280.371 Process Engineering Operations

Evaporation 1

Professor Marie Wong

Overview

- Common theme for evaporation and drying: removal of water by thermal vapourisation, i.e. thermal concentration
- Major unit operation in process industries
- Governed by heat and mass transfer
- Extends & integrates 2nd year material on
  - Mass & energy balances
  - Heat transfer
  - Mass transfer
  - Fluid mechanics

Learning objectives

You should be able to:

- Provide a justification for the selection of equipment for evaporation in a given processing situation

- Describe the major components and operation of single and multiple-effect evaporation systems

- Describe key mechanisms governing evaporator performance and the impacts of changes in feed, product or operating parameters on evaporator operation and energy efficiency

- Perform simple mass and energy balances for single and multiple-effect evaporation systems

Definition – Evaporation

- Evaporation is a process in which:
    - one or more volatile components are separated from a liquid mixture
    - by thermal vapourisation (and subsequent vapour condensation)
    - to provide a concentrated liquid product

- Sometimes condensed vapour
    - is the 1° product, e.g. potable water from seawater
    - is added back to the product, e.g. aroma recovery

MASSEY UNIVERSITY

Evaporation in the kitchen

Boiling water

Evaporation in the kitchen

Reduction of a Sauce

See the ring on the interior of the pan indicating the sauce has reduced by half

Evaporator → Dryer →

Evaporator →

Evaporators in Industry

What does an industrial evaporator look like?
How big is an industrial evaporator?
Are there different types?
Do different types have different names?
How do they work?
Where does the heat come from?

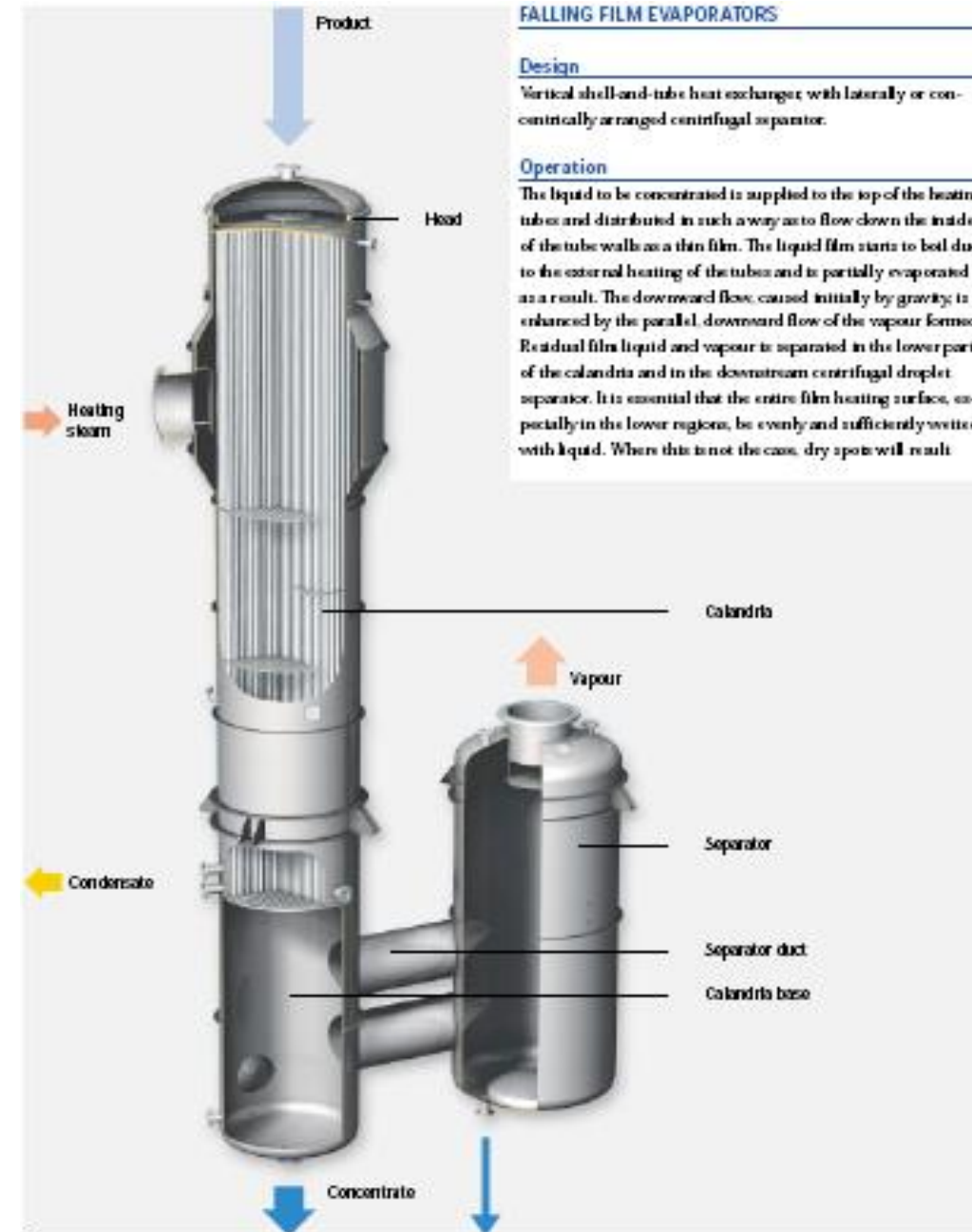How do we work out the size of an evaporator for a particular job?
What do we need to know to solve "evaporator problems"?

What you will learn:
- How evaporators work
- Familiarity with the symbols we use, and their units
- How to do Mass balances and Energy balances
- Familiarity with Mass balance and Energy balance questions
- Familiarity with steam tables
- Familiarity with different ways of drawing diagrams
- How to estimate boiling point elevation (Dühring Chart)

Industrial evaporator

The evaporator on the right is a **"falling film evaporator"**

Some evaporators have more than one stage, called an "effect".

In a multiple effect evaporator, the pressure changes.

Pressure is highest in the first effect and lowest in the last effect.

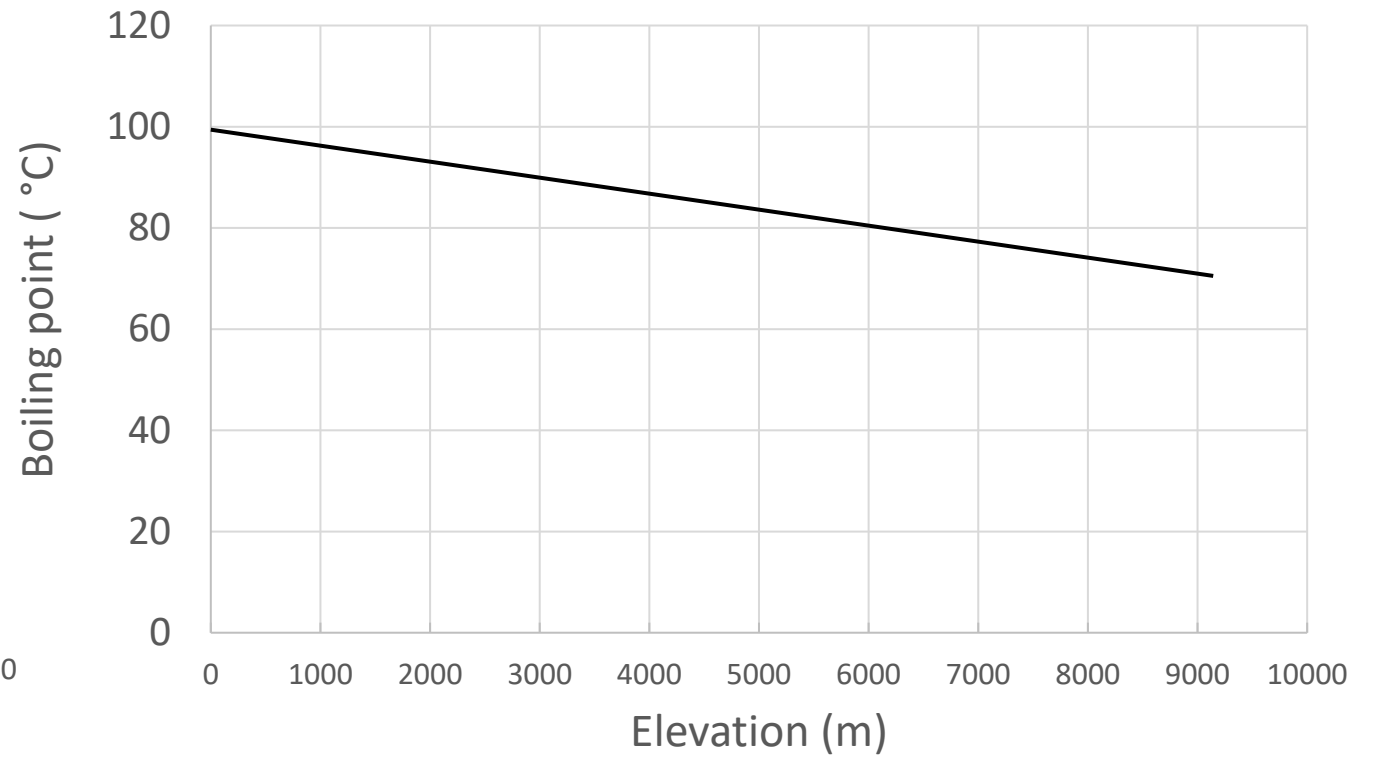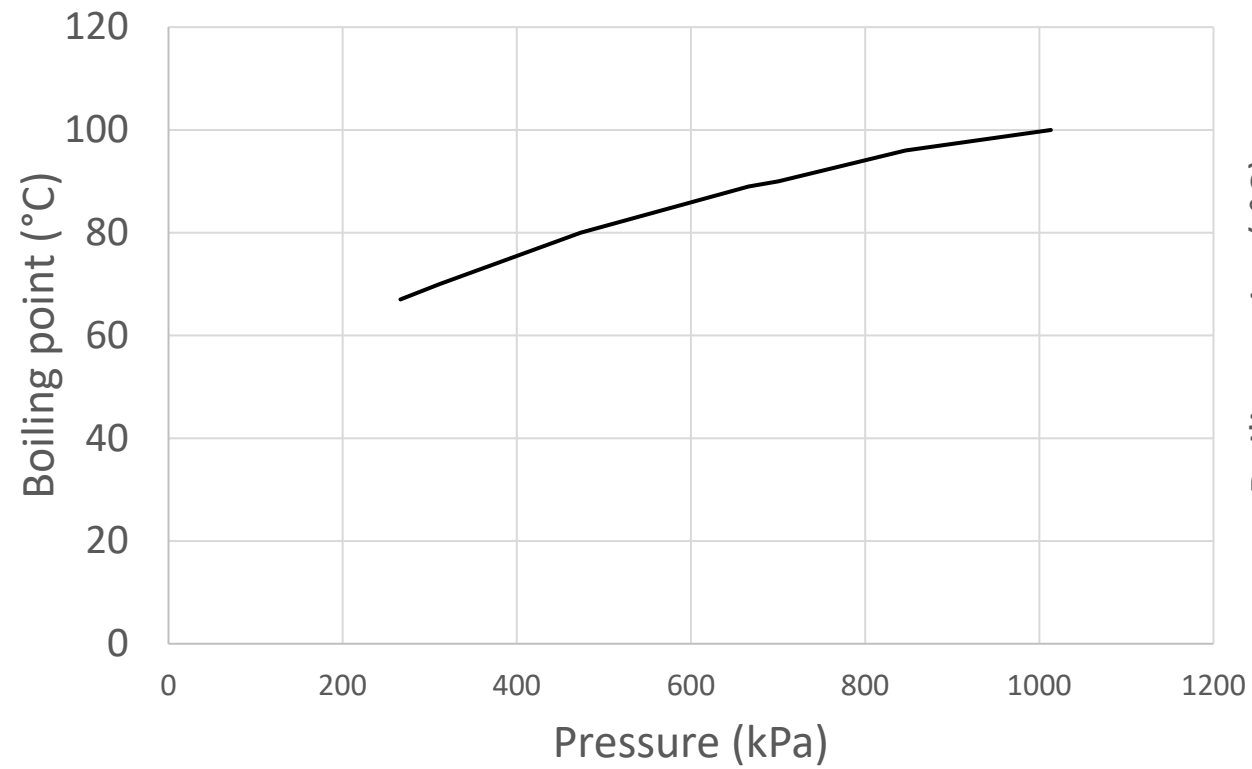In industry, evaporators can have up to 8 effects.
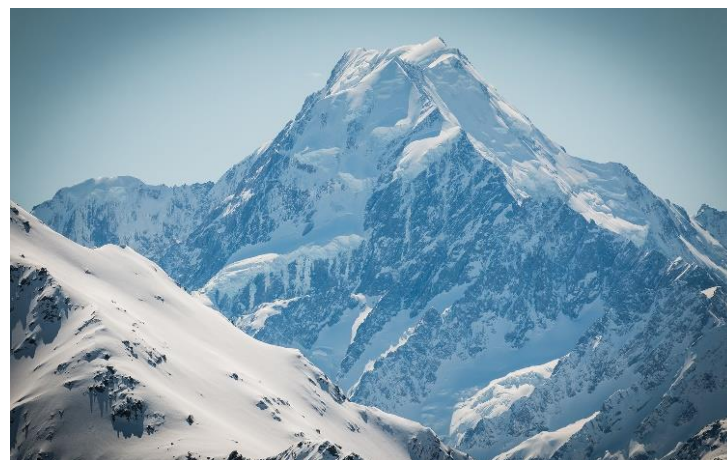

Multiple effect evaporators

Evaporation in the kitchen

Boiling water
- At atmospheric pressure

Mount Everest
8848 m

Aoraki/ Mount Cook
3724 m

Mount Kinabalu
4095 m

Massey University
STEAM TABLES

3 Saturated Data

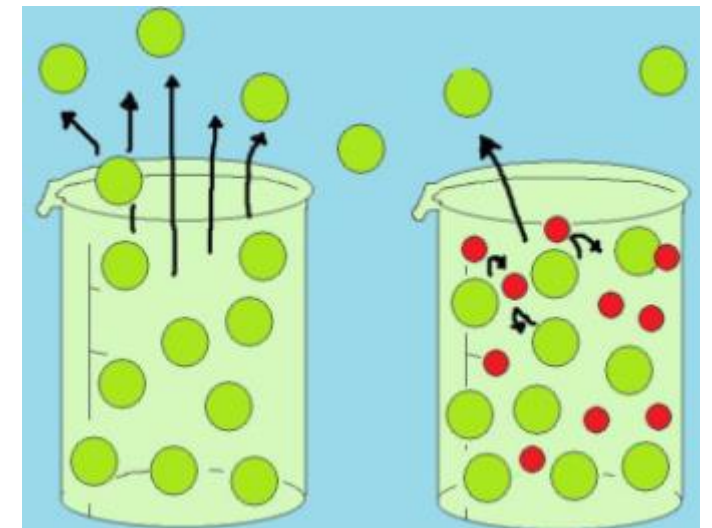| P	θ_{sat}	v_l	v_v	u_l	u_v	h_l	$\Delta(h_{vap})$	h_v	s_l	s_v
MPa	°C	m³/Mg		kJ/kg			kJ/kg		kJ/(kgK)	
0.0010	6.970	1.000	129178	29.30	2384	29.30	2484	2514	0.106	8.975
0.0015	13.02	1.001	87959	54.68	2393	54.68	2470	2525	0.196	8.827
0.0020	17.49	1.001	66987	73.43	2399	73.43	2459	2533	0.261	8.723
0.0025	21.08	1.002	54240	88.42	2404	88.42	2451	2539	0.312	8.642
0.0030	24.08	1.003	45653	101.0	2408	101.0	2444	2545	0.354	8.576
0.0035	26.67	1.003	39466	111.8	2411	111.8	2438	2550	0.391	8.521
0.0040	28.96	1.004	34791	121.4	2415	121.4	2432	2554	0.422	8.473
0.0045	31.01	1.005	31131	130.0	2417	130.0	2427	2557	0.451	8.431
0.0050	32.87	1.005	28185	137.7	2420	137.7	2423	2561	0.476	8.394
0.0060	36.16	1.006	23733	151.5	2424	151.5	2415	2567	0.521	8.329
0.0070	39.00	1.008	20524	163.3	2428	163.4	2408	2572	0.559	8.274
0.0080	41.51	1.008	18099	173.8	2431	173.8	2402	2576	0.592	8.227
0.0090	43.76	1.009	16199	183.2	2434	183.3	2397	2580	0.622	8.186
0.010	45.81	1.010	14670	191.8	2437	191.8	2392	2584	0.649	8.149
0.011	47.68	1.011	13412	199.6	2440	199.7	2388	2587	0.674	8.115

Add sugar
boiling point
changes

Add sugar
boiling point
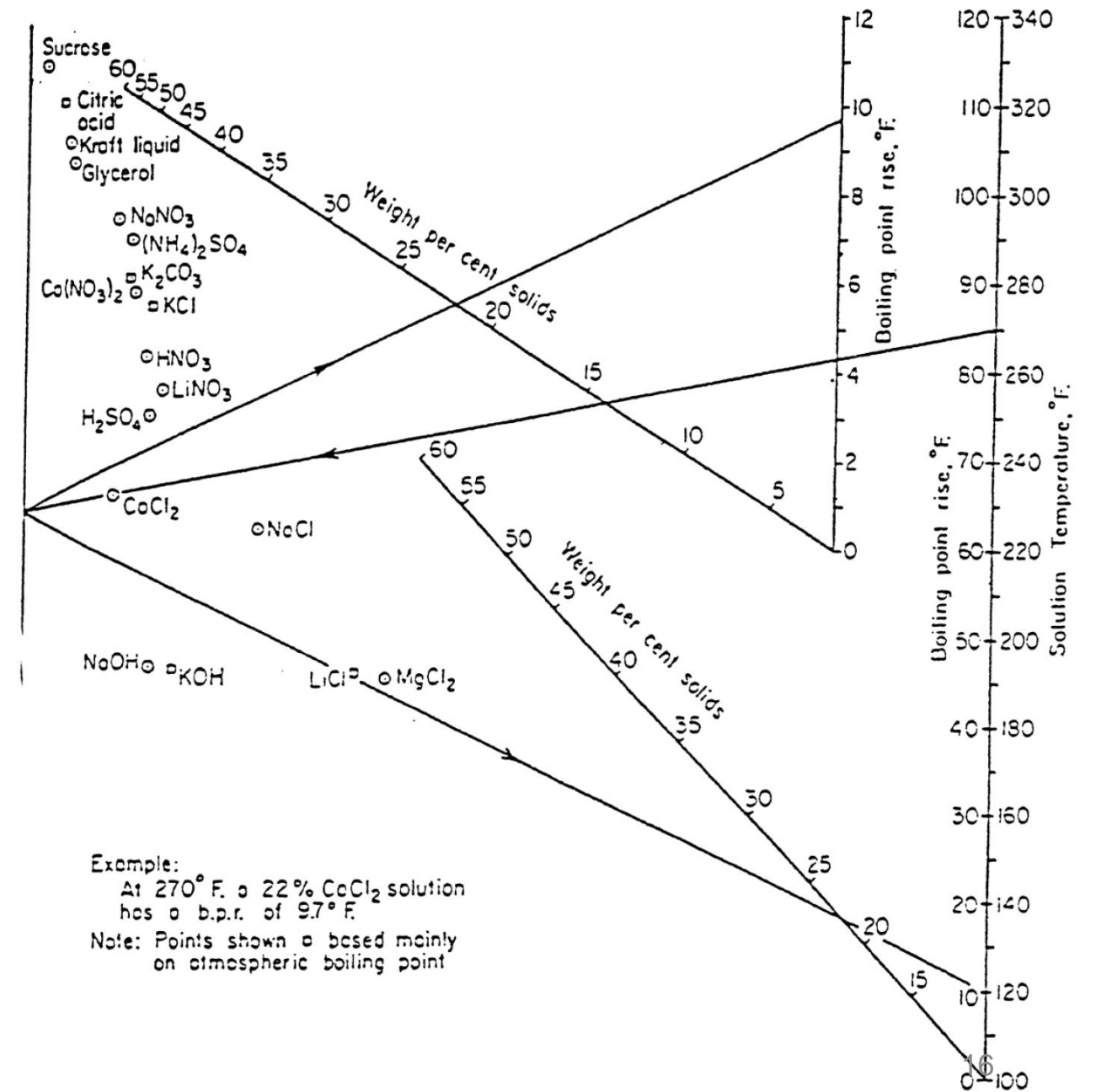changes

Colligative property
- boiling point elevation

Pure solvent   Solvent + solute

Calculate boiling point change

Rationale for using Evaporation

- Reduce volume, hence bulk & weight
- Improve product stability - Reduced a_w
- Improve energy efficiency prior to drying
- Increase concentration to promote crystallisation
- Vacuum operation common for heat sensitive materials

Applications

- Food industry
  - Concentration of liquid streams in dairy, starch, sugar, juice, and gelatine industries
- Chemical industry
  - Concentration of chemical and salt solutions, e.g. NaOH, KOH, $CaCl_2$
  - Removal & recovery of solvents
- Environmental
  - Minimization of effluent volumes in e.g. pulp & paper, brewing, chemical and pharmaceutical industries
- Production of potable/distilled/boiler water

Alternatives

- Water (solvent) could be removed as
  - Solid
    - Freeze concentration
  - Liquid
    - Membrane processes
    - Limited by maximum solute concentrate <30 – 40%
    - Energy efficient
  - Vapour
    - Dryers
    - Drying produces a solid product suitable for sale; however it is not very energy efficient at low solute concentrations

System components

- Feed system
  - Pump(s) ± pre-heaters
- Heat supply for evaporation
  - Usually, saturated steam
  - Steam (vapour) reuse systems commonly used
- Heat exchanger (calandria)
  - Produces 2-phase mixture: vapour + more concentrated liquid
- Vapour-Liquid separator
- Condensor
  - May assist vacuum operation
  - Additional means of removing non-condensable gases

MASSEY UNIVERSITY

Additional Costs

- Large heat transfer areas

- Provision of cooling water for vapour condensation and disposal of this stream

- Recovery of volatile flavour and aroma compounds

Steam

- Preferred heating medium

- Relatively cheap

- Temperature is controlled with pressure

- Good film heat transfer coefficients

- Compatible with other energy requirements of the process plant

Undesirable Changes
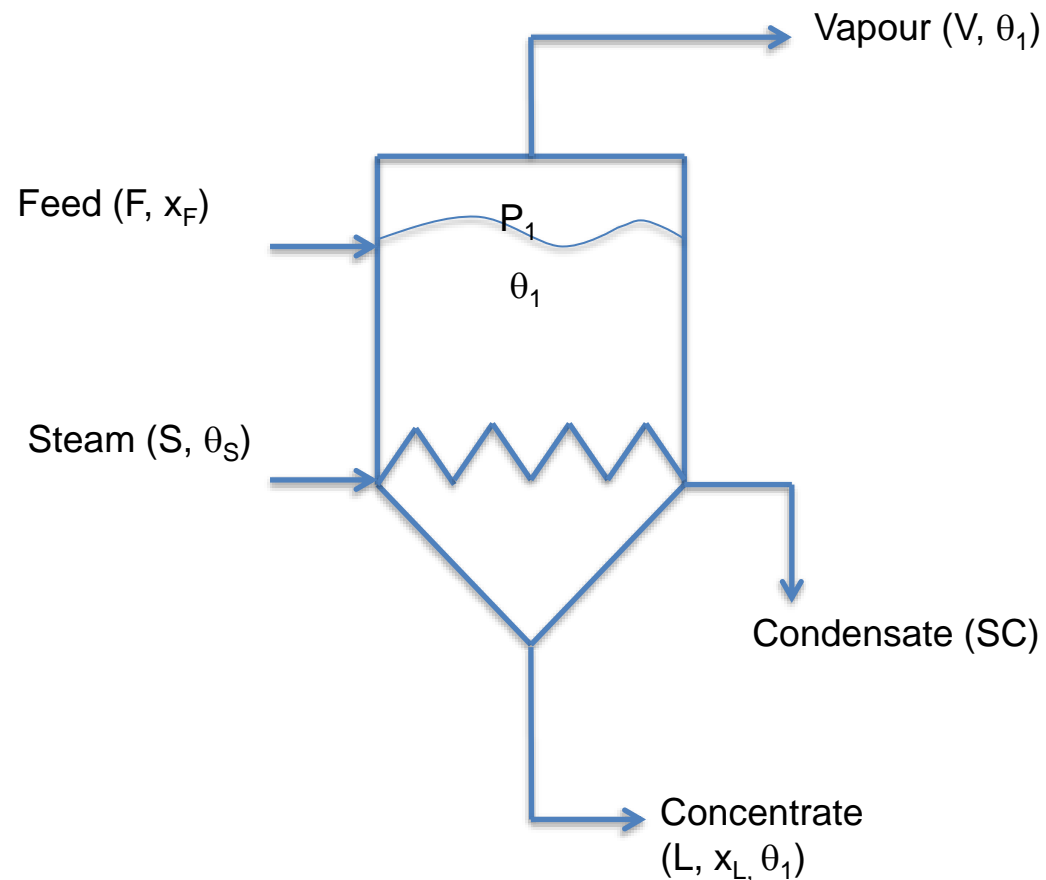
- Changes in colour, functionality, flavour changes

Minimised by operating at temperatures <100°C

- Operating under vacuum
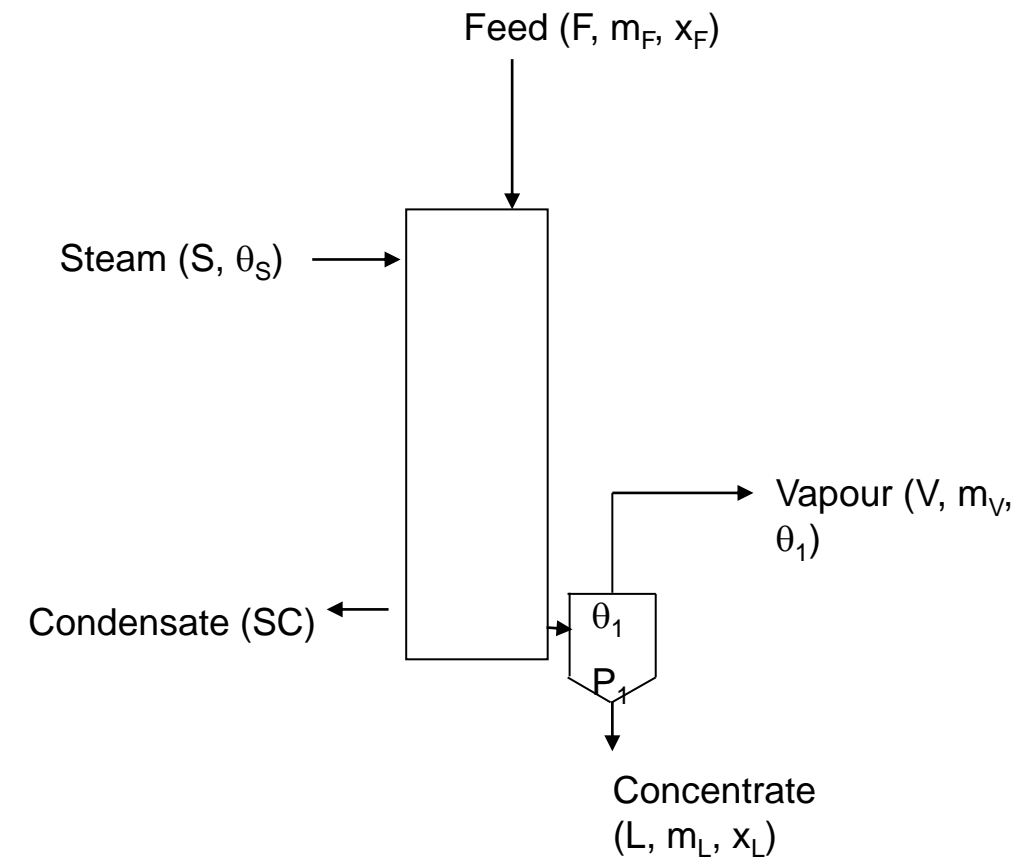- Maximum operating temperature 70 – 80 ^{o}C

Single effect (stage) evaporator.

Heat exchanger and V-L separator in one unit.

Heat exchanger and V-L in separate units.

Mass & energy balance – single effect

- Assumptions
  - Assume feed enters at its boiling point (neglect sensible heat effects)
  - Neglect variation of latent heat of water with temperature & pressure
  - No heat losses
  - Negligible heats of mixing & dilution
  - No leakages or losses of liquid in vapour stream
  - Negligible flow of non-condensable

Nomenclature

ϕ - rate of heat transfer (Watts or J s^{-1}) $\equiv$ q

θ - temperature (^{o}C)

P – pressure (Pa, mmHg)

U – overall heat transfer coefficient (W m^{-2} K^{-1})

h – enthalpy (J kg^{-1})

h_{fg} - latent heat of evaporation

x - mass fraction

m - Mass flow rate *(kg s^{-1} , kg h^{-1})*

Feed (F), Concentrate (L), Vapour (V), Steam (S),   Steam condensate (SC)

Mass Balances – steady state

- *Solute mass balance (assuming that no solute is carried over with the vapour)*

$$m_F x_F = m_L x_L \quad (1)$$

- *Overall mass balance*

$$m_F = m_L + m_V \quad (2)$$

MASSEY UNIVERSITY

Energy Balance

total heat entering = total heat leaving

$$m_F h_F + \phi = m_L h_L + m_V h_V \qquad (3)$$

Remember

$$\phi = m_S (h_S - h_{SC}) = m_S h_{fg} \qquad (4)$$

if the feed enters at the boiling point then $h_F \approx h_L$ and $h_V \approx h_L + h_{fg}$ so combining equations 2 and 3 we get:

$$\phi \approx m_V h_{fg} \qquad (5)$$

MASSEY UNIVERSITY

- HE sized in usual way

$$\phi = UA(\theta_S - \theta_1) \qquad (6)$$

U = overall heat transfer coefficient (W/m^{2}K)

    = f(system, liquid properties)

A = heat transfer area (m^2)

    = a major determinant of capital cost

θ_S = *temperature of inlet steam (*^{o}*C)*

θ_1 = *temperature of boiling liquid (*^{o}*C)*

Measures of Efficiency

- Energy efficiency can be reported as:

  - Evaporation heat input relative to total energy

$$\eta = \frac{m_V h_{fg\ vapour}}{\phi}$$

(7)

  - Steam economy

$$\eta_s = \frac{m_v}{m_s} = \frac{m_v}{\phi/h_{fg\ steam}}$$

(8)

Use SI Units when solving Problems

Convert units first where necessary, then proceed with the problem.

MASSEY UNIVERSITY

Question 1: Mass and energy balances on a single stage evaporator.

A 10wt% aqueous lactic acid solution (470 kg/hr) at 36°C is concentrated to 30wt% solution in a steam heated evaporator. Solvent vapour (steam) and concentrated solution leave the evaporator at 46°C and 10 kPa absolute. The steam heat source is at -61 kPa gauge. Assume c_p liq = 4 kJ/(kg.K).

(a)   Calculate the amount of concentrated lactic acid produced, the amount of solvent (steam) vapourised and the amount of heat supplied in the evaporator heat exchanger.

(b)   What size heat exchanger would be required if the overall heat transfer coefficient is 2000 W/(m².K) ?

(c)   How much -61 kPa gauge steam was consumed to provide the necessary heat? What is the energy efficiency and steam economy?

(d)   How much heat must be removed to condense the solvent vapour produced at 10 kPa ? How much 25°C water would need to be injected into a direct contact heat exchanger (at 10 kPa absolute) to condense the steam ?

Question 2: Mass and energy balances on a single stage evaporator.

A 50 m² heat exchanger is currently used in an evaporator to concentrate 0.72 kg/s of waste slurry from 20 wt% to 50wt% solids. The feed enters at its boiling point of 80°C and is heated with 20 kPa gauge steam .

(a)   Calculate the amount of concentrated waste produced, the amount of steam vaporised and the amount of heat supplied in the evaporator heat exchanger. What is the overall heat transfer coefficient of the heat exchanger ?

(b)   It is desired to process 20% more feed. What will be the new outlet solids concentration if the pressures are unchanged ? What pressure steam would be required to keep the outlet solids concentration at 50wt% ?