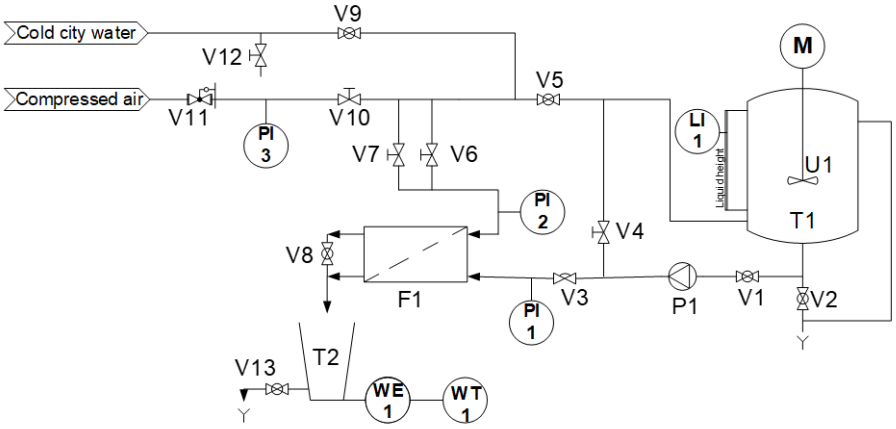
Average bubble size for the different experiments.

Experimental OTR (Oxygen transfer rate) and experimental and theoretical K_La for the experiments.

Exercise: 2A	**Filtration in plate and frame filter press**
Half-day	Type: Biotechnical chemical unit operation

Purpose:

The filtration of a magnesium phosphate aqueous suspension is carried out using a traditional horizontal plate and frame filter press with filter pads. The process occurs in several stages: preparation of the suspension, filtration, air deliquoring, filter cake washing, and air deliquoring. Filtration is performed at constant pressure. After the cake reaches saturation during the filtration phase, the residual liquid in the cake is minimized by blowing compressed air (air deliquoring) through the filter. Cake volume, resistance in the filter cake/filter cloth, and other filter properties are determined using a mathematical filter model and experimental results.



Exercise unit:

The filter press consists of six sets of frames and filter support plates. A stirred tank is used to prepare the suspension. A centrifugal pump pumps the suspension to the filter press, and the effluent is collected in a vessel on a scale. The suspension can be circulated, and the tank agitator keeps the suspension homogeneous. Cold city water is used for suspension preparation and filter cake washing, while compressed air is used for deliquoring the filter cake.

User interface:

Manual control and data collection.

Main reporting subjects

Determination of the specific filter cake resistance, cake voidage, cake density and the irreducible cake saturation

Determination of the resistance of filter cloth and the wash ratio.

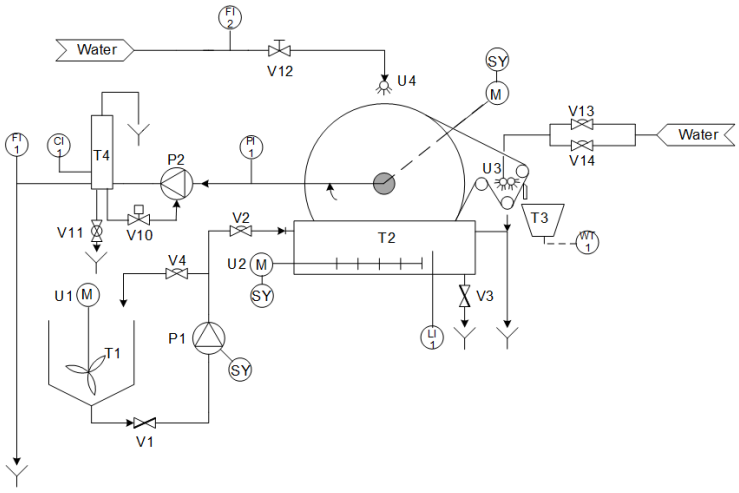
Estimation of amount of crystal water of magnesium phosphate based on a mass/molar balance.

Upscaling of an industrial sized filter press based on experimental data.

Exercise: 2B	**Rotary vacuum drum (RVD) filtration**
Full day	Type: Biotechnical chemical unit operation

Purpose:

The filtration performance of an insoluble, fine-grained product from an aqueous suspension is evaluated under various drum filter conditions. The test material used is gypsum ($CaSO_4$), mixed with a small quantity of filter aid. Variable rotary speed and drum submersion percentage are the parameters investigated during the filtration and drying processes. By using a mathematical filter model and experimental results from both the pilot experiment and a separate simple lab experiment, it is possible to determine the resistance in the filter cake and filter cloth, along with several other important filter characteristics.



Exercise unit:

The pilot plant rotary vacuum drum filter has a filter area of 0.50 m^2. The filter drum is connected to a vacuum pump. The filter cake can be washed by a sprinkler system before drying and is removed from the drum by a knife. The feed is contained in a trough with an oscillating-type agitator. The drum's rotational speed and the submersion depth of the drum, determined by the level in the trough, can be adjusted.
The feed is supplied by a pump from a 200-liter vessel equipped with an agitator, and the feed rate can be manually adjusted using a regulator valve.
A separate laboratory filtration experiment is conducted to determine the filter cloth resistance.

User interface:

Local PLC control of certain key parameters. Manual valve adjustment and manual data acquisition.

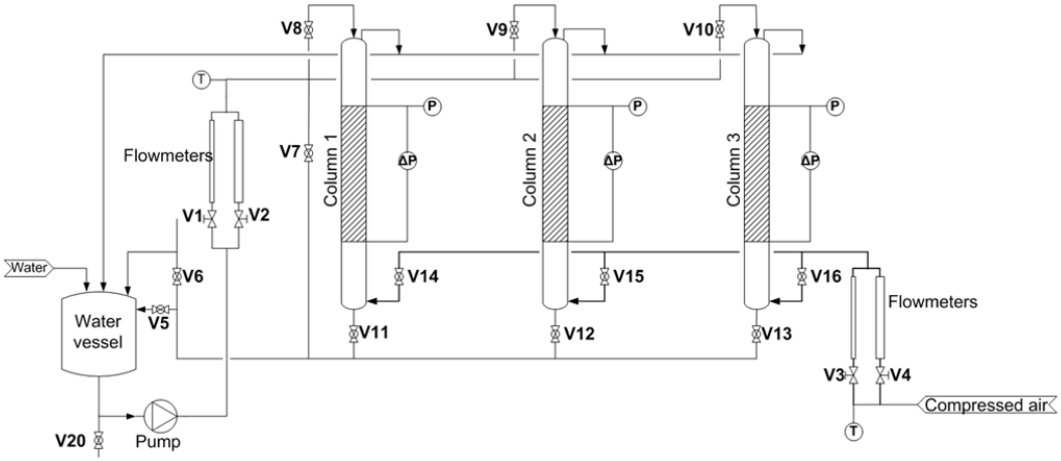
Main reporting subjects

For different rotational speed and submerged feed levels, the cake thickness, solid mass production rate, filtrate volume, filtration time and deliquoring time are measured.
The cake saturation, cake moisture, dry matter particle density, irreducible cake saturation and the cake porosity are calculated from the lab experiment to be used in the pilot experiment calculations.

Exercise: 2C	**Flow in packed columns**
Half-day	Type: Basic transport phenomena

Purpose:

In a system without mass transport, the basic hydrodynamic conditions are investigated for three columns packed with different packing materials: saddles, rings, and structured packing. Tests are performed with different air flows, as well as both water and air flows, at room temperature.



Exercise unit:

Three glass columns are filled with 8 mm ceramic Berl saddles, 8 mm glass Raschig rings, and structured stainless-steel packing (Mellapack 250Y) respectively. Air is introduced at the bottom of each column, and water can be added from the top or bottom of each column. Both air and water flow are manually adjustable. Pressure drops across the packing materials can be monitored using U-tube manometers.

User interface:

Manual control and data collection.

Main reporting subjects:

Pressure drops over columns at the different test conditions are calculated and compared to the measured values.

Wetting efficiencies and liquid hold-up numbers are calculated.

Visually observed flooding point is compared to calculated.

The results for the 3 different packaging materials are discussed.

Exercise: 3B	**Transport and separation of bulk solids**
Half-day	Type: Basic transport phenomena

Purpose:

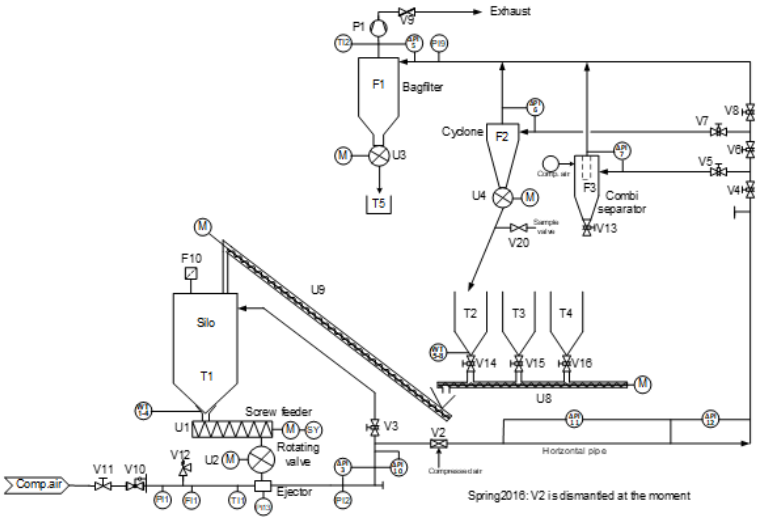
Using fine-grained sand, investigate the behavior of pneumatic transport in dilute-phase flow, including verification of the minimum transport velocities (saltation/choking). The separation of particles from the transport air is analyzed using three different separation units: a bag filter and two cyclone designs.

The unit includes various mechanical dosing devices and instrumentation for measuring air flows and pressures. Basic particle properties, such as bulk density and particle size distribution, are determined in the laboratory.

Exercise unit:

The pneumatic transport unit consists of a feed silo (T1) mounted on weighing cells to record the feed rate. The feed is transferred via a variable-speed screw feeder (U1) through a rotating valve (U2) into the pneumatic transport system, which conveys the gas-solid mixture to various separators. The system is constructed from aluminum piping, with some sections made of transparent plastic to allow visual observation of solid behavior.

The separated solids are collected in hopper T2, also placed on weighing cells. From T2, the solids can be returned to T1 using transport screws U8 and U9.



User interface:

Manual control and local PC base collection.

Main reporting subjects:

Pipe pressure drops with and without solids as a function of the superficial gas velocity. Compare experimentally found pressure drops across the various particle separators with theoretically determined values.

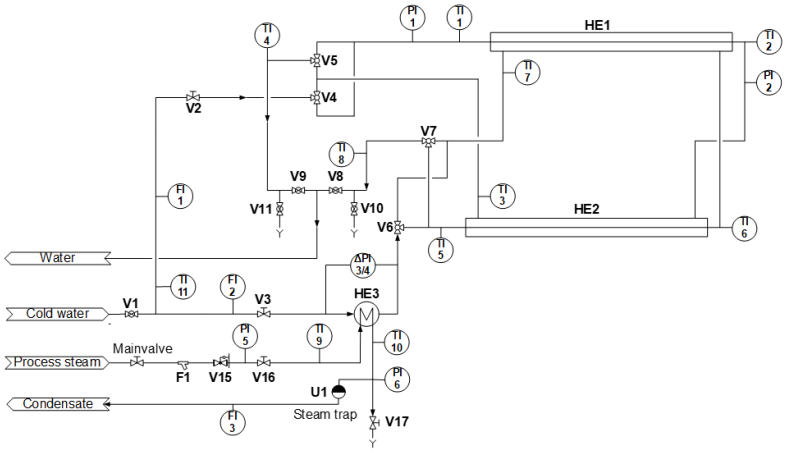
Determine separation efficiencies and particle size distribution of the product from the different separator units.

Design a cyclone with 90% separation efficiency based on experimental data.

Exercise: 4A	**Heat transfer**
Half-day	Type: Basic transport phenomena

Purpose:

The indirect heat exchange between two streams of water in concentric pipes is investigated experimentally, and the resulting heat transfer coefficients are compared with values from theoretical calculations. The same type of indirect heat transfer occurs in a plate heat exchanger, with condensing steam on one side and heated water on the other. Although the concentric pipes are insulated, some heat is lost to the surroundings. The heat and pressure losses are estimated and discussed. Co-current and counter-current flow, as two different operational conditions in the concentric pipes, are studied during this exercise.



Exercise unit:

The main components are two simple heat exchangers in series. Each consists of two concentric pipes arranged so that the two media can flow either co-current or counter-current. One medium is cold water, while the other is water heated by steam in a third plate-and-frame heat exchanger. Inlet and outlet temperatures, pressures, and flows for both the pipe heat exchangers and the plate heat exchanger are measured.

User interface:

Manual control and local PC based data collection.

Main reporting subjects

Heat transfer coefficients from the experiments for both tubular heat exchanges and the plate and frame heat exchanger are compared to values from theoretical calculations.

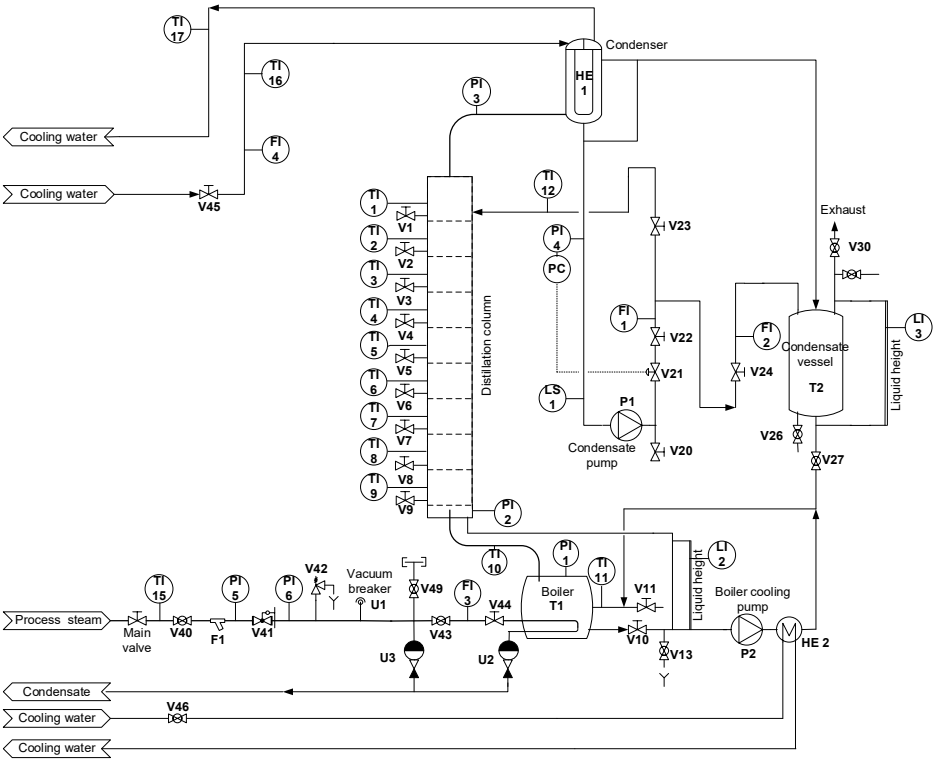
Experimental overall heat transfer numbers for each of the heat exchanger sections and for co-current as well as for counter-current conditions are calculated.

A heat balance to calculate heat losses is done. Pressure losses for both tubular and plate and frame units are calculated.

Exercise: 5A	**Distillation in a bubble cap column**
Full day	Type: Traditional technical chemical unit operation

Purpose:

A continuous separation of water and isopropanol takes place in a bubble cap column with 9 trays. Water and isopropanol (2-propanol) form an azeotrope at about 68 mol-% isopropanol, which is the highest possible concentration that can be achieved by distillation of the dilute solution. During the experiment, a portion of the distillate is used for reflux, and the remainder is returned to the boiler. In this way, the process can run continuously in a steady state without the need for additional feed.



Exercise unit:

The unit includes a column with 9 trays, each equipped with 3 bubble cap units. It has a steam-heated boiler containing about 400 liters of water/isopropanol mixture. The vapor from the boiler enters the column from the bottom, and the vapor exits from the top, where it is condensed by cooling water. A portion of the condensate is sent to the condensate vessel as the product, while the remainder is returned to the column as reflux. Most of the temperatures, as well as the flows of condensate, steam, cooling water, and some pressures, are recorded.

User interface:

Web-based user interface via a tablet, supervisory control and data acquisition (SCADA) system.
A video presentation of the exercise and its details is available as a supplement to the written manual.

Main reporting subjects

Development of a T-xy diagram, a bubble point curve and a dew point curve based on the experimental data and Raoults law, Antoine equation and Margules equation.
Use the McCabe-Thiele method to calculate the number of theoretical stages. Also, total efficiency and a heat balance are done.
The impact related to changes in reflux is explained.

Exercise: 5B	**Batch distillation**
Half-day	Type: Traditional technical chemical unit operation

Purpose:

In a packed column, a batch distillation is carried out to separate water and a simple alcohol. The process is performed under a constant reflux ratio, so the distillate and still compositions continuously change over time. The initial distillate contains the highest concentration of the light component (alcohol), but as the distillation proceeds, the distillate composition becomes increasingly concentrated with the heavier component. The progress of the separation process is monitored by determining the concentration of samples from various locations within the unit and at different times, through density measurements.

Exercise unit:

The unit is a packed glass column with Mellapak 250Y packing. The packing height is 1.68 m. Heating is provided by a steam-heated boiler containing the initial water/ethanol mixture to be distilled. The vapors leaving the column are condensed in a heat exchanger using cold water, with part of the condensate directed to the condensate vessel and the remainder returned to the top of the column as reflux. The reflux ratio can be adjusted manually.

User interface:

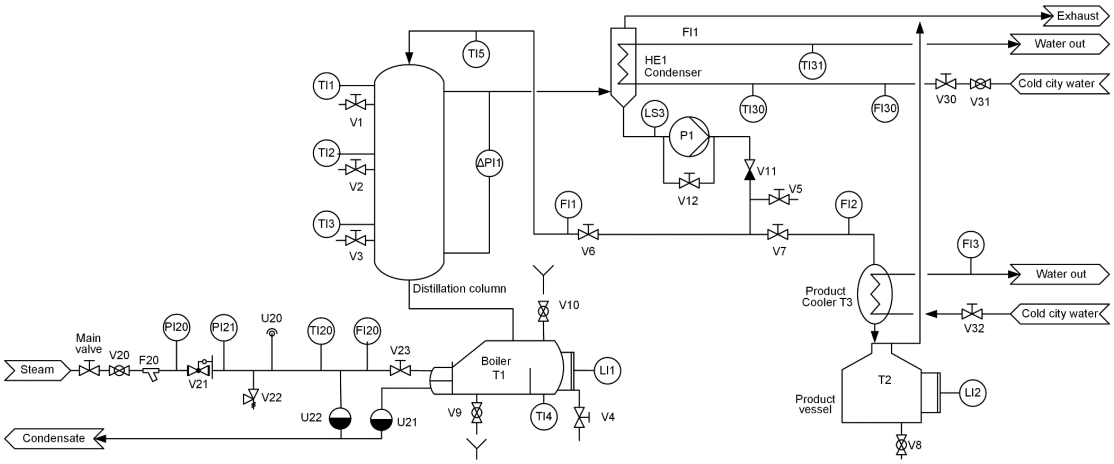
The unit is controlled manually partly via a tablet as supervisory control and data acquisition (SCADA system).

Main reporting subjects

Calculation of distillate composition during the process and compared to measured.

Calculation of number of theoretical stages using the McCabe-Thiele method and minimum reflux ratio.

Determine mass balances, heat balance and enthalpy demand of evaporation.



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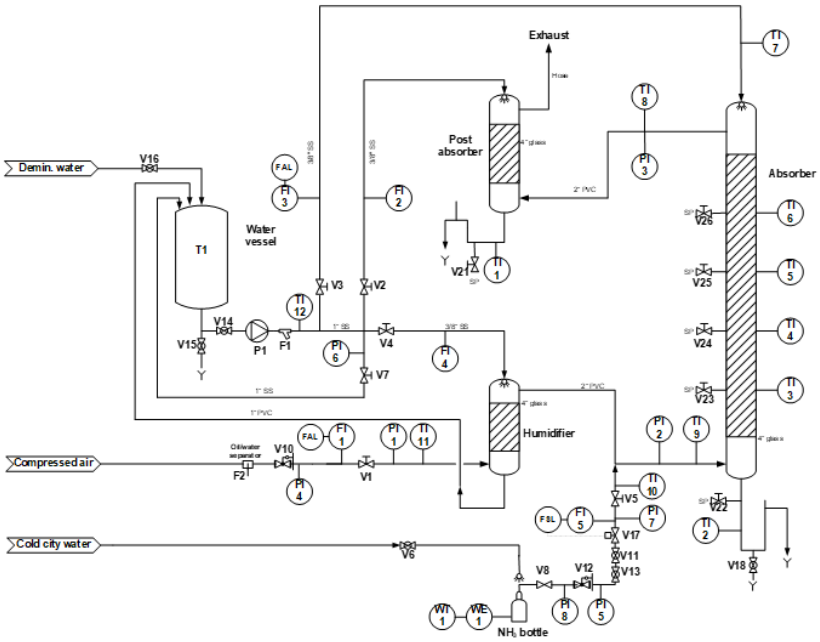
Exercise: 6A	**Absorption in a packed column**
Half-day	Type: Traditional technical chemical unit operation

Purpose:

Air mixed with ammonia gas is scrubbed with water in a packed absorber column. The ammonia concentration profile in the absorption liquid throughout the column is measured under two conditions: high and low water flow in the absorber.



Exercise unit:

The main component is the absorber column, a 3.7 m high glass tube with 1.9 m of effective absorption height filled with Raschig rings. To ensure no ammonia gas is released into the environment, a small post-absorber column is installed before the exhaust. A third column, the air humidifier, is used to saturate the inlet air to the absorber. Ammonia gas is introduced into the air stream just before the absorber.
Demineralized water is pumped to the top of all three columns, counter-current to the upward gas flow. Liquid and gas flows, as well as relevant pressures, are measured.

User interface:

Manual control and local PC based data collection.
A video presentation of the exercise and its details is available as a supplement to the written manual.

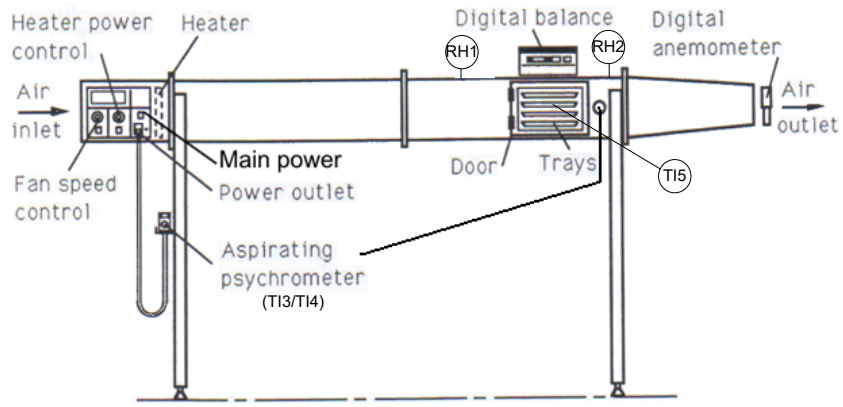
Main reporting subjects:

System mass balances for ammonia.
The number of absorption stages is calculated using the McCabe-Thiele method and the Kremser equation. Additionally, the number of transfer units and the height of a transfer unit are determined.
Calculation of a scaled-up column to comply with a certain maximum ammonia emission.

Exercise:	**7A**	**Drying in a tunnel dryer**
Half day		Type: Traditional technical chemical unit operation

Purpose:

In a simple tunnel dryer without recirculation, a solid product, moist vermiculite, is dried. Data are collected during the drying process and compared with theoretical values. Heat and mass balances, theoretical calculations of drying time, and constructions in the Mollier diagram (H-X diagram) or psychrometric diagram are part of the report.



Exercise unit:

The unit is a modified Armfield Tray Dryer consisting of a horizontal square air duct (the orange unit). Air is drawn into the duct by a variable-speed axial fan and passes through an electrical heater with temperature control.

Inside the dryer, up to four metal trays can be placed to hold the product being dried. The trays are attached to a balance to monitor the weight loss of the product during the drying process.

The temperature and humidity of the air upstream and downstream of the product trays are measured.

User interface:

Manual control and data collection.

Main reporting subjects:

Heat and mass balances, experimental and theoretical calculations of drying time.

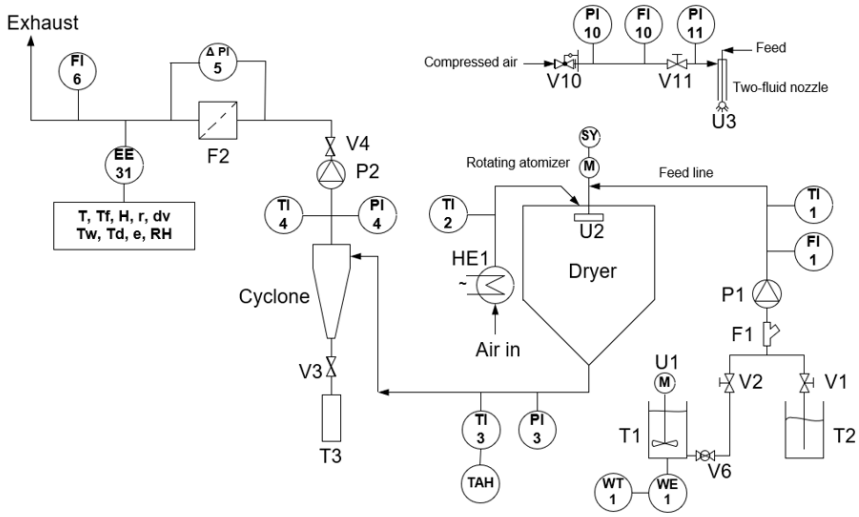
Overall thermal efficiency and the maximum thermal efficiency are calculated.

Constructions of the drying processes in a Mollier diagram (H-X diagram)/ psychrometric diagram.

Exercise: 7B	**Spray drying**
Full day	Type: Traditional technical chemical unit operation

Purpose:

Using a large pilot spray dryer with a rotating atomizer and a maltodextrin solution, drying experiments simulating a typical food product solution are performed. Parameters such as drying air temperature and droplet size can be adjusted during the experiments.



Exercise unit:

The cylindrical drying chamber has a volume of 1.21 m^3. The inlet air duct is heated by an electrical heater. The dryer can be operated with a rotating atomizer with variable speed or a two-fluid atomizing nozzle. The feed suspension is supplied by a variable-speed membrane pump and introduced into the drying chamber via the rotating atomizer wheel at the top of the chamber. Hot air enters the top of the dryer and exits at the bottom, where it passes through a cyclone for separation of the solid product. The airflow is provided by a fan located after the cyclone. Inlet and outlet air conditions are measured.

User interface:

Manual control and data collection.

Main reporting subjects:

Based on measurements and other data, heat and mass balances as well as constructions in the Mollier diagram (H-x diagram) are conducted.
Thermal efficiencies, average droplet size, drying time and gas residence time are calculated.
Product particle size distribution and the moisture content of the product is determined by laboratory analysis.
Theoretical cyclone particle cut size is calculated and compared to the experimental measured.

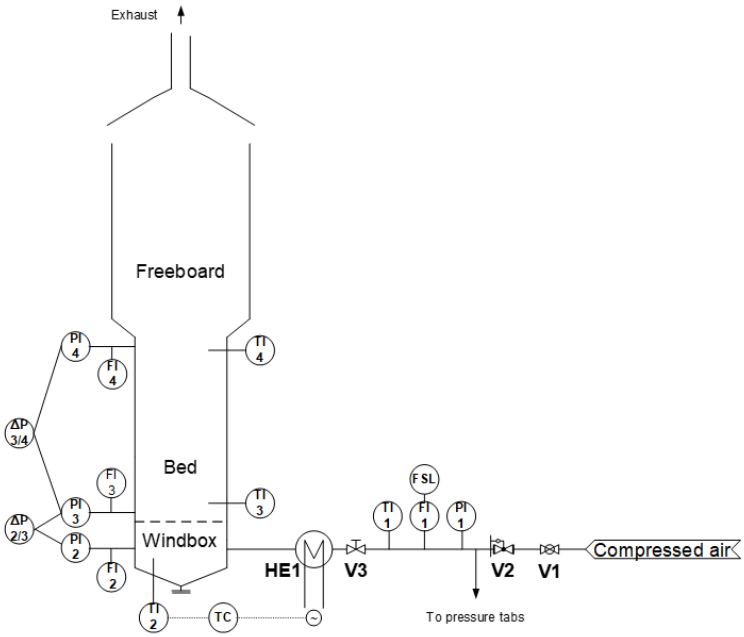
Exercise: 7C	**Fluid bed drying**
Half-day	Type: Traditional technical chemical unit operation

Purpose:

In a small batch fluidized bed, the fluidization properties and drying characteristics of a particulate product, silica gel, are investigated. First, an experiment using dry product and ambient air temperature is conducted to examine the fluidizing characteristics. Next, a batch drying of the wet product is carried out to analyze the actual drying process in comparison with theory.

During the drying process, the constant drying period is identified, and the drying rate is determined.

A lab sieving analysis is performed to determine the particle size distribution of the product.



Exercise unit:

The fluidized bed consists of two sections: the bed section, with a stainless-steel perforated distributor plate at the bottom, and the freeboard section above the bed. The fluidization air enters the fluidized bed from the bottom, through the perforated plate, and exits at the top. The inlet air flow and temperature can be controlled, and bed temperatures and pressure drops across perforated plate and product bed can be measured.

User interface:

Manual data collection. Partly control via a tablet as supervisory control and data acquisition (SCADA system).

Main reporting subjects:

Curve pictures of the drying process are generated. Calculations of the minimum fluidization velocity and terminal fluidization velocity.

The pressure drop across the air distributor plate and the product bed at both room temperature and drying temperature is compared with the theoretically expected pressure drop.

The drying rate is calculated, and the drying process is plotted in a H-X (Mollier) diagram.

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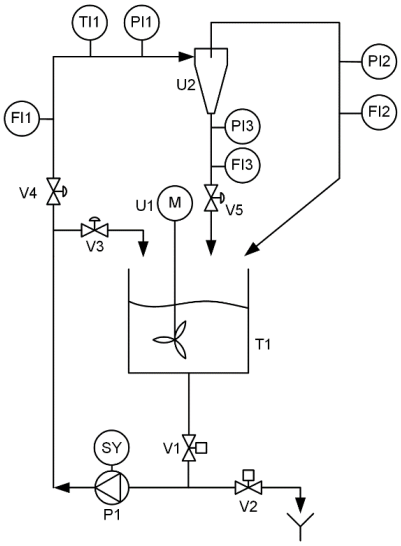
Exercise: 8B	**Hydrocyclone separation**
Full day	Type: Biotechnical chemical unit operation

Purpose:

A pilot plant hydrocyclone battery is used to separate potato starch from an aqueous suspension under various operating conditions, such as flow rates, concentration, and pressure, to identify the optimal separation efficiency. The data collected during this exercise will also be used to determine the upscaling of the hydrocyclone separation process to an industrial scale.



Exercise unit:

The unit consists of a battery of hydro cyclones with space for up to 14 cyclones; however, for this experiment, only 4 cyclones are utilized. These cyclones are made of nylon, with an approximate diameter of 1 cm and a length of 9 cm. The hydro cyclones are fed by a centrifugal multistage pump from a 200-liter vessel equipped with a stirrer. The separated fractions (overflow and underflow) can be returned to the feed vessel. Pump speed adjustments are possible using a frequency converter.
Samples are taken from the feed, overflow, and underflow to determine starch concentration.

User interface:

Web-based user interface via a tablet, supervisory control and data acquisition (SCADA) system.

Main reporting subjects:

Efficiencies for the various feed flow / overflow ratios. Concentrations in underflows.
Mass average particle size, theoretical cut size and sedimentation and residence time.
Calculation of Eulers and Stokes numbers and comparison to Stokes law.
Based on the experimental data, a scale up is done for a large industrial hydrocyclone.

Exercise: 8C	**Liquid – liquid extraction**
Full day	Type: Traditional technical chemical unit operation

Purpose:

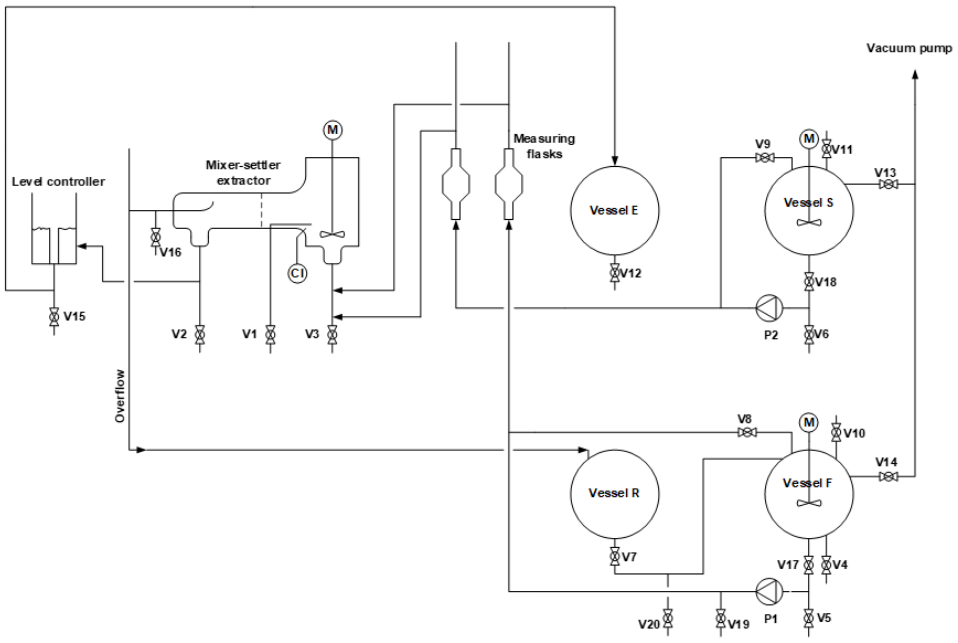
In the experiment, acetic acid (HAc) dissolved in n-paraffin oil (C10-C13) is extracted with water at room temperature in a mixer-settler extractor. The equilibrium distribution coefficient of HAc between the two phases is determined after sufficient reaction time to reach equilibrium conditions. For a fixed flow of feed (paraffin oil + HAc) and solvent (water), the relevant mass transfer data for HAc is determined for two mixing speeds, and for both oil-in-water (O/W) and water-in-oil (W/O) conditions.

Exercise unit:

The unit consists of four 100-liter glass vessels: Feed (oil with HAc), solvent (Dem. water), raffinate, and one for the extract. Two piston pumps with variable drives pump the feed and solvent to a mixer-settler unit with a variable-speed stirrer, where the extraction takes place. HAc concentrations, conductivity, and volumes are measured to determine extraction efficiency, mass balances and mass transfer data.

User interface:

Manual control and data collection.



Main reporting subjects:

Mass balances and extraction efficiencies, mass transfer rates and residence times are calculated.
A 3-phase diagram of the extraction process is done.

Exercise: 8D	**Solid – liquid extraction**
Full day	Type: Traditional technical chemical unit operation

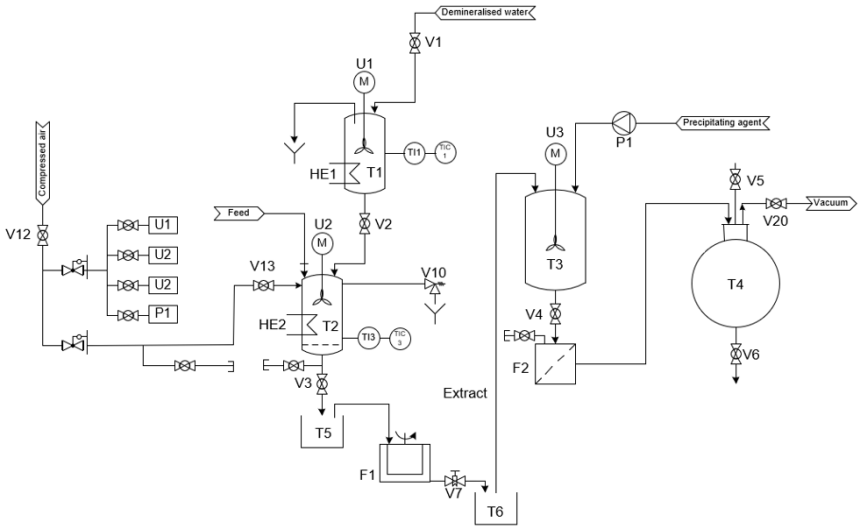
Purpose:

Pectin is extracted from lemon peels using hot, acidified water. It is then isolated by precipitation from the solution using alcohol, followed by filtration. A laboratory experiment is conducted to mimic the pilot process. Mass balances and extraction yields for both the pilot and laboratory experiments are calculated

Exercise unit:

The unit consists of a 20-liter glass vessel where the liquid for extraction can be heated to the prescribed temperature. The hot liquid is then fed into the extractor, where the pH and temperature are adjusted to initiate the extraction process. The suspension is filtered using a basket centrifuge, and the liquid is transferred to the precipitation vessel containing 95% ethanol. The precipitated pectin is then filtered using a simple filter basket, isolated, and dried.

Temperatures can be controlled and monitored



User interface:

Manual control and data collection.

A video presentation of the exercise and its details is available as a supplement to the written manual

Main reporting subjects:

Mass balances and extraction yields for pilot and lab exercise.

Effective diffusion coefficient and rate constant of pectin are determined.

Data is used to do an upscaling to an industrial size reactor.

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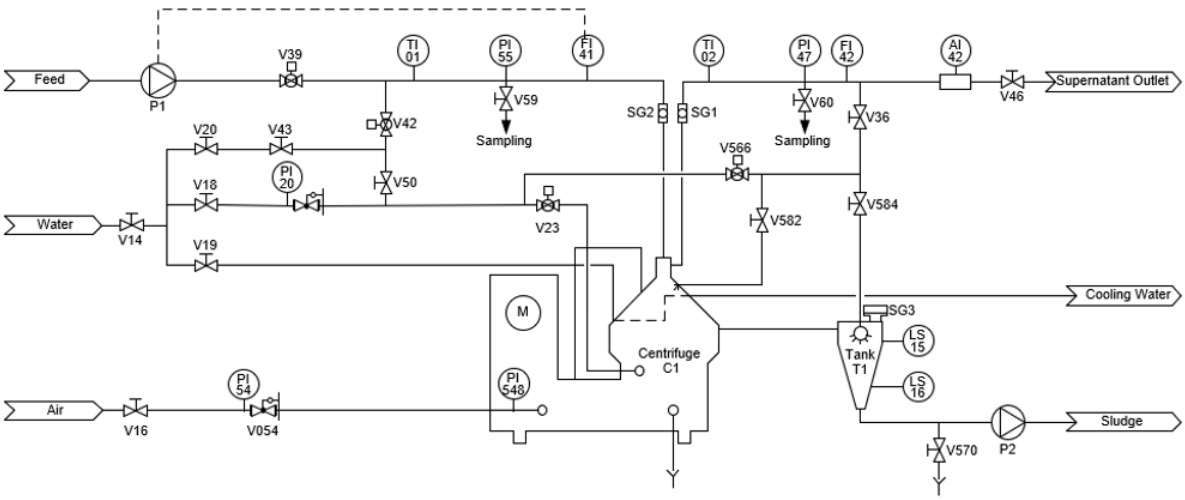
Exercise: 8E	**Centrifugation**
Half-day	Type: Biotechnical chemical unit operation

Purpose:

The behavior of a disc stack centrifuge is demonstrated by separating a suspension of bakers yeast and water, simulating a fermentation broth. The centrifuge will be operated as a clarifier. The operating conditions, feed flow and back pressure influence on separation quality is investigated. Microscopy with camera and digital image generation and lab centrifuge analysis of samples are part of the exercise.

Exercise unit:

The unit is a GEA Pathfinder 5 type disc stack centrifuge with separator cyclone (sludge) tank. The feed is provided from an external tank using an adjustable peristalctic pump. The inlet piping to the centrifuge contains a tempeture indicator, a pressure indicator and a flow indicator. A sight glass is provided to observe the feed. The clear liquid product from the centrifuge, the supernatent or centrate, leaves the centrifuge from the top and the outlet pipe contains a sight glass, a temperature indicator, a pressure indicator, a flow indicator and a turbidity meter. Inlet flow and centrifuge back pressure can be adjusted.



User interface:

Web-based user interface via a tablet, supervisory control and data acquisition (SCADA) system.
Manual valve adjustment.

Main reporting subjects:

Experiments with different feed flows and centrifuge back pressures are conducted. Separation efficiencies, G-numbers and liquid and solids residence time in the bowl are determined.
The yeast cell average size is determined by microscopy and is used to determine the theoretical terminal settling velocity at the feed inlet point of the centrifuge and at the bowl periphery using Stokes law.
An upscaling to industrial centrifuge size is done based on experimental results.

Exercise: 9A	**Crystallization of citric acid**
Full day	Type: Biotechnical chemical unit operation

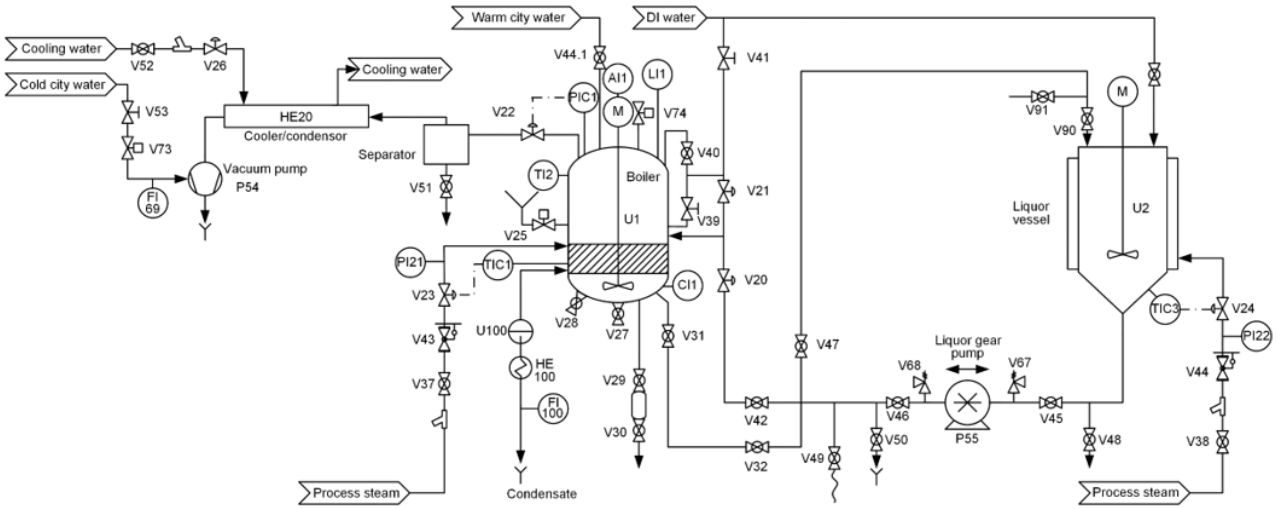
Purpose:

The purpose of the experiment is to monitor and control the crystallization of citric acid by evaporating a semi-concentrated acid solution under vacuum in a 300-liter crystallizer vessel. The physicochemical behavior of the citric acid-water mixture is studied from the beginning until crystallization occurs. The crystalline product is analyzed for quality and purity

Exercise unit:

The unit consists of a 300-liter boiler (crystallizer), a tank for semi-concentrated feed, and a vacuum system with a vacuum pump and condenser. The crystallizer vessel is equipped with a jacket for steam heating. Temperature, pressure, and conductivity sensors are used to control the unit and the crystallization process. Additionally, a video microscope camera can be used to visually monitor the crystallization process.

Titration and laboratory analysis are performed to monitor the concentration process and assess the quality of the final crystalline product



User interface:

Web-based user interface via a tablet, supervisory control and data acquisition (SCADA) system.

A video presentation of the exercise and its details is available as a supplement to the written manual

Main reporting subjects:

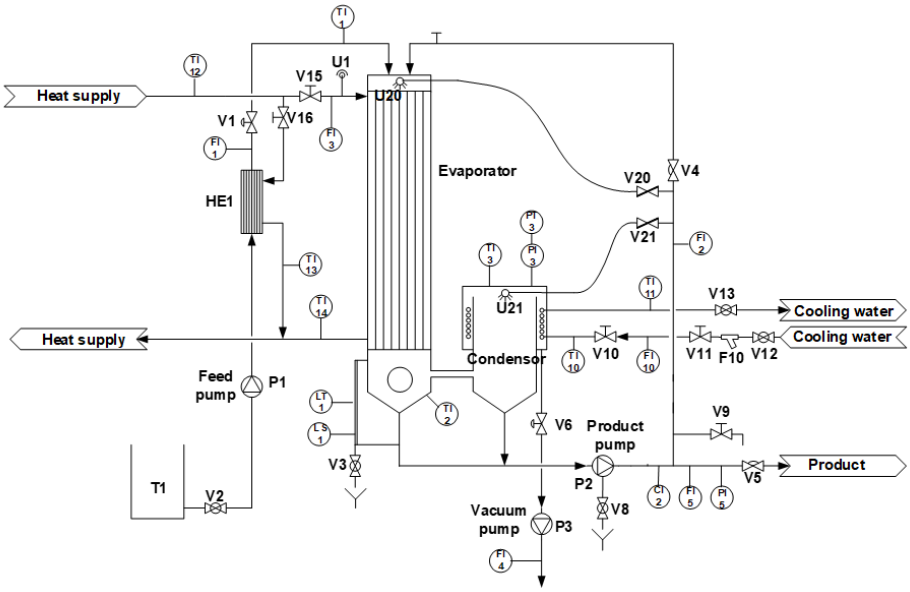
Physical-chemical behavior of citric acid-water mixture from start until crystallization is studies. Mass balances of water and citric acid. Heat balance for a selected time interval and determination of the heat transmission coefficient of the boiler. Experimental and theoretical energy consumption.

Experimental and theoretical crystallization yield and purity of final crystals.

Exercise: 9B	**Falling film evaporation**
Full day	Type: Traditional technical chemical unit operation

Purpose:

A dilute sugar solution is concentrated through vacuum evaporation using a vertical falling film evaporator. The main challenge in this process is to observe and adjust various flows and operating conditions to achieve a steady-state operation



Exercise unit:

The main components of the unit include the vertical evaporator with the calandria pipe section, the condenser/separator and vacuum pump, the feed pump, the product/recirculation pump, and a heat supply system with a plate heat exchanger for preheating the feed.

The solution to be concentrated is introduced at the top of the evaporator and distributed through a system of distributor pipes over the inlets of the vertical heating tubes, known as the calandria. The solution flows downward by gravity as a thin film along the inner walls of the calandria tubes. On the outside of these tubes, within the shell of the evaporator, the heating medium, hot water, is circulated.

The concentrated product exits from the bottom of the unit, where part of it can be recirculated to the top of the evaporator for further concentration, while the remaining portion is collected as the final product.

User interface:

Web-based user interface via a tablet, supervisory control and data acquisition (SCADA) system.

A video presentation of the exercise and its details is available as a supplement to the written manual.

Main reporting subjects:

Mass balances, heat balances, evaporation rate and liquid residence time are calculated.

The overall heat transfer coefficient and the specific heat consumption are determined. The experimental results are also used to determine and upscale the main conditions for a multi-effect, large scale plant.

Exercise: 10A Ultrafiltration

Full day Type: Biotechnical chemical unit operation

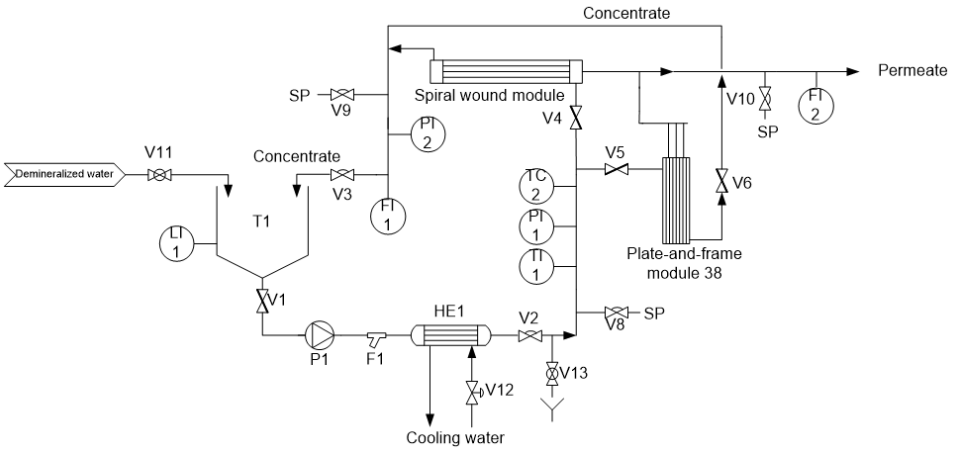
Purpose:

The purpose of this cross-flow filtration exercise is to investigate the properties of a polysulfone ultrafiltration membrane and analyze the process response when concentrating a dextran polymer (MW 40,000). The effects of feed rate, pressure, and polymer concentration on water flux, retention, and concentration polarization are examined.

Exercise unit:

The unit is a batch-operated, manually controlled pilot plant ultrafiltration (UF) system from Alfa Laval, equipped with a 4 m^2 spiral-wound polysulfone membrane with a molecular weight cut-off (MWCO) of 10,000. The system consists of a feed tank, a feed/circulation pump, a cooler for feed temperature control, and the membrane unit.

Temperature and flow meters monitor the feed, permeate, and retentate flows, while pressure indicators measure the cross-membrane pressure. Flow and back pressure to the module are manually controlled using diaphragm valves.



User interface:

Web-based user interface via a tablet, supervisory control and data acquisition (SCADA) system.

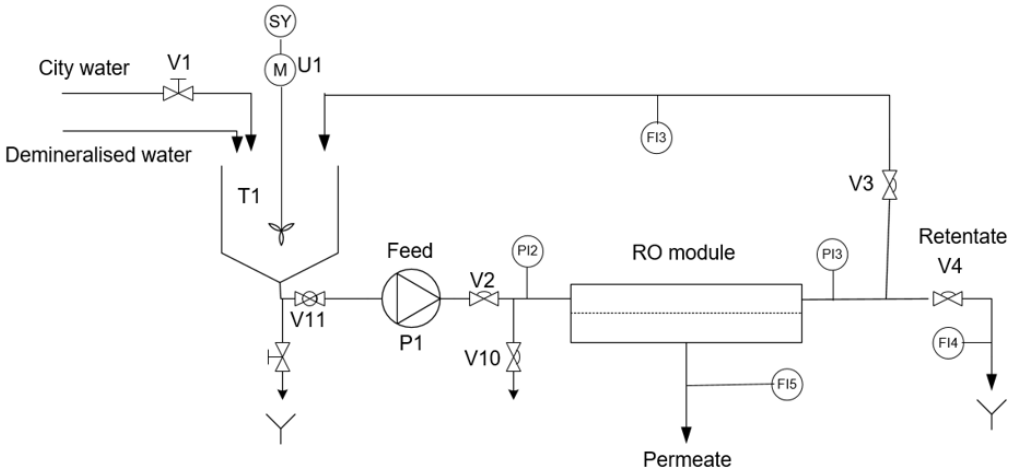
Main reporting subjects:

Flux – membrane differential pressure relationship for water and dextran solution at different feed flow rates. Dextran mass balance. Observed and theoretical dextran retentions at the different test conditions. Testing of the gel layer model. Calculation of the osmotic pressure contribution and the mass transfer coefficient (k) for the membrane.

Exercise: 10B	**Desalination by Reverse Osmosis**
Half-day	Type: Biotechnical chemical unit operation

Purpose:
Investigation of the flux properties of an RO membrane and the process performance when producing at different feed flows, cross membrane pressures and water-salt concentrations.

Exercise unit:
The unit contains a RO-membrane unit made as a spiral wound module, a feed tank with agitator, a high-pressure multistage centrifugal pump for recirculation and some instrumentation.
The membrane is a composite polyamide polymer, PERMAQ1-4040 from BWT with an area of 7.9 m^2 and a minimum NaCl retention of 99.3%.



User interface:
Manual control and data collection.

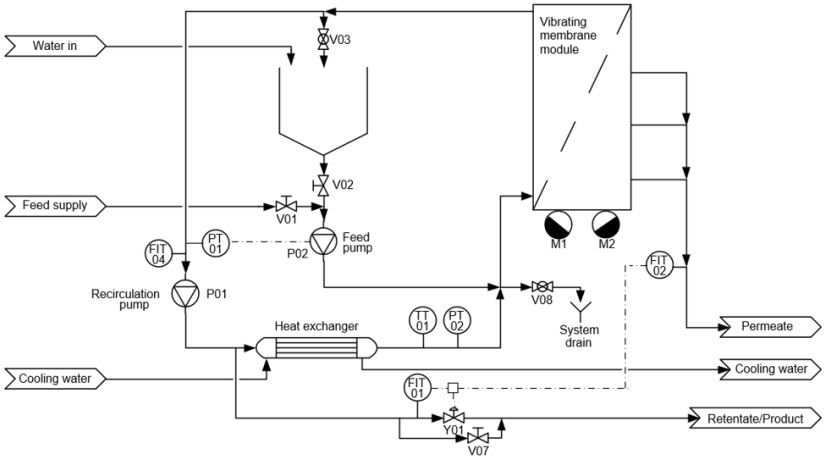
Main reporting subjects:
Water flux-pressure relationship, permeability coefficients and salt retention for the different test conditions.
Use of Darcys law and van Hoffs equation to calculate membrane surface feed concentrations.
Estimation of polarization concentration and mass transfer coefficients.
Upscaling of a RO seawater plant based on experimental data.

Exercise: 10C	**Ultrafiltration by a vibrating membrane unit**
Full day	Type: Biotechnical chemical unit operation

Purpose:

Investigation of the properties of an ultrafiltration membrane and the process response when concentrating a polymer; dextran T40 (MW 40,000). The special feature for this unit is a novel technology where the membrane modules are vibrating. Contrary to traditional static membrane units the vibration of the membranes is expected to reduce the fouling tendency.

During the experiment, the impact of cross flow velocity (mix feed rate), pressure, and polymer concentration on water flux, dextran retention, and concentration polarization are determined.



Exercise unit:

The equipment is a 7.5 m^2 Vibro Pilot membrane separation unit from SANI Membranes. The unit has a retentate recirculation loop using a centrifugal pump. The feed system consists of a stainless-steel tank with a centrifugal feed pump. The unit may also be fed from an external feed source. The system has two pressure sensors measuring the pressure before and after the membrane unit. A pressure sensor located in the exit line of the module is used in a pressure control loop to control the inlet feed pump speed (flow) to achieve the indicated pressure set-point. Two flowmeters are used to control the concentration degree of the retentate via a flow ratio control using valve.

User interface:

Web-based user interface via a tablet, supervisory control and data acquisition (SCADA) system.

Main reporting subjects

Flux – membrane differential pressure relationship for water and dextran solution at different feed flow rates. Dextran mass balance. Observed and theoretical dextran retentions at the different test conditions. Testing of the gel layer model. Calculation of the osmotic pressure contribution and the mass transfer coefficient (k) for the membrane.

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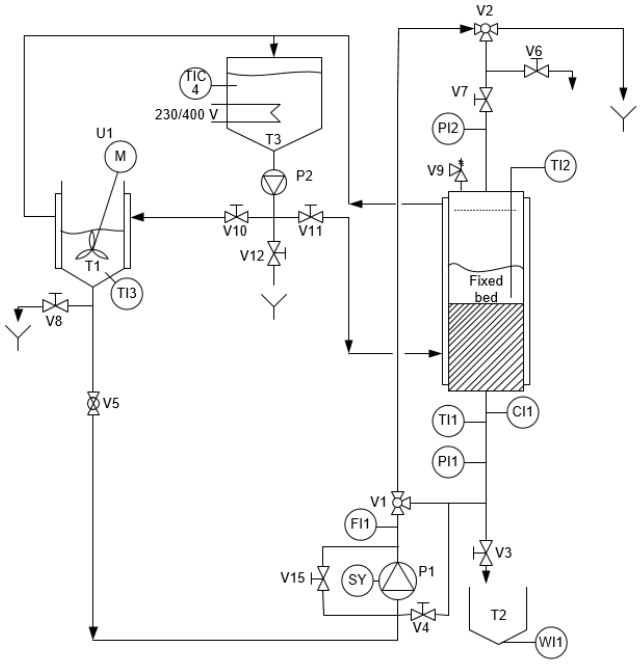
Exercise: 11B	**Fluid bed reactor – Ion exchange**
Full day	Type: Biotechnical chemical unit operation

Purpose:

The pilot plant experiment will investigate the response of the resin through exchange of the bound hydrogen ions with sodium or calcium ions from the feed solution and the consecutive regeneration using nitric acid. During these processes a number of experimental data are obtained. The exchange isotherms of the same resin will be studied during laboratory experiments. A lab work is included to determine the isotherm of the resin.



Exercise unit:

The fixed-bed reactor is a glass cylinder equipped with a water jacket. It has a diameter of 100 mm and a length of 1 m. The feed is stored in a steel vessel (T1) and pumped to the reactor using a gear pump (P1) with manual feed flow control. The process time, feed flow, and temperatures are controlled and recorded, along with conductivity. The outlet volume is monitored using a scale.

The temperature of both the reactor jacket and the feed vessel jacket can be controlled by a separate electrically heated water bath unit (T3) via the temperature controller (TIC4).

The resin used is Amberjet 1200, with a specified exchange capacity of approximately 2.0 eq/L of resin and a cross-linking degree of 8% DVB.

User interface:

Web-based user interface via a tablet, supervisory control and data acquisition (SCADA) system.

A video presentation of the exercise and its details is available as a supplement to the written manual.

Main reporting subjects

Plot the breakthrough curves of the ion exchange operation as well as of the regeneration.

Calculate the overall theoretical capacity based on the experimental data (for pilot scale as well as lab scale) and compare with the supplier information

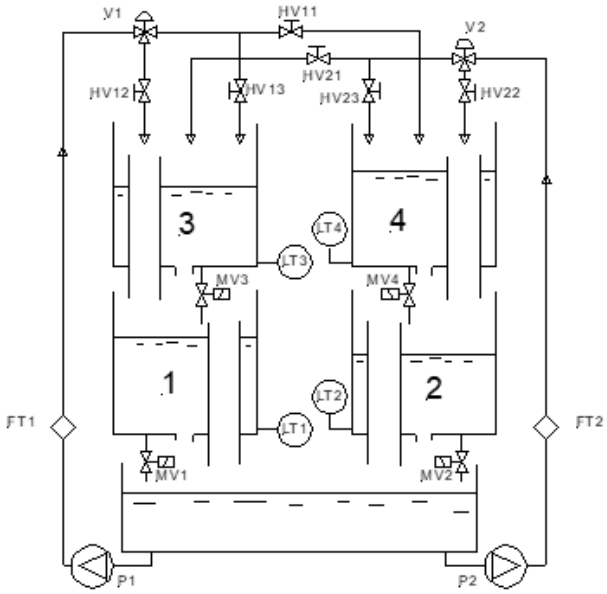
Based on experimental data design an up-scaled bed with the overall theoretical capacity 500 times that of the pilot unit and 95 % column utilization.

Exercise: 12A	**Process control – 2 tank**
Half-day	Type: Basic transport phenomena

Purpose:

This exercise investigates the effect of different disturbances on the liquid levels in two serially connected tanks, initially in steady state, and to investigate the effect of PID control used to maintain steady state when the system is disturbed.

Bode diagrams created by Matlab/Python code are used to represent frequency response characteristics of a transfer function model.



Exercise unit:

Four tanks can be supplied individually with liquid. The liquid flow can be controlled manually by hand-operated valves. Feed pumps are controlled by a user interface on the computer. The liquid to the lower tanks can also be decided by an overflow from the upper tanks. The flow through the pumps and the liquid level in the tanks are recorded by the computer and displayed on the screen. The collected data is stored in a logfile.

User interface:

Manual control and local PC based data collection.

Main reporting subjects:

Using the results from the exercise to investigate various parts of the process dynamics.

Derive a second order differential equation to describe the level height in the lower tank. Make an optimization algorithm which optimizes the gain K and time constant α, so the numerical solution fits the experimental data.

Make Bode diagrams for the upper and lower tanks using the transfer function given in the manual with the found gain and time constants.

Discuss the influence of the different controller parameters and disturbances in the experiments and recommend the optimal controller parameters. V

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Exercise: 13A	**Organic synthesis**
Full day	Type: Traditional technical chemical unit operation

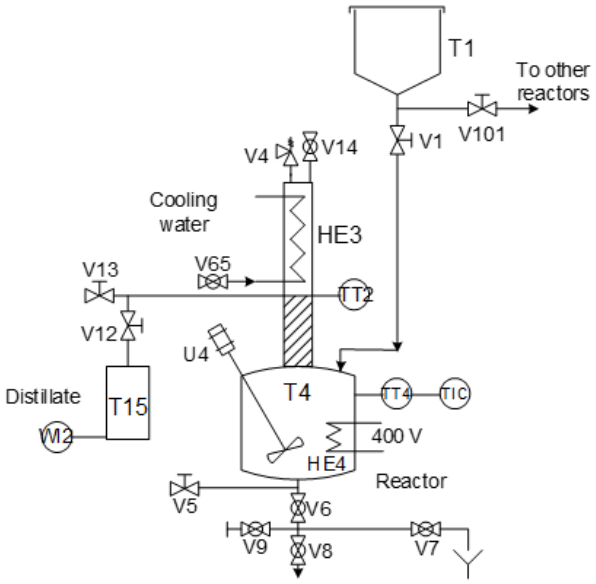
Purpose:

The exercise involves conducting a large-scale esterification batch process based on the reaction between formic acid and methanol, with sulfuric acid serving as a catalyst. The objective is to produce methyl formate as the final product. The yield, reaction equilibrium, and kinetics are determined. Special attention is given to safety precautions during this exercise.

The synthesis plant is designed as a multipurpose, flexible unit capable of handling various reactions under different conditions. However, only a part of the plant is used for this specific exercise. Stirrer motors are pneumatically driven, all vessels and pipes can be flushed with nitrogen to eliminate the risk of explosions or fire, and all components are grounded to prevent the buildup of static electric charges.

Exercise unit:

The P&I diagram illustrates the main part of the plant, including the feed vessel (T1) and the reactor (T4), which consists of a 20-liter spherical glass bowl where the esterification takes place. A rectifying column is positioned above the reactor, with a water-cooled condenser at the top.



The formed methyl formate exits through a pipe located between the rectifier and the condenser and is collected in a tank placed on a scale.

User interface:

Manual control and local PC based data collection.

Main reporting subjects:

Methanol-methyl formate composition formation is plotted in a T-xy diagram.

Mass balance, process yield, product purity and the reaction equilibrium constant for the process.

Use ΔG and the Gibbs-Helmholtz equation to compare experimental and theoretical equilibrium constant.

Propose a flow diagram and reactor type and process conditions for a continuous process.

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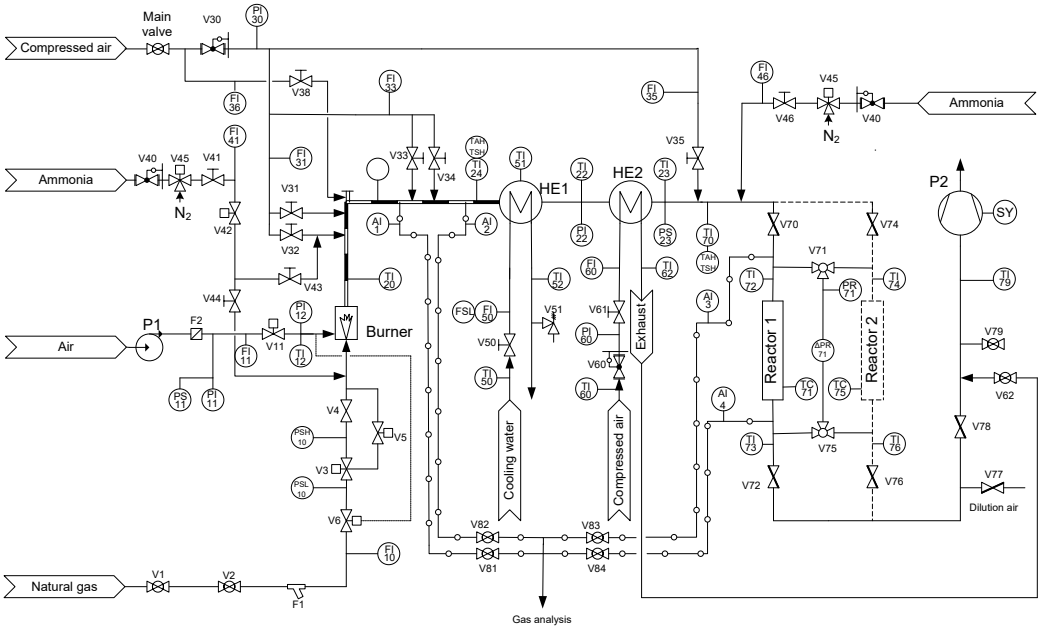
Exercise: 13C	**High temperature processes**
Full day	Type: Traditional Technical Chemical Unit Operations

Purpose:

Demonstration of various high temperature processes, technologies, methods and equipment, including burner design and operation, high temperature heat exchange process, and combustion gas analysis.

Exercise unit:

The unit contains a gas burner, a combustion chamber, a heat exchanger battery with a gas/liquid exchanger followed by a gas/gas exchanger and a Selective Catalyst Reduction catalyst unit using ammonia for NO_x removal. The plant is connected to the gas analyzer system. Gas flow and temperatures can be controlled. There are 4 points for gas sampling. Various interlocks and alarms are provided to ensure safe operation.



User interface:

Manual control and local PC based data collection.

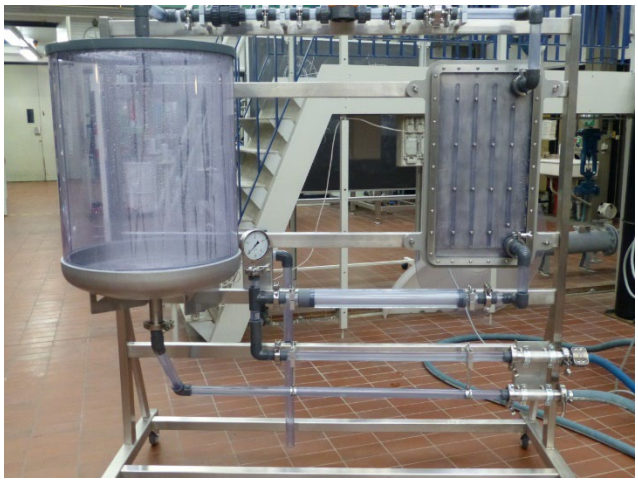
Main reporting subjects:

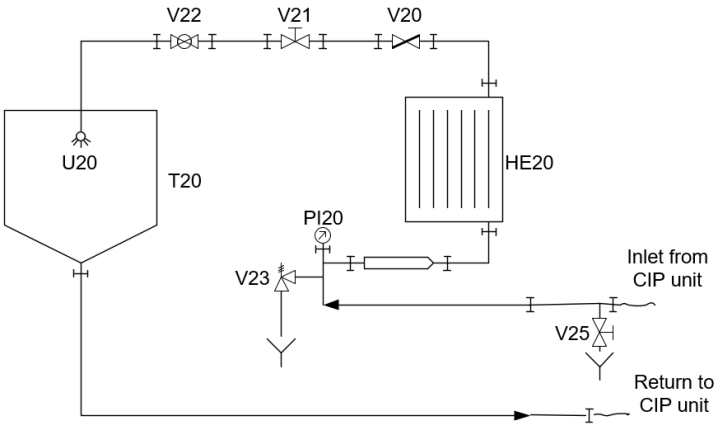
Graph of the flue gas composition and the combustion temperature.
Experimental and theoretical heat transfer numbers (U and h) and specific heat loss for heat exchangers.
Comparison of combustion temperature with expected adiabatic flame temperature at actual condition

Exercise: 13D	**Cleaning in Place (CIP)**
Full day	Type: Biotechnical chemical unit operation

Purpose:

The Pilot Plant mobile CIP unit is connected to a model process plant which consist of various simulated types of industrial equipment; tank, piping, valves, heat exchanger. Mustard is applied at strategic places inside the equipment to simulate dirt. The exercise will perform different CIP procedures varying the liquid flow, temperature and cleaning chemicals. Evaluation of cleaning efficiency is done visually.





Exercise unit:

The unit consists of a mobile CIP unit (not shown in picture or P&I diagram) to provide the cleaning fluid to a model plant which simulates different industrial equipment and components which typically are difficult to clean, including a tank with a spray nozzle, different valves and pipe sections and a simulated heat exchanger. In various spots of the plant, it is possible to apply dirt (mustard). The model plant constructed in transparent plastic (PVC) to facilitate the visual progress of the cleaning process and to help identify critical hygiene issues. A special metal plate with chequered pattern is covered with mustard in a specific thickness and inserted into a pipe section. After the cleaning sequences the cleaning efficiency is evaluated based on the exposed metal surface.

User interface:

Manual control and data collection.
A video presentation of the exercise and its details is available as a supplement to the written manual.

Main reporting subjects:

This is a very “qualitative” exercise, and few calculations are made (Re numbers).
A comparison of cleaning efficiency of all tests is done based on visual observations.
An ideal CIP sequence for a complex bioprocess cleaning situation is suggested based on observations.
Hot spots (Hard to clean areas) are identified, and design improvement suggestions are made.
A narrative about cleaning chemistry is to be included based on literature study.

Exercise: 14A	**Fermentation**
2 full days	Type: Biotechnical chemical unit operation

Purpose:

In this two-day exercise, mass transfer experiments, sterilization, and batch cultivation of the yeast *Saccharomyces cerevisiae* ("baker's yeast") will be done. The exercise includes assembling, sterilization, starting, and operating a 50-liter pilot scale fermenter.

During the process, optical density (OD), dry weight (DW), glucose (substrate), ethanol (product), and off-gas concentrations (CO_2) will be monitored to assess mass transfer efficiencies and volumetric mass transfer coefficients as a function of mixing and aeration.

For course 28123 "4 weeks Summer University for International Students", two student teams will collaborate to do the two days exercise. Two reports will be generated: one for mass transfer experiments and one for the fermentation results. Each team will submit their separate reports.

Exercise unit:

The exercise will be performed in one of our modern Sartorius 50 liters bioreactors with its advanced local PLC control system.

User interface:

Local PLC and data acquisition.

Main reporting subjects:

Calculation of sterilization efficiency.

Examination of aeration (DO) and stirring. Calculation of experimental Kla and comparison to online data.

Determination of specific growth rate, max. growth rate and yields.

Observation and discussion of the physiological phenomenon in yeast, named the Crabtree effect.

Exercise: 15A	**Homogenization – High pressure cell rupture**
Full day	Type: Biotechnical chemical unit operation

Purpose:

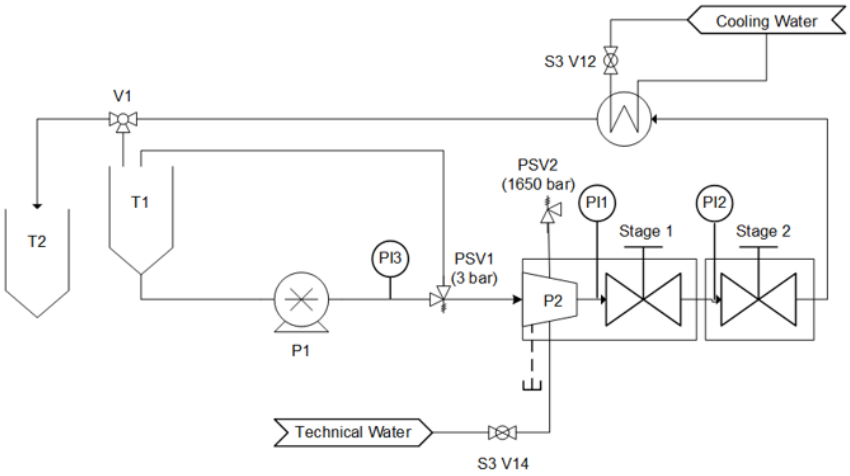
Demonstrate the effectiveness of high-pressure homogenization in disrupting cells using a bakers yeast suspension. Under varying pressures (100 - max. 1500 bar), examine the extent of cell disruption and the release of intracellular components under controlled conditions.

Lab tests include microscopy and cell counting to quantify cell disruption, dry cell mass measurement to assess solids content, and protein quantification using the Bradford assay to evaluate the efficiency of intracellular release.

Exercise unit:

The unit consists of a feed tank (T1). A pump (P1) transports the suspension to the compression head, operating at a maximum pressure of 3 bar. In the compression chamber, the pressure is increased to a maximum of 1500 bar using a ceramic multistage piston pump (P2).

The pressurized liquid first passes through the primary homogenization valve (Stage 1), where the pressure is monitored at PI1. It then flows through the secondary homogenization valve (Stage 2), with pressure monitored at PI2, before exiting the pressure chamber at ambient pressure. A cooling coil can be used to cool the sample before it is either recirculated to Tank T1 or harvested into an external tank (T2).



User interface:

Manual control and data acquisition. Various lab exercises are included.

Main reporting subjects:

Determine impact force in the cells and % of killed cells at different pressures. Discuss the necessary force to cause cell disruption.

Based on the velocity calculating the slit width as well as the acceleration of the cells of the 4 different pressure setpoints. Calculate protein release based on given cell composition given.

Design of homogenization unit for given large scale feed.