Energy in technical and biological systems
WS 2017-2018

Lecture 5

Digestion and utilisation of biogas

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Typical examples → Biogas plant

Source: www.haase-energietechnik.de
HAASE Biogasanlage auf Gut Söder mit einer elektrischen Leistung von 700 kW aus der Vergärung von Schweinegülle, Roggenkorn und Maissilage

Typical examples → Sewage sludge digestion Sewage gas

Source: www.lenntech.com/.../ sludgestabilisation.htm

Typical examples

→ **Sewage sludge digestion**
Sewage gas

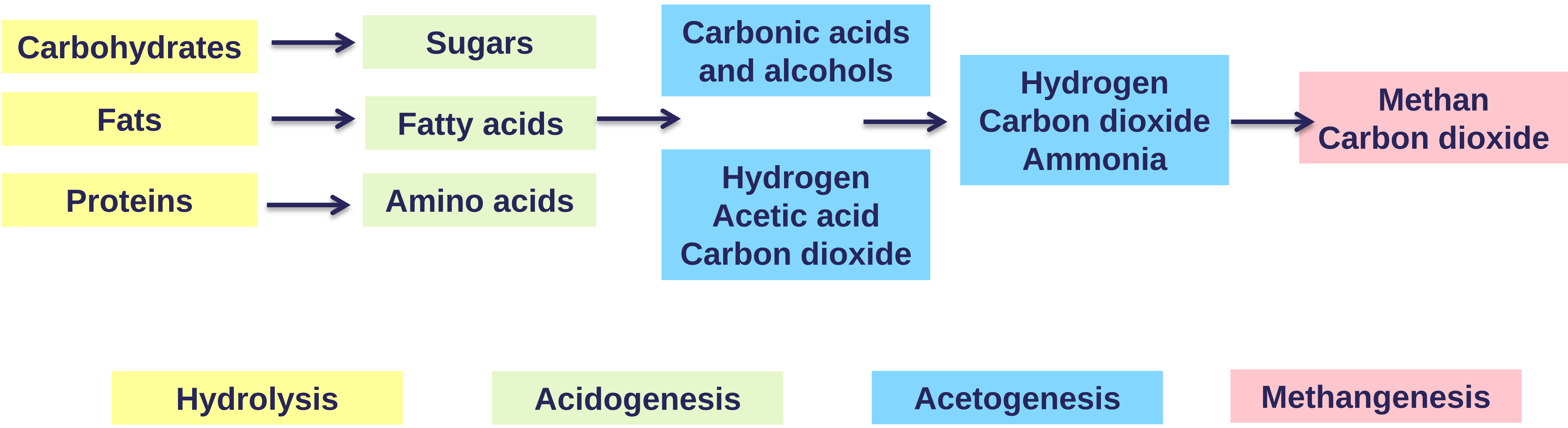
Egg-shaped ???

Source: www.lenntech.com/.../ sludgestabilisation.htm

Typical examples → Landfill gas

Source: www.u-t-b.de/.../ gasturbine-loerrach.php
Deponie Scheinberg

Key process stages of anaerobic digestion



Simplified generic chemical equation for the overall processes:

$$C_6H_{12}O_6 \rightarrow 3\,CO_2 + 3\,CH_4$$

Key process stages of anaerobic digestion

In most cases, biomass is made up of large organic polymers. For the bacteria in anaerobic digesters to access the energy potential of the material, these chains must first be broken down into their smaller constituent parts. These constituent parts, or monomers, such as sugars, are readily available to other bacteria. The process of breaking these chains and dissolving the smaller molecules into solution is called **hydrolysis**. Therefore, hydrolysis of these high-molecular-weight polymeric components is the necessary first step in anaerobic digestion. Through hydrolysis the complex organic molecules are broken down into simple sugars, amino acids, and fatty acids.

Acetate and hydrogen produced in the first stages can be used directly by methanogens. Other molecules, such as volatile fatty acids (VFAs) with a chain length greater than that of acetate must first be catabolised into compounds that can be directly used by methanogens.

The biological process of **acidogenesis** results in further breakdown of the remaining components by acidogenic (fermentative) bacteria. Here, VFAs are created, along with ammonia, carbon dioxide, and hydrogen sulfide, as well as other byproducts. The process of acidogenesis is similar to the way milk sours.

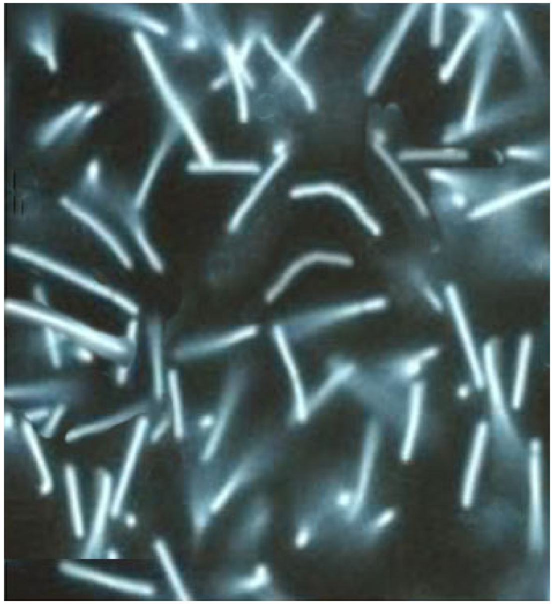
The third stage of anaerobic digestion is **acetogenesis**. Here, simple molecules created through the acidogenesis phase are further digested by acetogens to produce largely acetic acid, as well as carbon dioxide and hydrogen.

The terminal stage of anaerobic digestion is the biological process of **methanogenesis**. Here, methanogens use the intermediate products of the preceding stages and convert them into methane, carbon dioxide, and water. These components make up the majority of the biogas emitted from the system. Methanogenesis is sensitive to both high and low pHs and occurs between pH 6.5 and pH 8. The remaining, indigestible material the microbes cannot use and any dead bacterial remains constitute the digestate.

Key process stages of anaerobic digestion

Hydrolysis | Acidogenesis | Acetogenesis | Methangenesis

Bacteria: Acetogens | Methanogens



Source: wikipedia

- Sensitive to environmental conditions !!!
- Choice of process parameters (temperature, pressure, pH-value) with respect to methanogens
- Methanogenesis is the slowest process step.

Optimal process parameters

Methanogens

Different species of bacteria are able to survive at different temperature ranges:

15 to 20°C: psychrophile or psychrophilic bacteria.

35 to 40°C: mesophiles or mesophilic bacteria.

55 to 60°C: thermophiles or thermophilic bacteria.

by operational experience → **Mesophiles**

- Pesticide
- Antibiotics
- Disinfectants

- anaerobic conditions
- absence of gaseous oxygen
- pH = 6.5 to 7.5
- Temperature = 35°C

Properties of biogas

$$\underbrace{C_6H_{12}O_6 \rightarrow 3\,CO_2 + 3\,CH_4}$$

Methan
Carbon dioxide

Biogas

$$CH_4 \quad \sim 66\,\%$$

$$CO_2 \quad \sim 33\,\%$$

$$H_2S, NH_3, O_2, H_2 \quad 0.1 - 1\%$$

Lower Heating Value $\quad \mathrm{LHV} \quad 6.7\,\dfrac{\mathrm{kWh}}{m^3_{Standard}}$

Pure Methane $\quad \mathrm{LHV} \quad 10.0\,\dfrac{\mathrm{kWh}}{m^3_{Standard}}$

Lower heating value

1 m³ of biogas = x litre of petrol

Lower Heating Value (LHV) of biogas:	**6.7 kWh/m³**
Lower Heating Value (LHV) Petrol:	**43,5 MJ/kg = 12,0 kWh/kg**
Density of petrol:	**ρ = 726 kg/m³**

Lower heating value

1 m³ of biogas = x litre of petrol

Lower Heating Value (LHV) of biogas:	6.7 kWh/m³
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Density of petrol:	ρ = 726 kg/m³

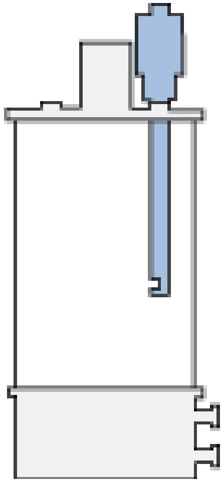
$$6.7\,\frac{\text{kWh}}{\text{m}^3}\Big/12.0\,\frac{\text{kWh}}{\text{kg}} = 0.56\,\frac{\text{kg}}{\text{m}^3} = \frac{0.56}{0.726}\,\frac{\text{liter}}{\text{m}^3} = 0.77\,\frac{\text{liter}}{\text{m}^3}$$

1 m³ of biogas = 0.77 litre of petrol

Kinetics of chemical reactions

$$C_6H_{12}O_6 \rightarrow 3\,CO_2 + 3\,CH_4$$

Substrate + **Bacteria** ⟶ **More Bacteria** + **Product**



Laboratory fermenter

Kinetics of chemical reactions

$$C_6H_{12}O_6 \rightarrow 3\,CO_2 + 3\,CH_4$$

Substrate + **Bacteria** ⟶ **More Bacteria** + **Product**

Monod* **bacterial growth rate (i.e. cell division rate):**

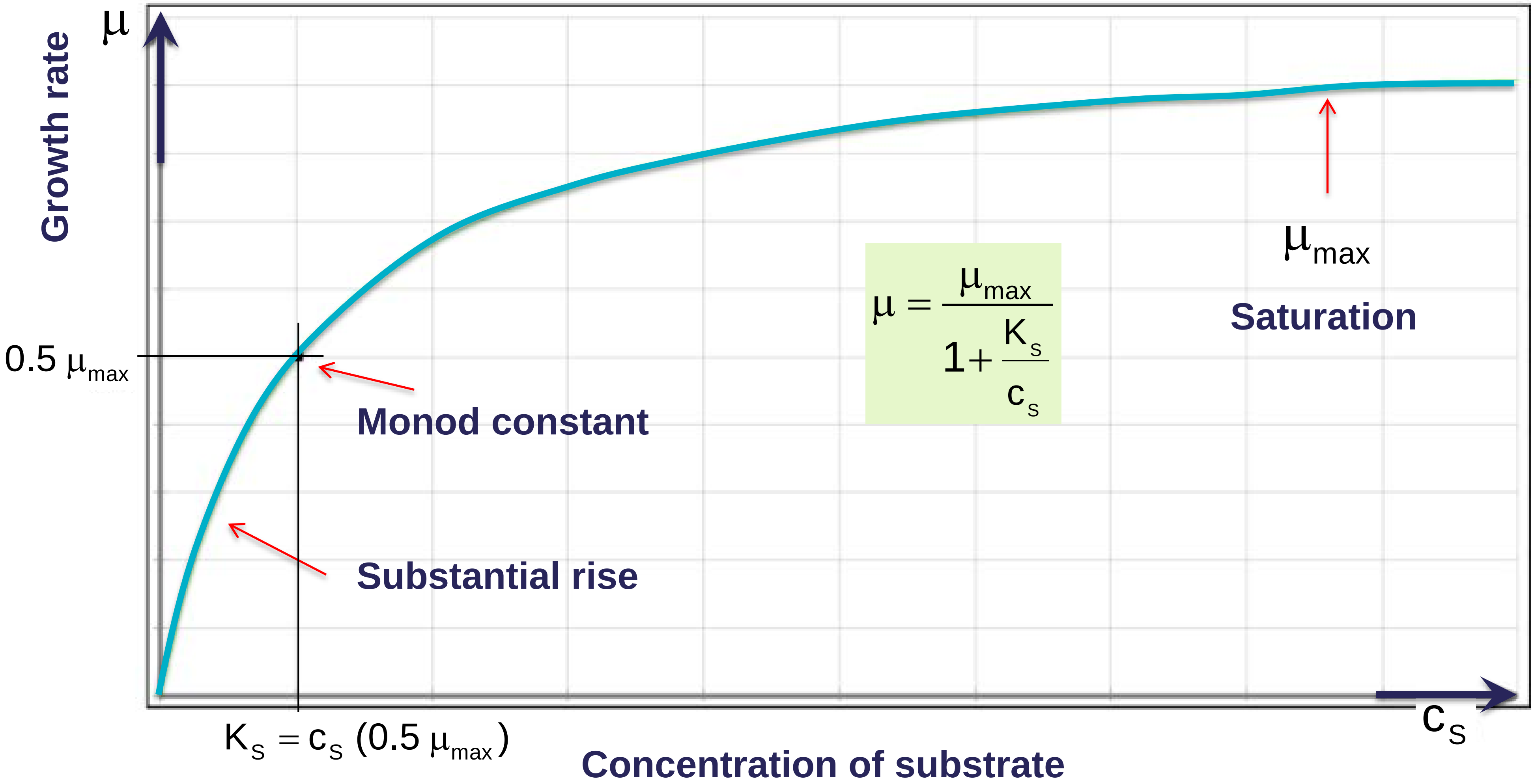
Empirical equation

$$\mu = \frac{\mu_{max}}{K_S + c_S} \cdot c_S \qquad [\mu] = \left[\frac{1}{s}\right] \qquad [c] = \left[\frac{mg}{l}\right]$$

$$\mu = \frac{\mu_{max}}{1 + \frac{K_s}{c_s}}$$

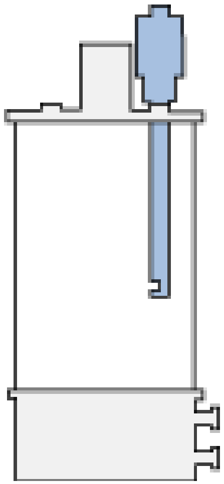
****Jacques Monod (1949)***

Monod bacterial growth



Substrate utilisation vs. bacteria growth

Substrate + **Bacteria** → **More Bacteria** + **Product**



Laboratory fermenter

Substrate utilisation

Substrate + **Bacteria** ⟶ **More Bacteria** + **Product**

The rate of substrate utilisation is a function of the substrate concentration.

The rate of substrate utilisation is proportional to the concentration of the bacteria present .

$$-\frac{d}{dt}c_S = \frac{1}{Y_{B/S}} \cdot \mu \cdot c_B$$

Yield coefficient

$$Y_{B/S} = -\frac{\mu \cdot c_B}{\frac{d}{dt}c_S}$$

More bacteria

$$Y_{B/S} = -\frac{\mu \cdot c_B}{\Delta c_S}$$

Substrate utilisation

Substrate utilisation vs. bacteria growth

Substrate + **Bacteria** ⟶ **More Bacteria** + **Product**

More bacteria

Yield coefficient

$$Y_{B/S} = -\frac{\mu \cdot c_B}{\Delta c_S}$$

Substrate utilisation

Typical value

$$Y_{B/S} \approx 0.03 = 3\%$$

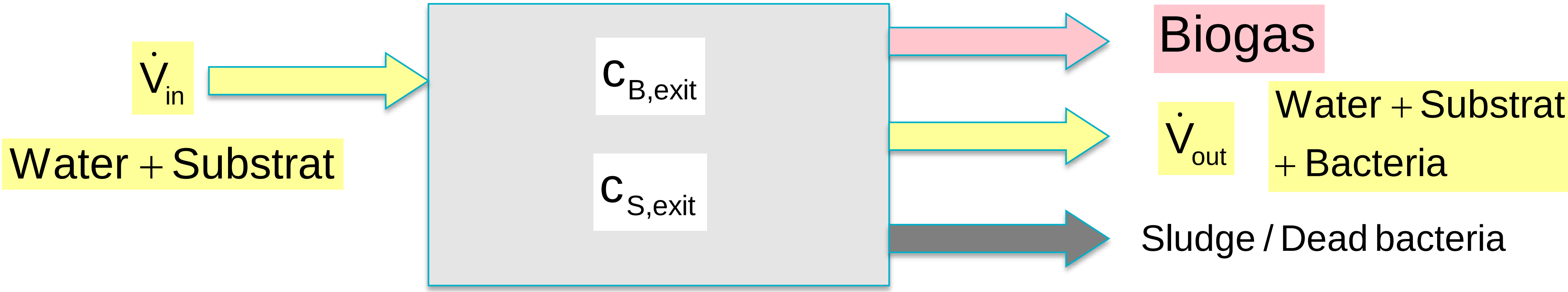
97 % of substrate is utilised to produce biogas !!!

Mass of bacteria ≈ constant; acts as a catalyst

Continuous Stirred Tank Reaktor (CSTR)

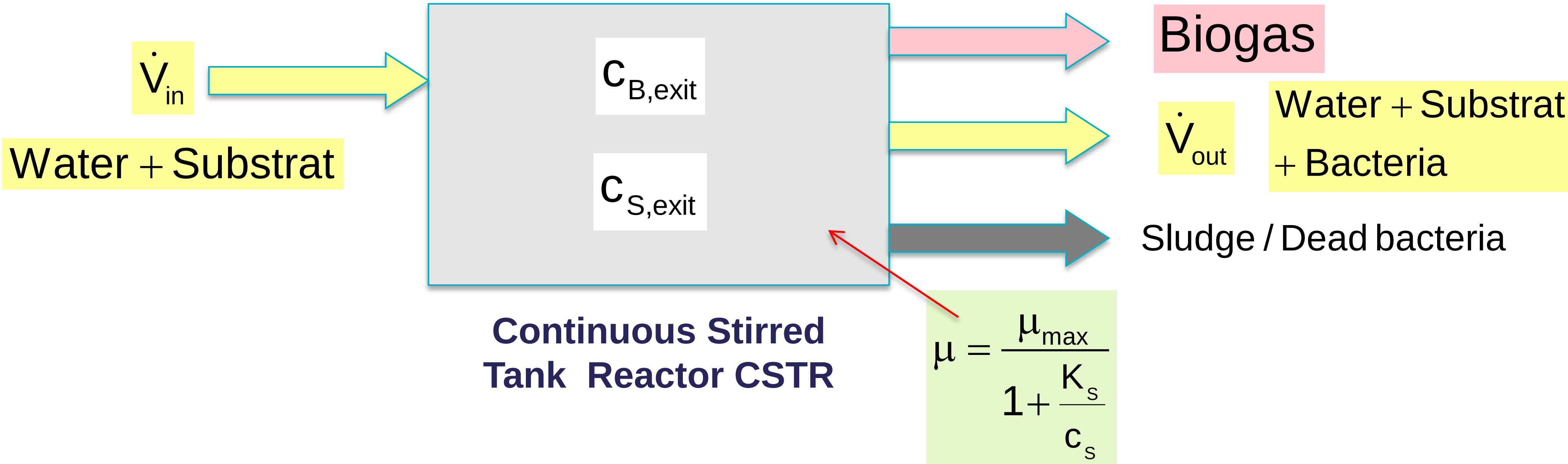
Source: www.danfoss.com/Germany/ NewsAndEvents/Archive...

Steady-state operation



Continuous Stirred Tank Reactor CSTR

Steady-state operation

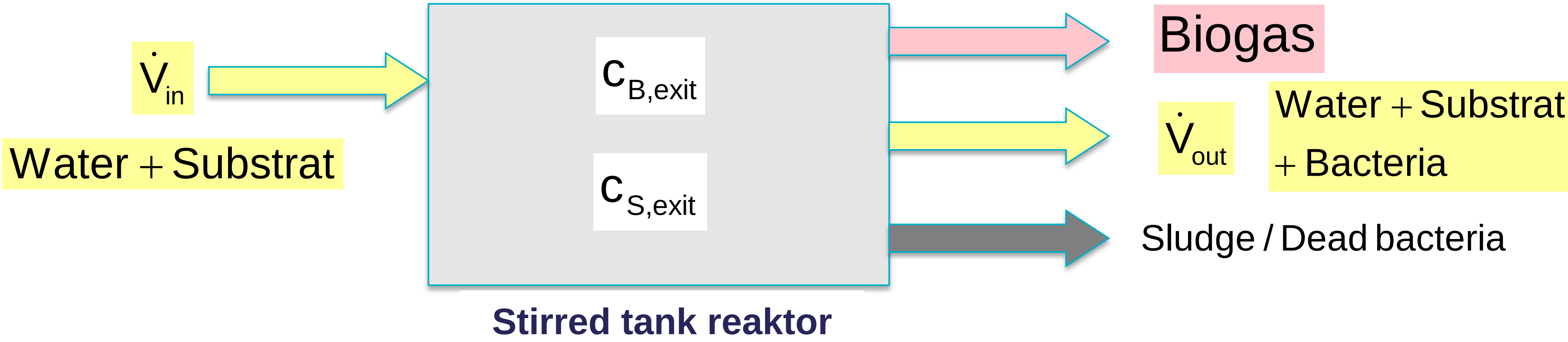


Death rate

$$\frac{d}{dt}m_B = V\cdot\frac{d}{dt}c_B = \dot{V}\,(c_{B,in} - c_{B,exit}) + V\cdot(\mu\cdot c_{B,exit} - k_D\cdot c_B)$$

Growth

Steady-state operation



$$V \cdot \cancel{\frac{d}{dt}} c_B = \dot V \left(\cancel{c_{B,in}} - c_{B,exit}\right) + V \cdot \left(\frac{\mu_{max} \cdot c_{S,exit} \cdot c_{B,exit}}{K_S + c_{S,exit}} - \cancel{k_D} \cdot c_B\right)$$

$c_B = \text{const.}$

$= 0$

small

Steady-state operation

$$c_{B,exit} = \frac{V}{\dot{V}} \cdot \frac{\mu_{max} \cdot c_{S,exit} \cdot c_{B,exit}}{K_S + c_{S,exit}}$$

Residence time $\tau = \frac{V}{\dot{V}}$

$$K_S + c_{S,exit} = \tau \cdot \mu_{max} \cdot c_{S,exit}$$

$$\frac{K_S}{c_{S,exit}} = \tau \cdot \mu_{max} - 1$$

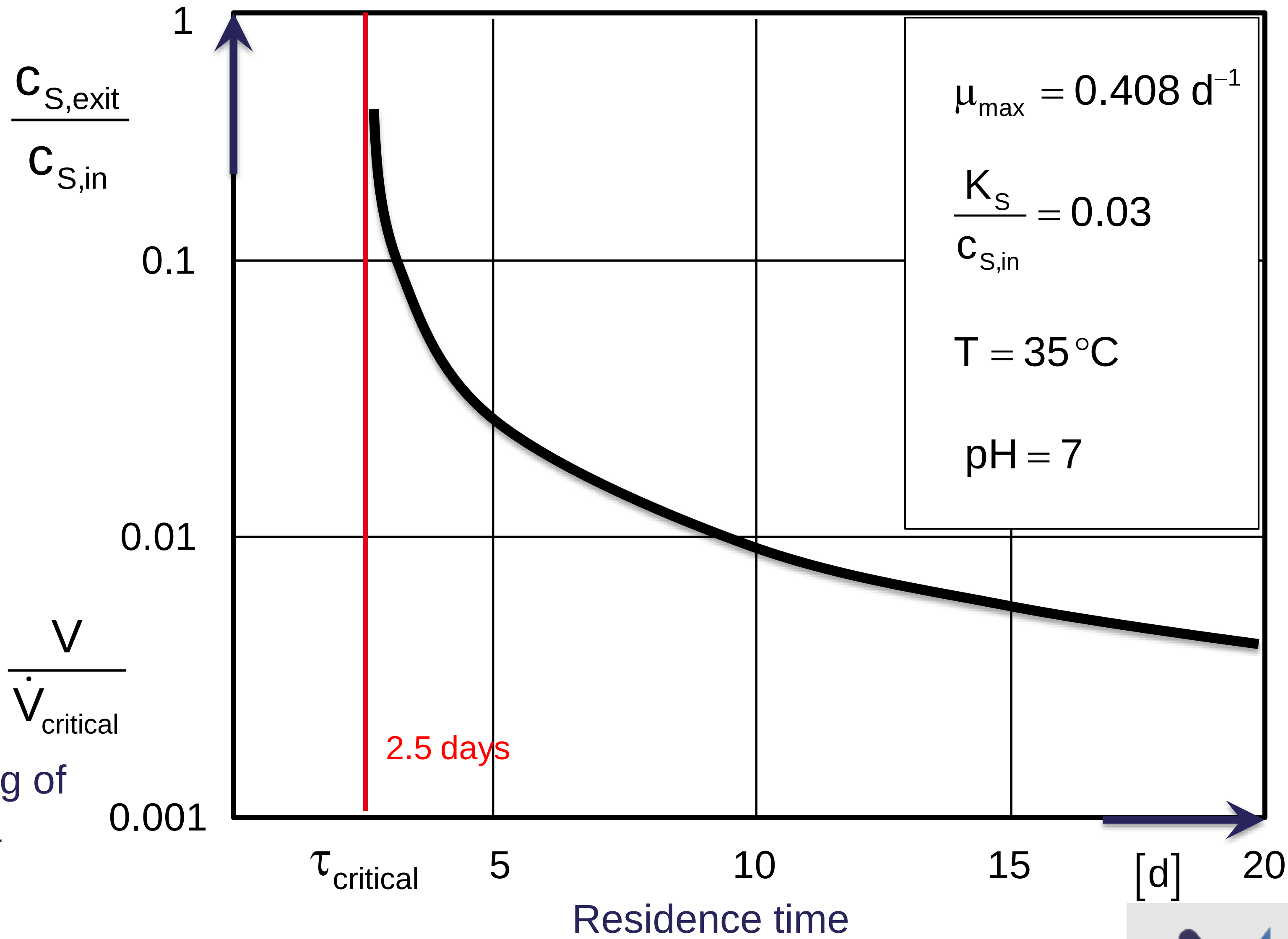
$$c_{S,exit} = \frac{K_S}{\mu_{max} \cdot \tau - 1}$$

Yield coefficient

$$Y_{B/S} = \frac{c_{B,exit}}{(c_{S,in} - c_{S,exit})}$$

$$c_{B,exit} = Y_{B/S}\,(c_{S,in} - c_{S,exit})$$

Example: Degradation of acetic acid



$$\mu = \frac{\mu_{max}}{1 + \frac{K_s}{c_s}}$$

$$\tau_{critical} = \frac{V}{\dot{V}_{critical}}$$

Leaching of bacteria