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Drying Process and Energy Economics

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KEY QUALIFICATIONS	Drying technology, Thermal process engineering, Heat and mass transfer, Food Technology, Food properties and quality, Refrigeration Air conditioning

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2011 – 2012	Post-Doc at NTNU, *Energy efficiency in drying processes*
2007 – 2011	PhD at NTNU, *Study of high intensity, airborne ultrasound in atmospheric freeze drying.*
2002 – 2007	University of applied science, Konstanz Germany, Process and Environmental engineering, Diploma thesis: *Dimensioning of drying and conditioning unit for soybeans.*

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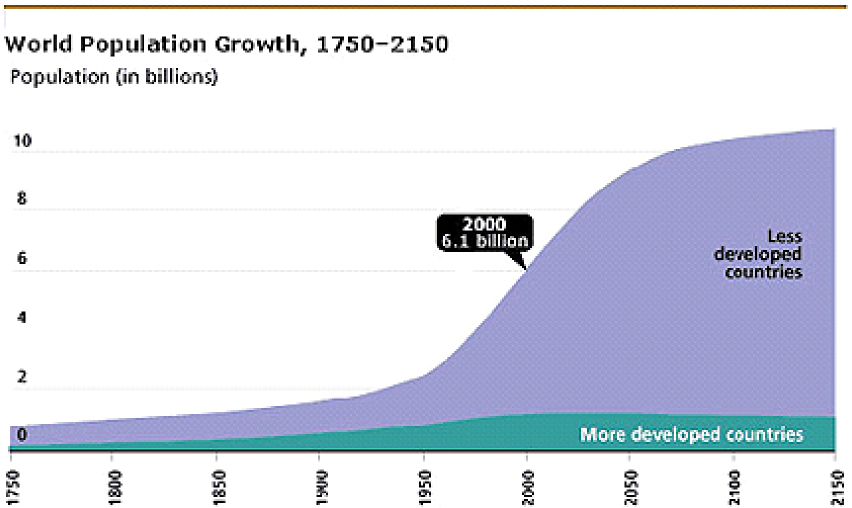
Agenda:

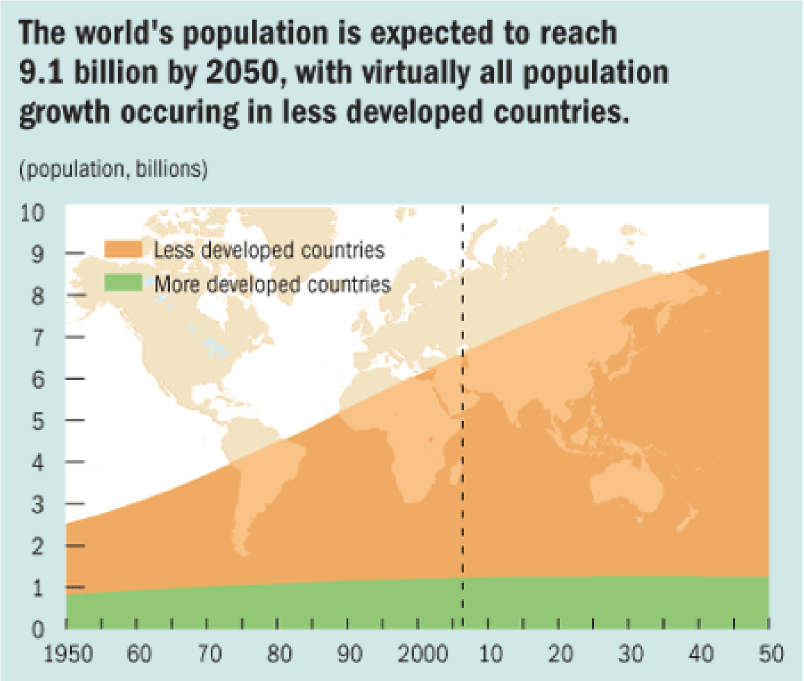
1. Some facts about Food and Energy
2. Drying economics (for dry-cured products)
    1. Heated ambient air drying (HAAD)
    2. Heat pump drying (HPD)
    3. Modelling (dynamic object-oriented models)
3. Energy efficient drying concepts for clipfish
    1. HPD vs. HAAD
    2. HPD + storage drying
    3. Intermitted drying

1. Some "facts" about food and energy

- World population of 13 billion by 2100
- Increase is the main "problem" for food security

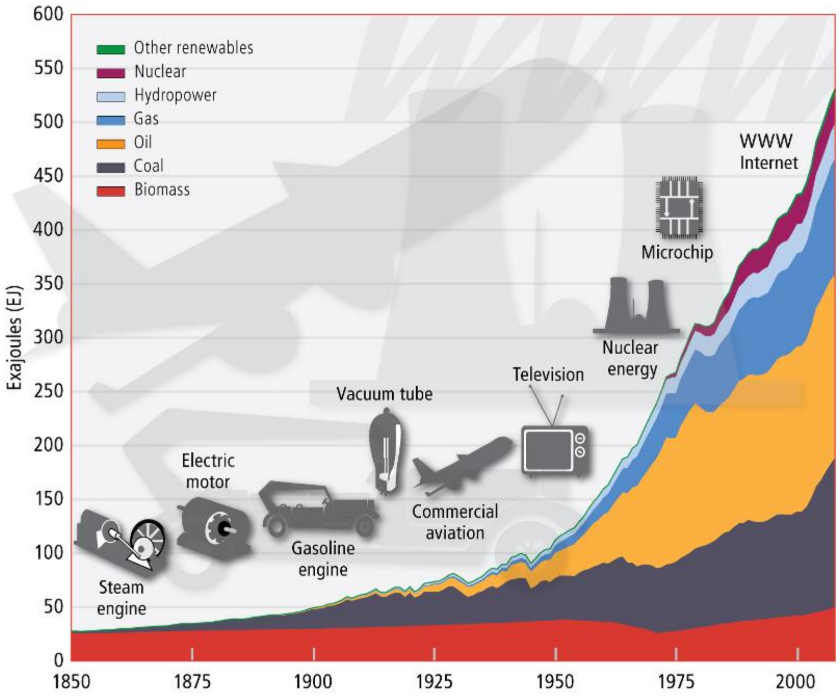


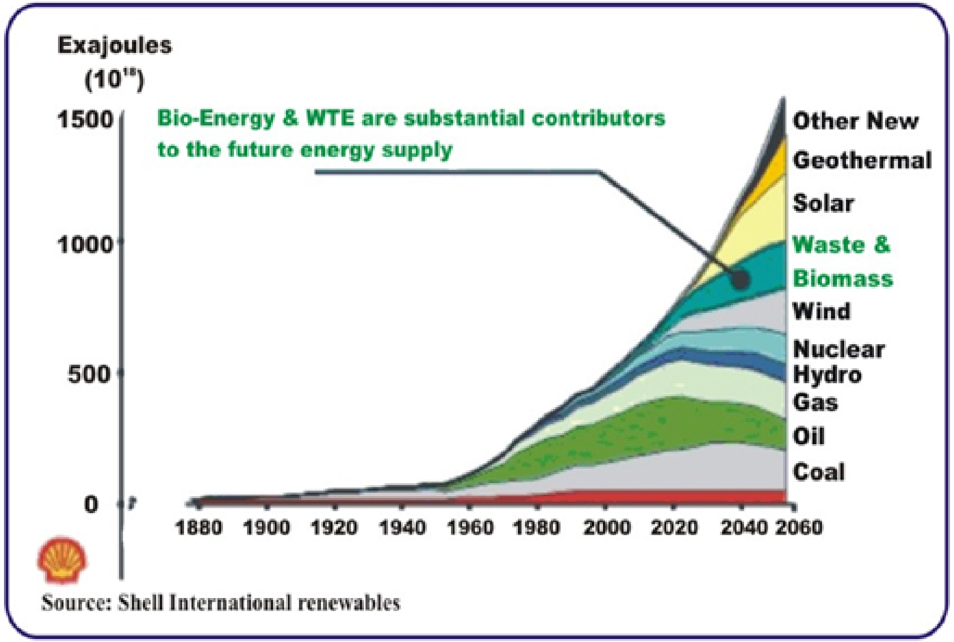
Source: United Nations, *World Population Prospects, The 1998 Revision*; and estimates by the Population Reference Bureau.



1. Some "facts" about food and energy

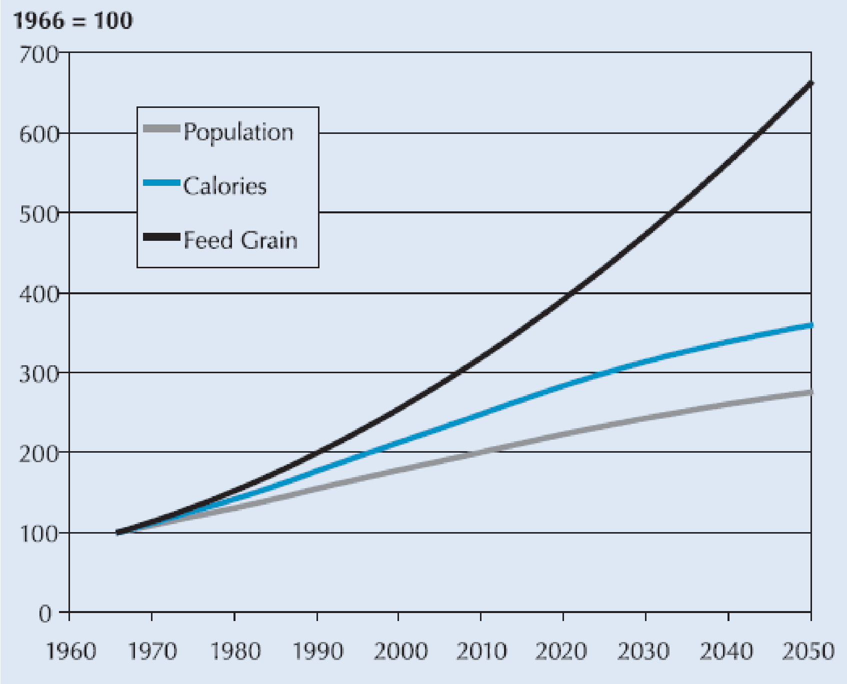
- Increased energy demand





1. Some "facts" about food and energy

- Food demand in the future
  - Increased demand for meat and dairy

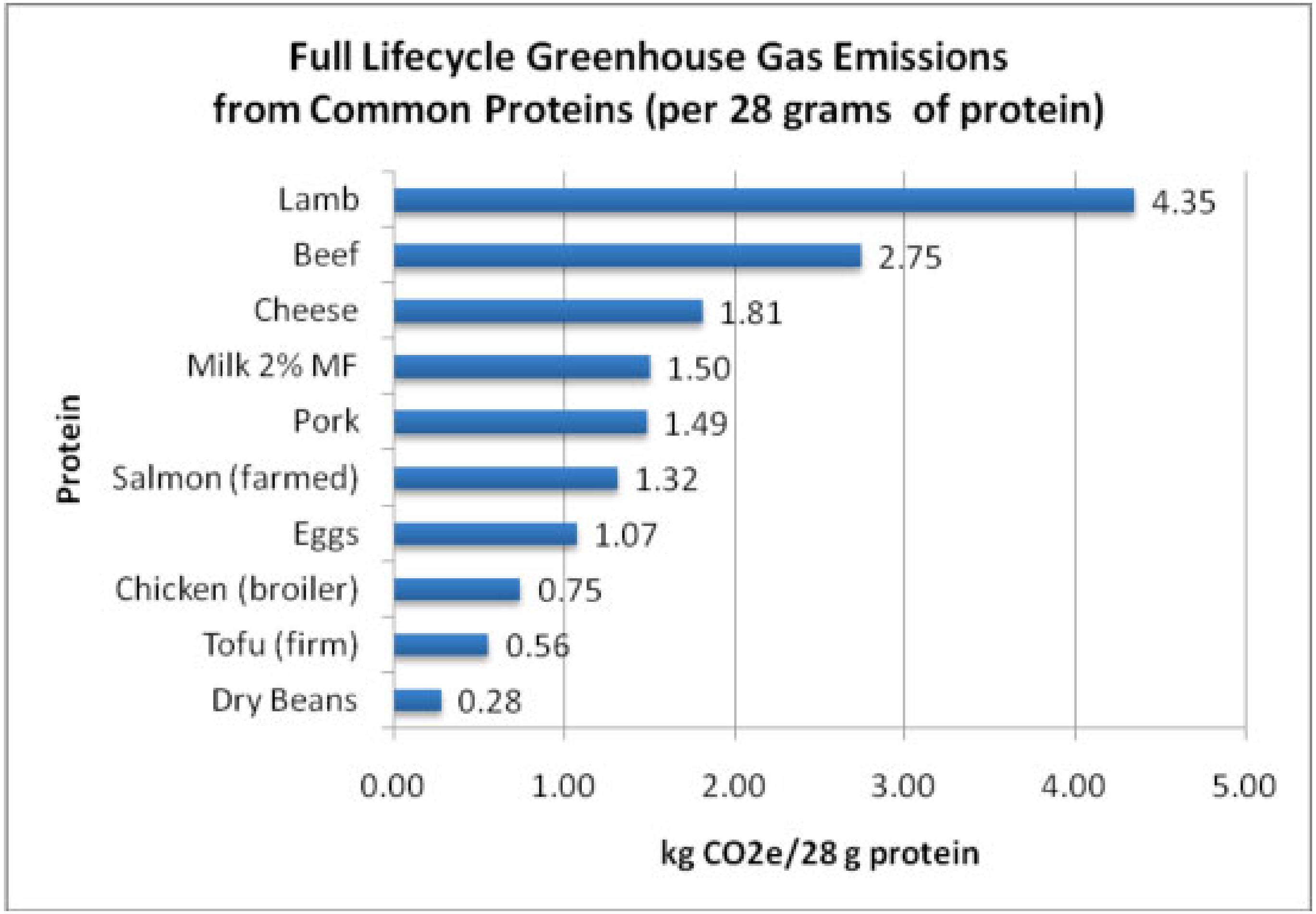


Three indicators of world food demand

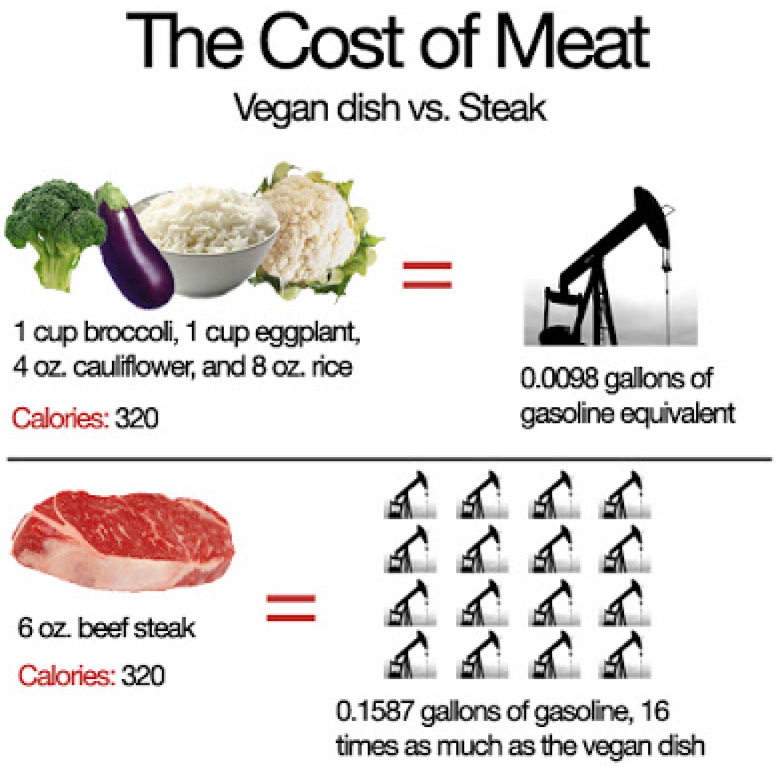
Crop	1969	2009	Percent Increase
Sugar Cane	538	1,661	**209%**
Maize	270	819	**203%**
Wheat	309	686	**122%**
Rice, paddy	296	685	**131%**
Cow Milk	358	583	**63%**
Potatoes	278	330	**19%**
Vegetables	71	249	**251%**
Cassava	95	234	**146%**
Sugar Beets	217	227	**5%**
Soybeans	42	223	**431%**
Total	**2,474**	**5,697**	**130%**

Increase in World Production of Top Ten Major Commodities (1969 – 2009) (million metric tons)

1. Some "facts" about food and energy



1. Some "facts" about food and energy



Feed to food ratios:

10 kg grain	→ 1 kg beef
4-5.5kg grain	→ 1 kg pork
2.1-3 kg grain	→ poultry meat
1.2 kg feed	→ 1 kg fish

1. Some facts about food and energy

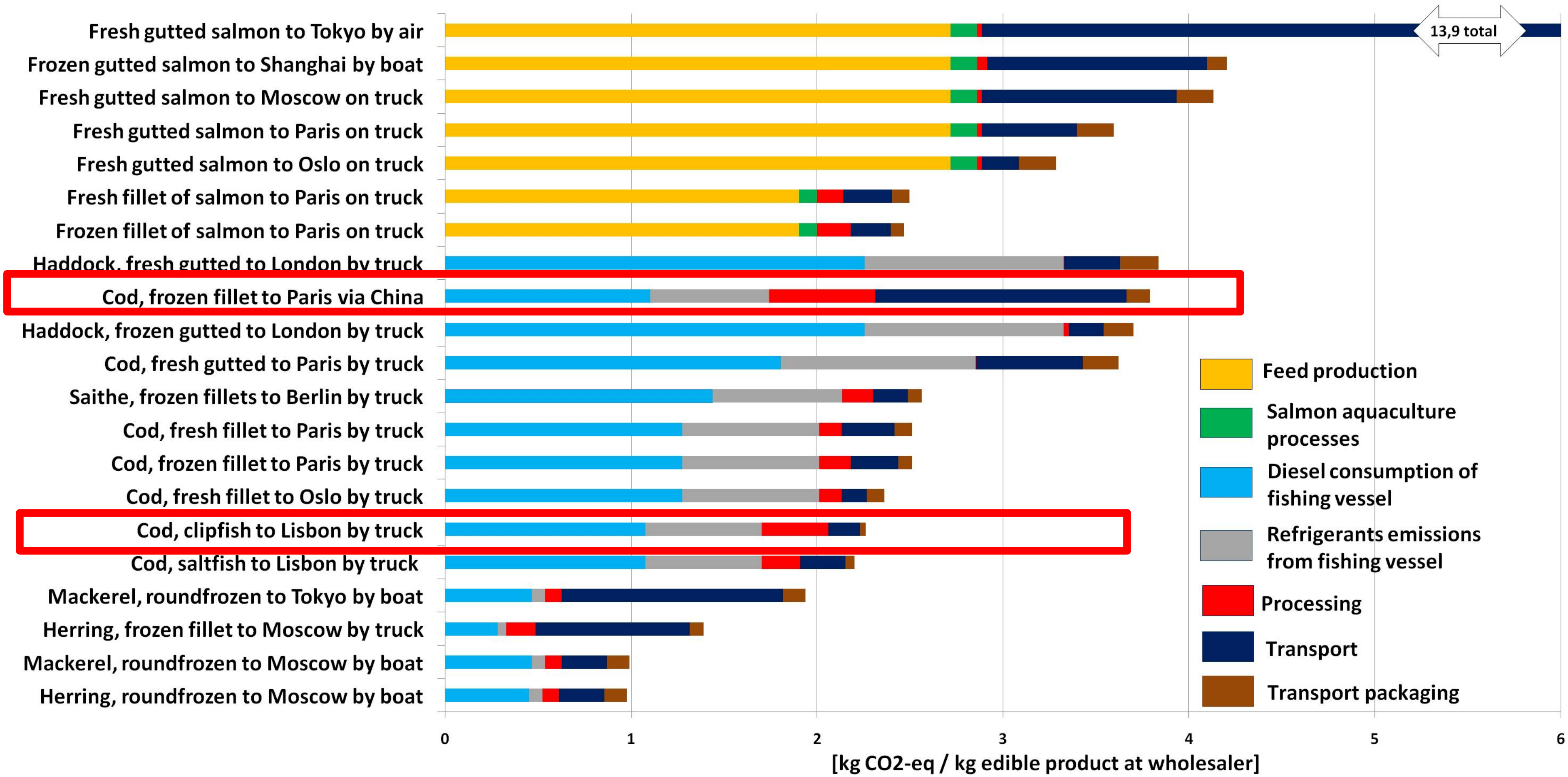
Table 1: List of Foods By Energy Required to Produce One Pound

Food	Energy (kWh) to Produce 1 Lb
Corn	0.43
Milk	0.75
Apples	1.67
Eggs	4
Chicken	4.4
Cheese	6.75
Pork	12.6
Beef	31.5

Table 2: Energy Efficiency of Various Foods (Measured as Food Calories / Energy Used in Production) [8]

Food	Calories / Lb	Energy Efficiency
Corn	390	102%
Milk	291	45%
Cheese	1824	31%
Eggs	650	19%
Apples	216	15%
Chicken	573	15%
Pork	480	8.5%
Beef	1176	4.3%

1. Some "facts" about food and energy



1. Background for food and energy research

- Growing population → increasing demand and dependency for
  - Food (→ meat = feed problem)
  - Energy (what is the future energy source?)
- "Feed to Food" production stands for a large emission for green house gases
- Better usage of available food (and feed) sources
  - **Food preservation will be a key element in this**

    → drying vs. freezing
- Higher efficiencies, new technologies
- How to influence producers and consumers?

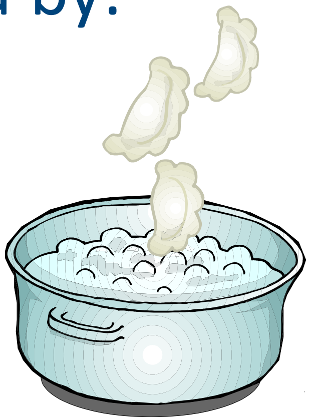
  → **Money (~ energy prices)**

  → **Legislative**

2. Drying economics

Drying: removal of moisture (water) from a solid by:

- Evaporation
  - →Heat transfer controlled
  - →Boiling point (Evaporators)
  - →Vacuum (Freeze) Drying



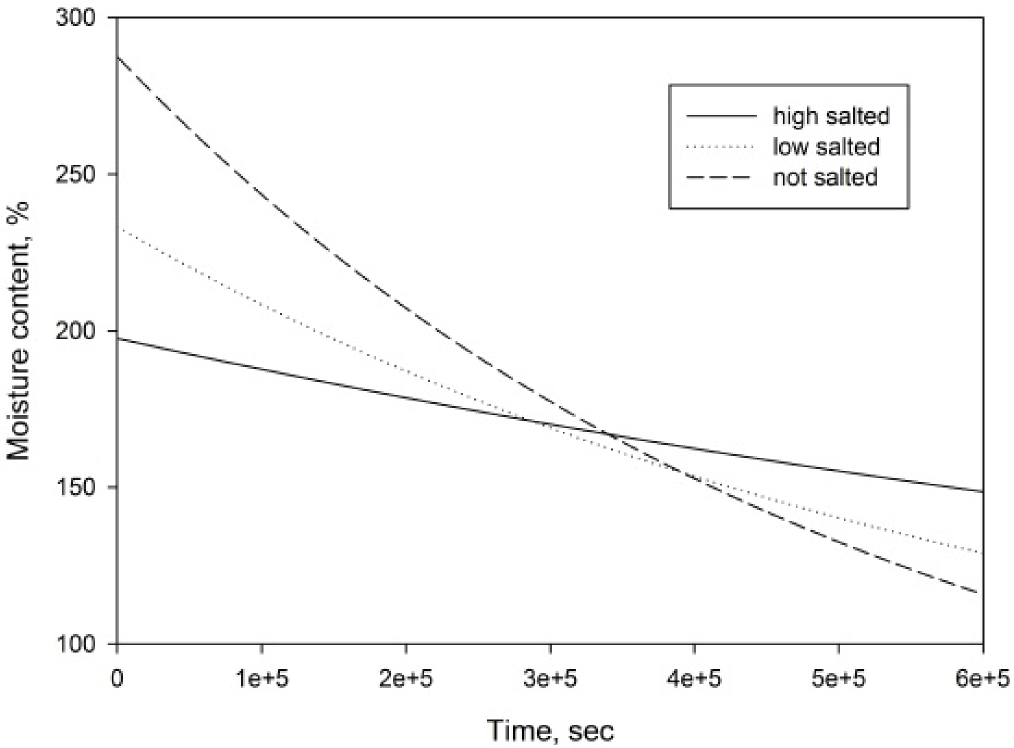
- Vaporization (convective drying)
  - →Mass transfer controlled, due to pressure gradient
  - →Convective drying temperatures up to 100°C

2. Drying economics

- Porosity or void fraction 0 to 1 (0% - 100%)
- Drying behavior = moisture loss over time
  - → Drying curve
  - → Measured as:
    - Humidity difference
    - Continuous or intermitted weighing
  - → Model
- Every product has different characteristic drying behavior under different conditions
- Latent heat of evaporation ≈ 2250 kJ/kg ≈ 0.63 kWh/kg (ideal)
  real: ≈ 3500 - 6000 kJ/kg ≈1 – 1.6 kWh/kg
- Drying is quite often the most energy demanding process in the production
- Salt is a barrier for water-vapor transfer

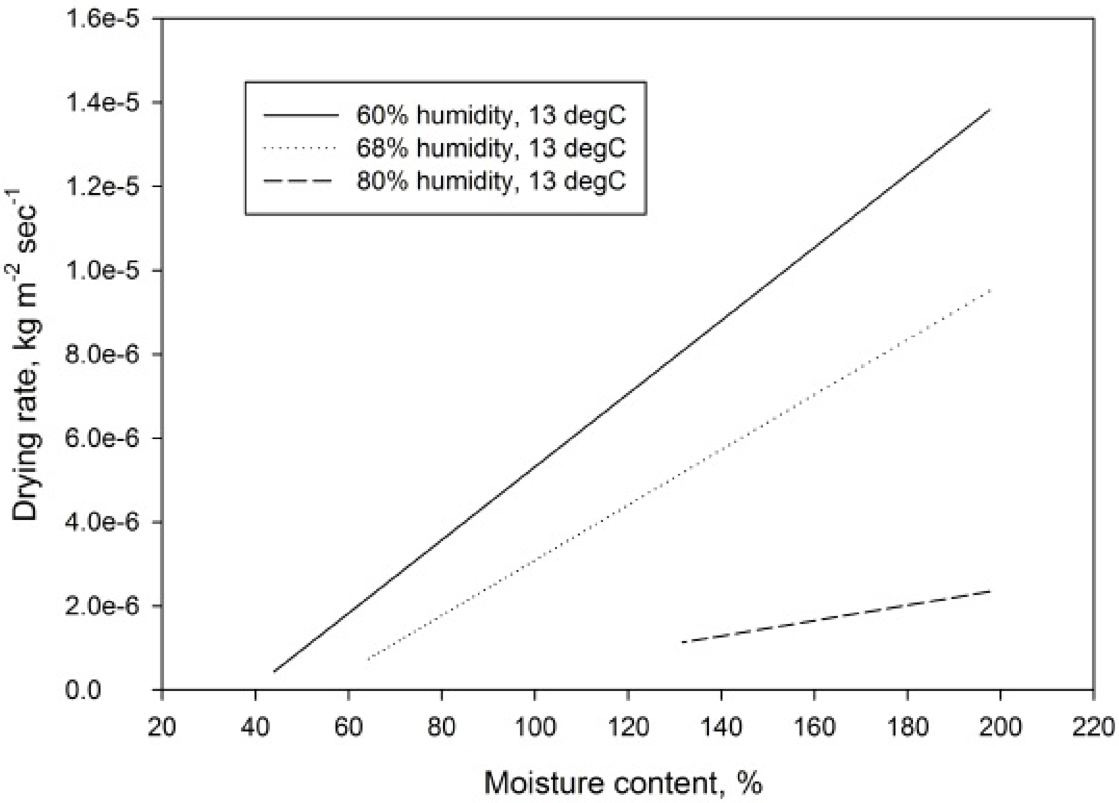
2. Drying economics

- Which product is more economical in drying (→drying efficiency)



2. Drying economics

- Influence of temperature and relative humidity

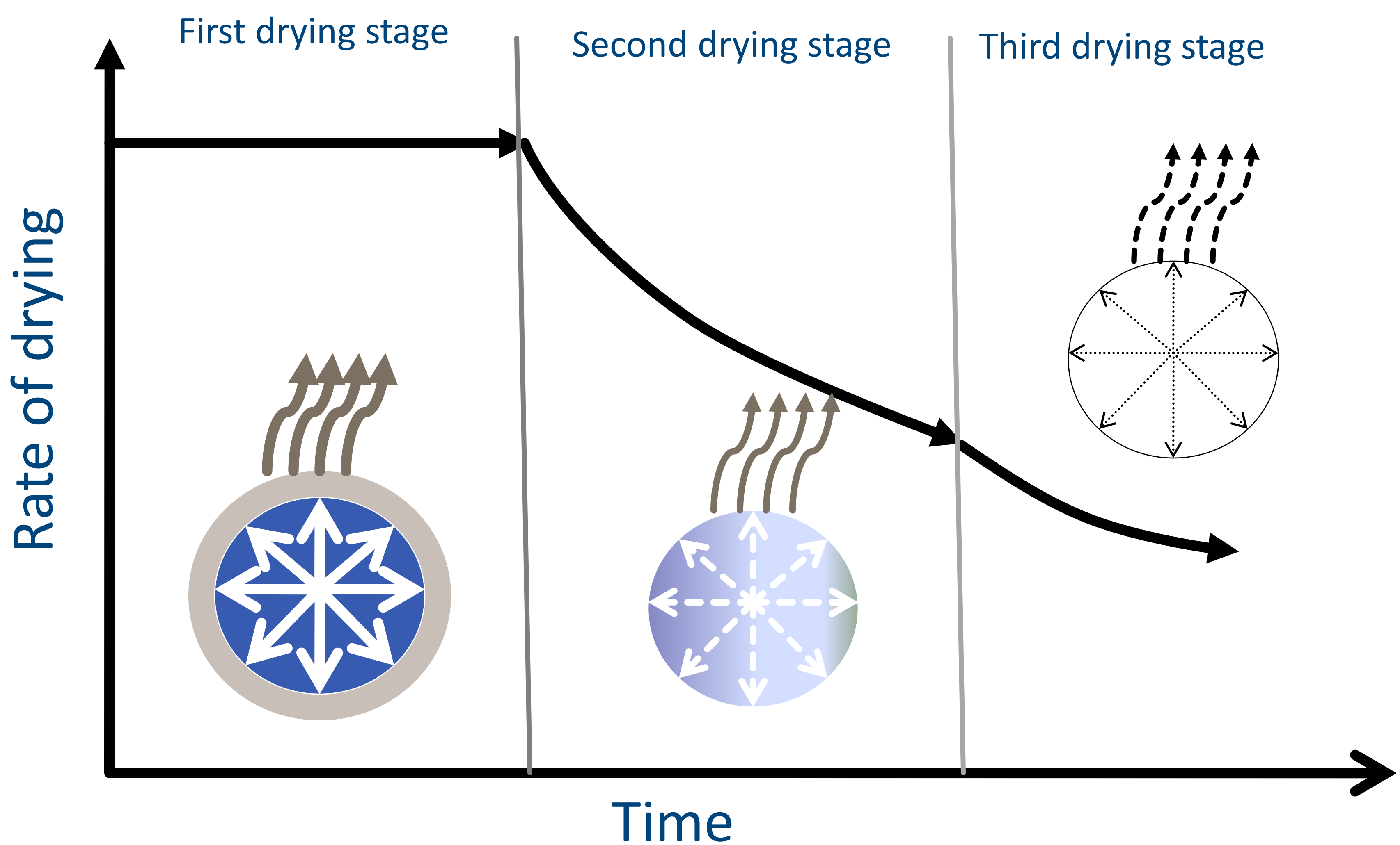


2. Drying systems

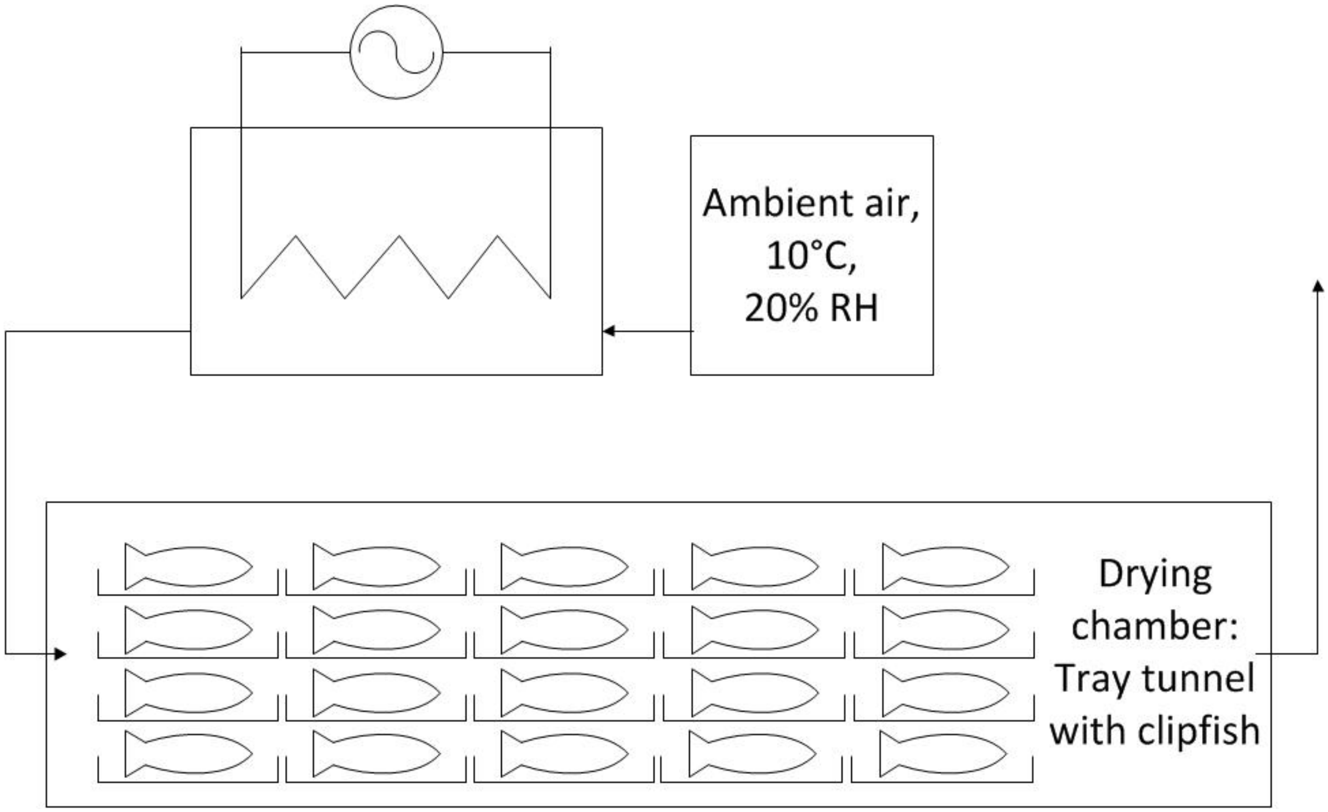
- Indirect dryer
- Direct dryer
- Rotary dryer
- Fluidized bed dryer
- Drum dryer
- Tunnel dryer
- Spray dryer
- Freeze drying
  - Vacuum
  - Atmospheric
- Microwave drying
- Ultrasonic drying
- Solar drying
- Spouted bed drying
- Impingement drying
- Conveyor drying
- Infrared drying
- Superheated steam drying
- …..

- Food drying
- Fish and seafood drying
- Grain drying
- Fruits and vegetables
- Drying of pharmaceuticals
- Drying of nanosized products
- Drying of ceramics
- Drying of biofuels
- Drying of textiles
- Drying of paper
- Drying of mineral products
- Drying of waste
- Drying of polymers
- Drying of enzymes
- ….

2. Drying theory



2.1 Heated ambient air drying



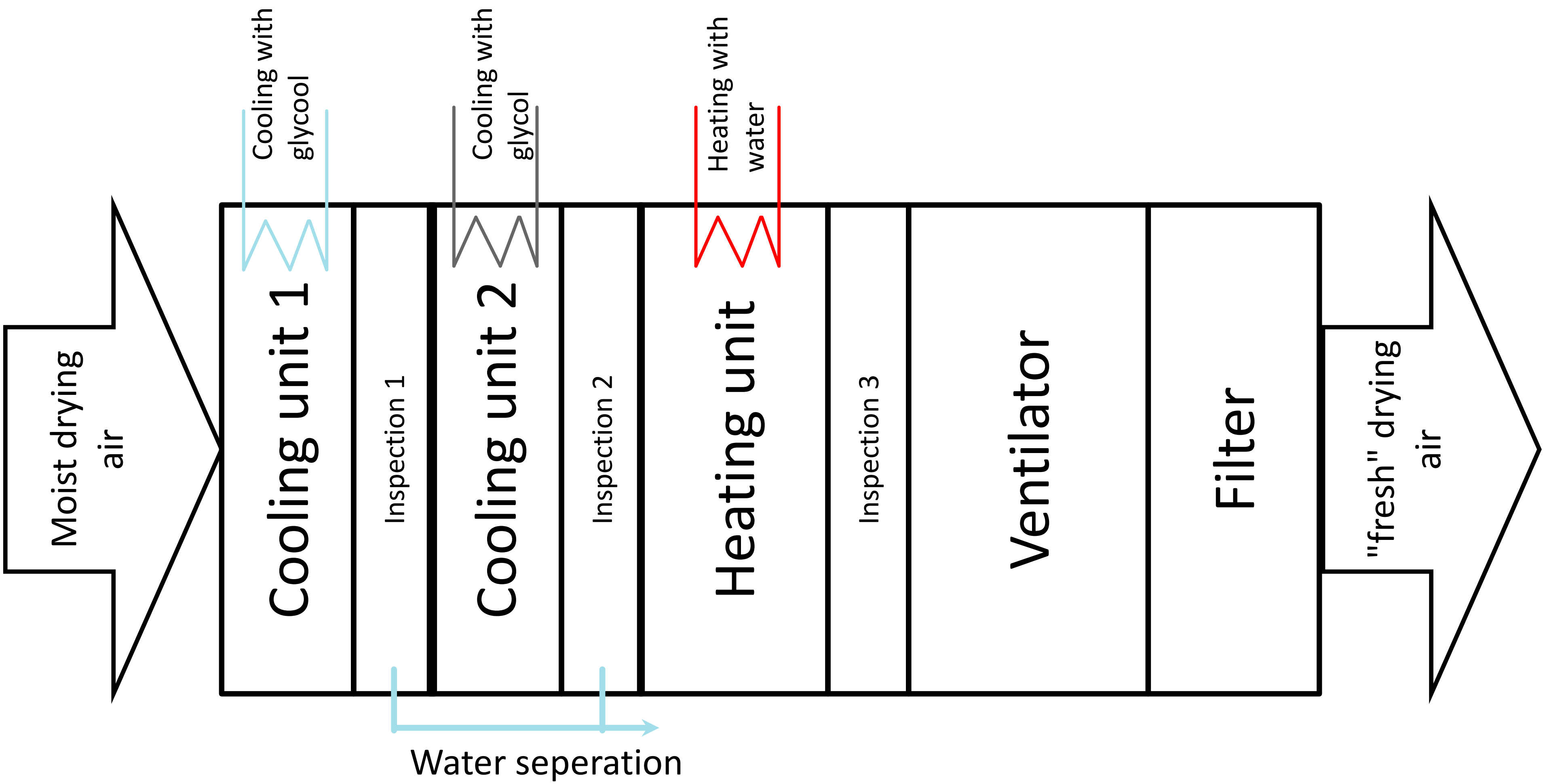
2.1 Heated ambient air drying

- Low system efficiency (depends also on product and quality demands)
- High energetic losses (factor is multiplied with energy prices)
- Simple system, easy to control
- Solar heating is possible
- Relative humidity is depends on ambient conditions and by-pass regulation

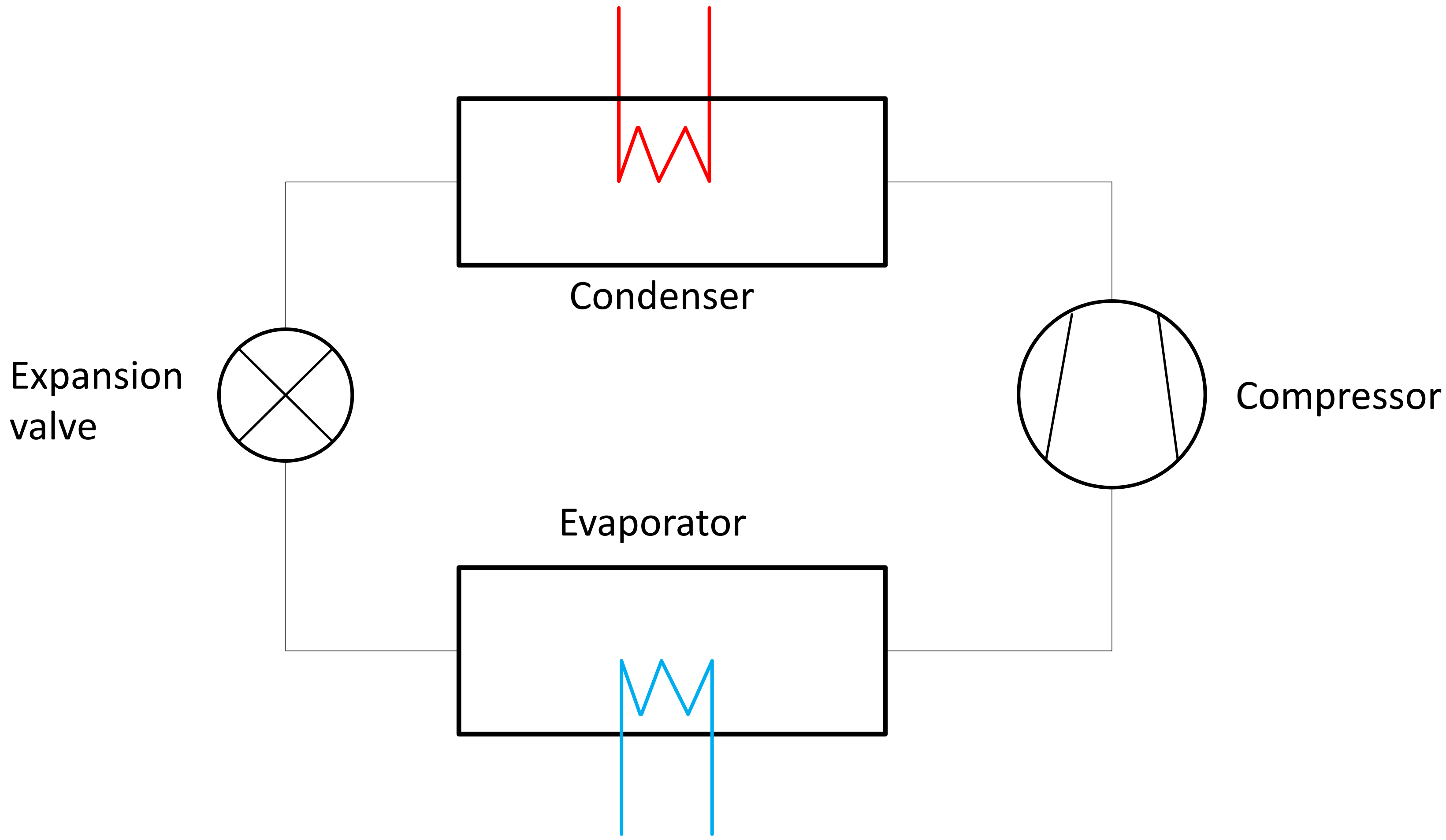
Table 1
General comparison of heat pump dryer with vacuum and hot air drying [15].

	Hot air drying	Vacuum drying	HPD drying
SMER (kg H_2O/kWh)	0.12–1.28	0.72–1.2	1.0–4.0
Drying efficiency (%)	35–40	⩽70	95
Capital cost	Low	High	Moderate
Running cost	High	Very high	Low

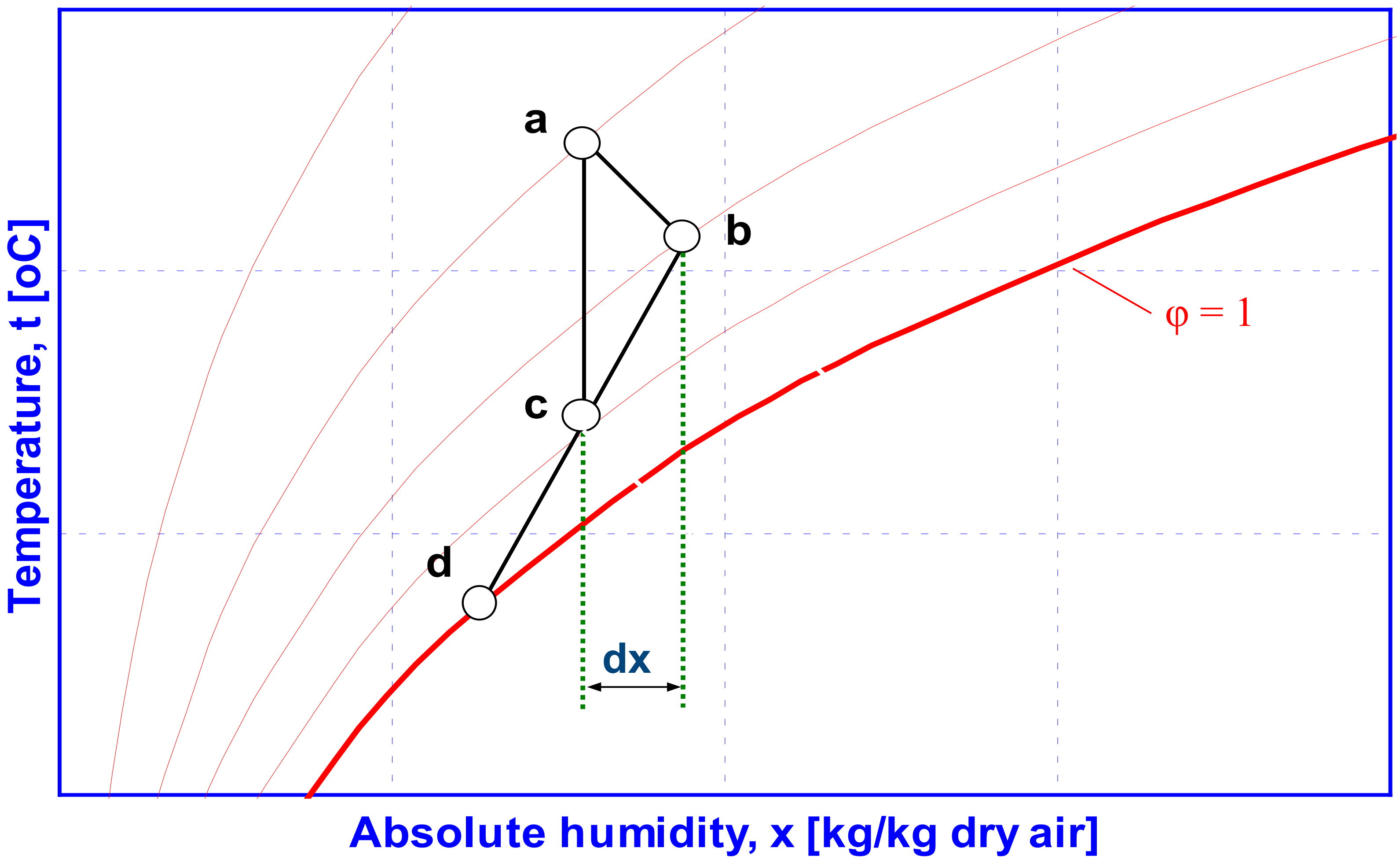
2.1 Drying systems (closed)



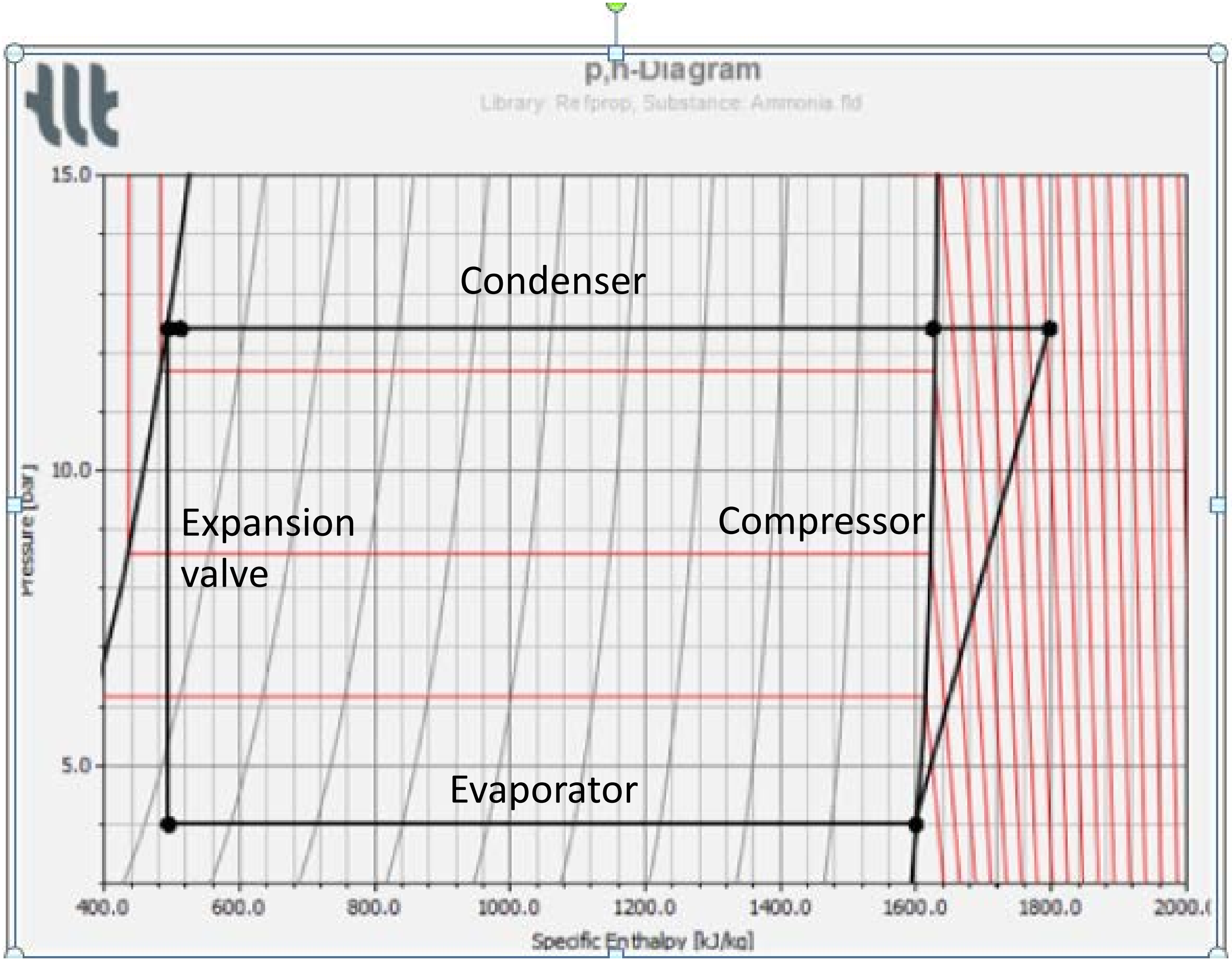
2.2 Heat pump drying: general about heat pumps



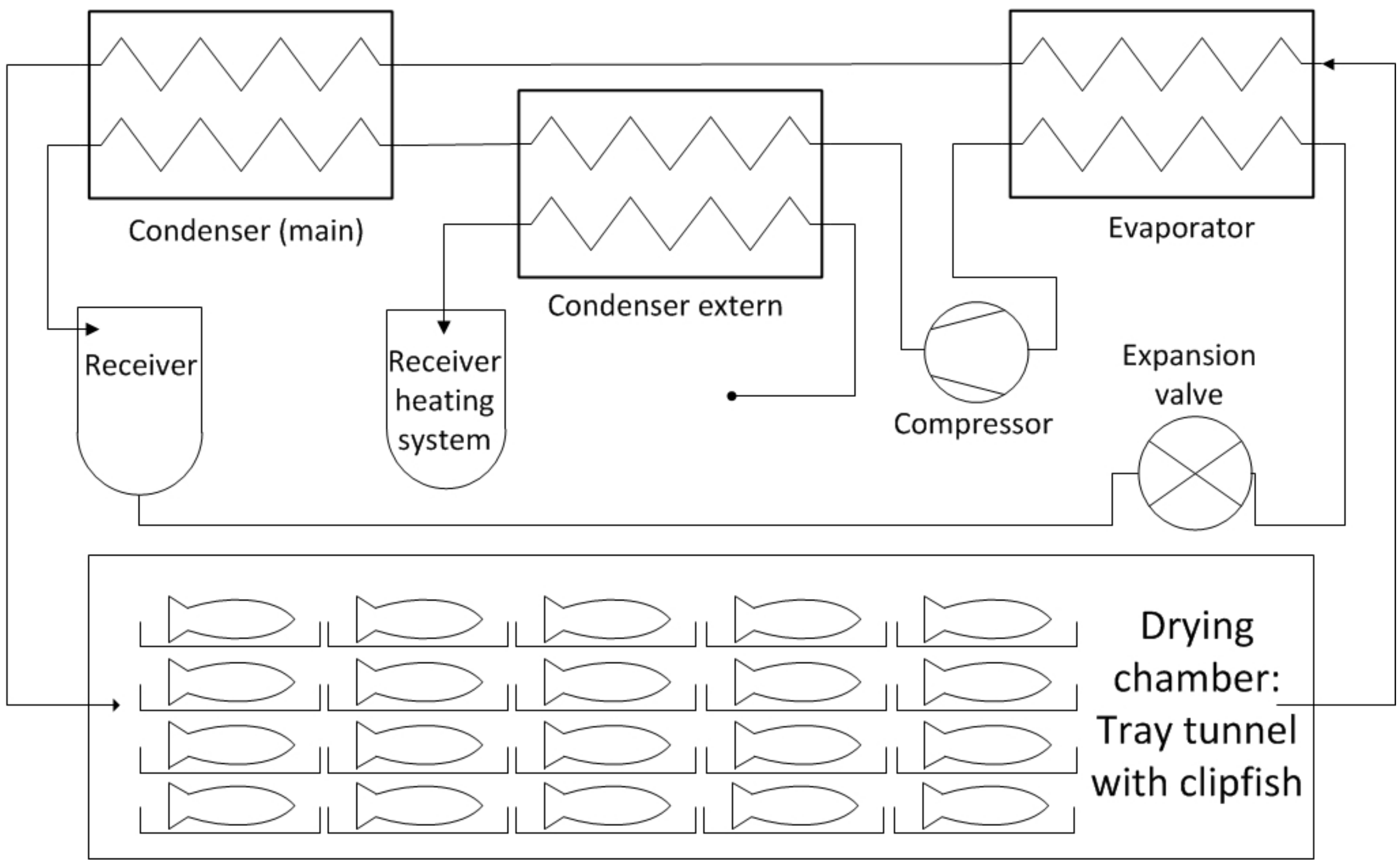
1.b Drying theory: moist air diagram



2.2 Heat Pump Drying: log-p-h diagram



1.b Heat pump drying



2.2 Heat Pump Drying

- Closed system
- Uses electric energy (preferable supplied from a renewable grid)
- Same drying process than in HAAD
- 75% more energy efficient
- More complex to control
- Higher investment costs

Table 1
General comparison of heat pump dryer with vacuum and hot air drying [15].

	Hot air drying	Vacuum drying	HPD drying
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Capital cost	Low	High	Moderate
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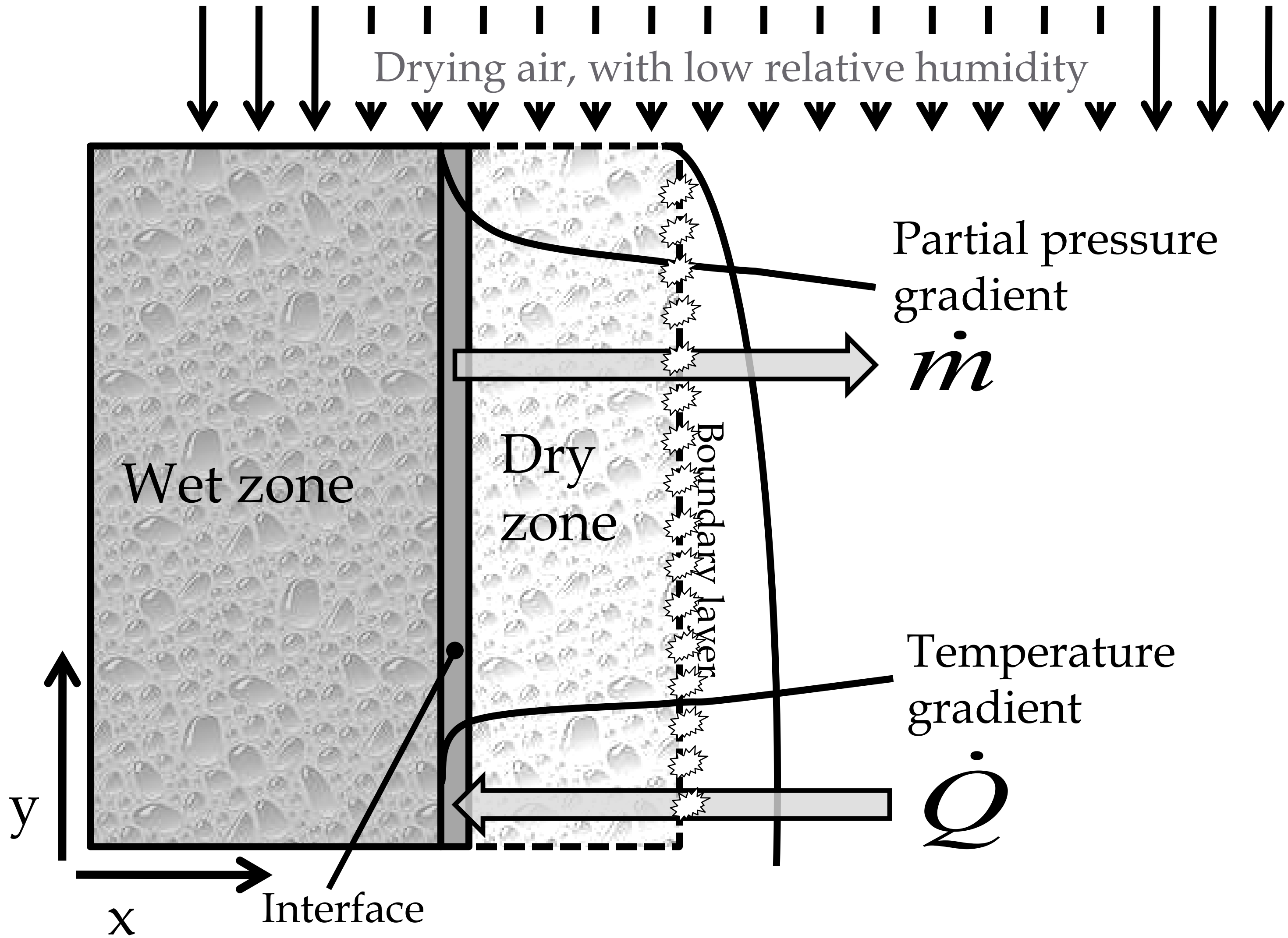
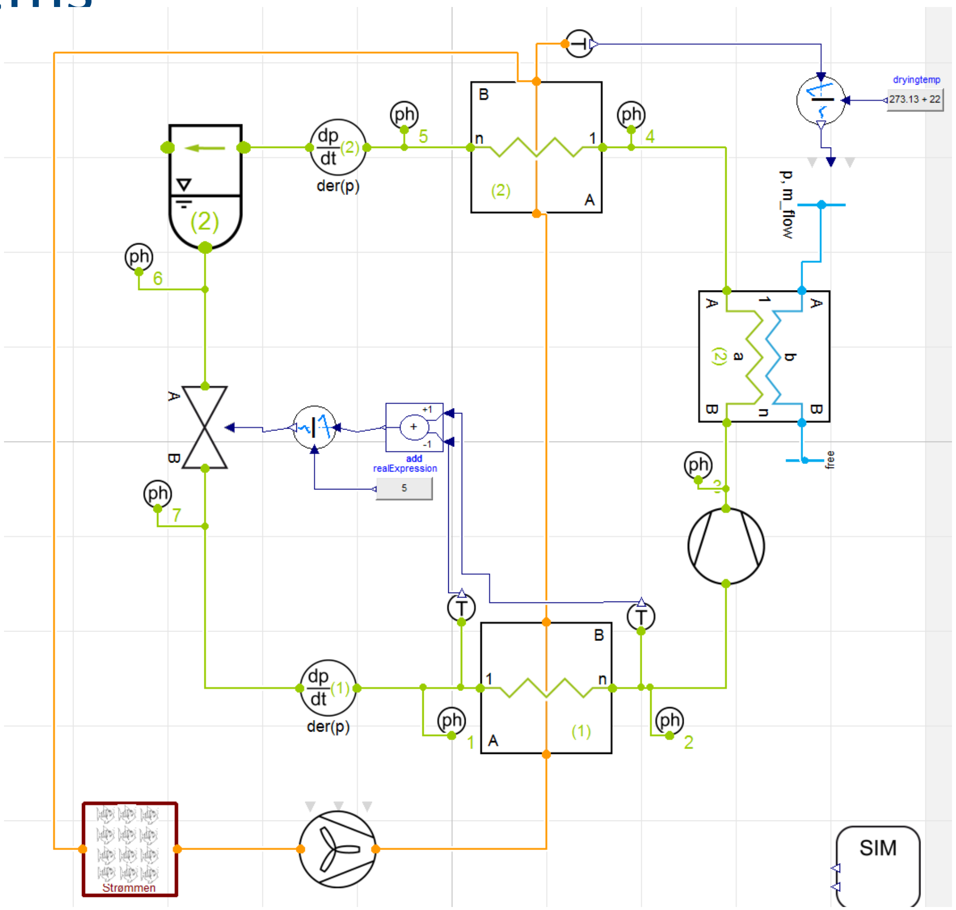
2.3 Modelling: second drying period



2.3 Modelling of drying systems

- Object orientated modelling
  - Dymola – Dynamic Modelling Laboratory
  - TIL – Library
  - Physical models

- Objects for
  - Heat exchangers
    - Moist air – refrigerant
    - Refrigerant – water (or air)
  - Compressor
  - Expansion valves
  - Ventilator
  - Drying model



2.3 Modelling of drying systems

- Condenser and Evaporator
  - Based on geometry
  - $\Delta\dot{Q} = \Delta\dot{Q}_{in} - \Delta\dot{Q}_{out}$
  - $\dot{m}_{in} = \dot{m}_{out}$
  - ....

$$\text{QdotHydraulic} = \frac{\text{heatPort}.Q_{\text{flow}}}{\text{cellGeometry.nParallelHydraulicFlows}}$$

$$\text{wallTemperature} = \text{heatPort}.T$$

$$\delta_T = \text{heatPort}.T - \text{refrigerant}.T$$

$$\text{heatPort}.Q_{\text{flow}} = \text{heatTransfer.alphaA}\left(\text{heatPort}.T - \text{refrigerant}.T\right)$$

$$\text{mass} = \text{cellGeometry.volume}\,\text{refrigerant}.d$$

$$\frac{\text{d refrigerant}.h}{\text{d}\,t} = \frac{1}{\text{mass}}\left(\text{portA}.H_{\text{flow}} - \text{portA}.m_{\text{flow}}\,\text{refrigerant}.h + \text{portB}.H_{\text{flow}} - \text{portB}.m_{\text{flow}}\,\text{refrigerant}.h + \text{heatPort}.Q_{\text{flow}} + \text{cellGeometry.volume dpdt}\right)$$

if steadyStateContinuity then

$$\text{portA}.m_{\text{flow}} + \text{portB}.m_{\text{flow}} = 0$$

else

$$\text{drhodt}\cdot\text{cellGeometry.volume} = \text{portA}.m_{\text{flow}} + \text{portB}.m_{\text{flow}}$$

end if

3. Modelling of drying systesm

- Compressor

equation

$$\text{outlet.mDot} + \text{inlet.mDot} = 0$$
$$\text{outlet}.h = 500e3$$

// this value should be calculated with isentropic efficiency

$$\text{inlet.mDot} = \text{Vol} \cdot n \cdot \text{volEff} \cdot \text{refIn}.d$$

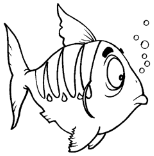
- Valve

equation

$$\text{outlet.mDot} + \text{inlet.mDot} = 0$$
$$\text{outlet}.h = \text{inlet}.h$$
$$\text{inlet.mDot} = \text{Aeff} \cdot \sqrt{2 \text{refIn}.d \left(\text{inlet}.p - \text{outlet}.p\right)}$$

- Controllers
  - PID controller of the valve which ensures that the refrigerant in the evaporator is superheated
  - PID controller, which regulates the heat flows in the two condensers in a way that the drying temperature at the inlet is stable

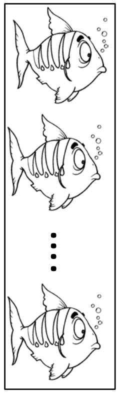
3. Model of drying systems



- Different models
  - **Weibull: 99.924%**
  - **Strømmen: 99.903%**
  - Fick: 99.703%
  - Fick (Arrenhius diffusion): 98.610%

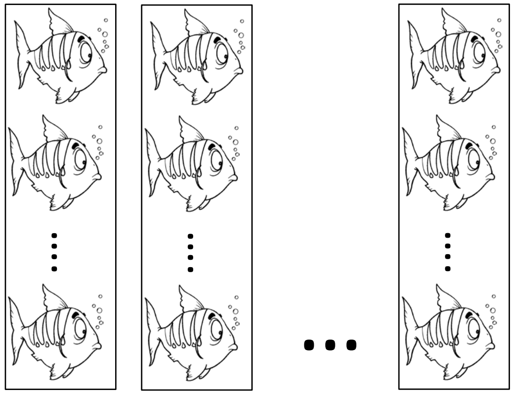
$$\frac{\mathrm{d}\,\text{waterremoved}}{\mathrm{d}\,t} = \frac{\frac{1}{R\cdot\text{temperature}}\,\text{area}}{\left(\frac{1}{\beta}\right)+\left(\frac{\text{thicknessdrylayer}\cdot\text{diffresistance}}{\text{diffusion}}\right)}\left(\text{pfish}-\text{pair}\right)$$

- Drying model for the tunnel
  - smallest unit is one clipfish
  - mass transfer controlled, depending on
    - internal and
    - external resistance



- summed up to a single row (cross sectional area of the tunnel)

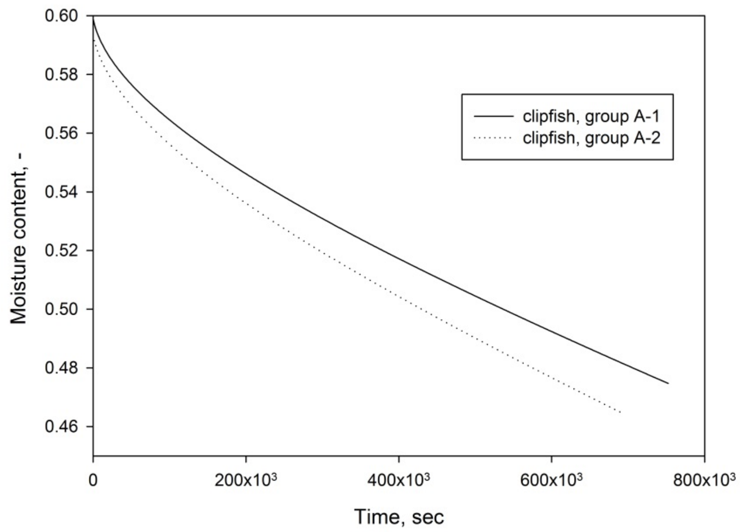
3. Modelling of drying systems

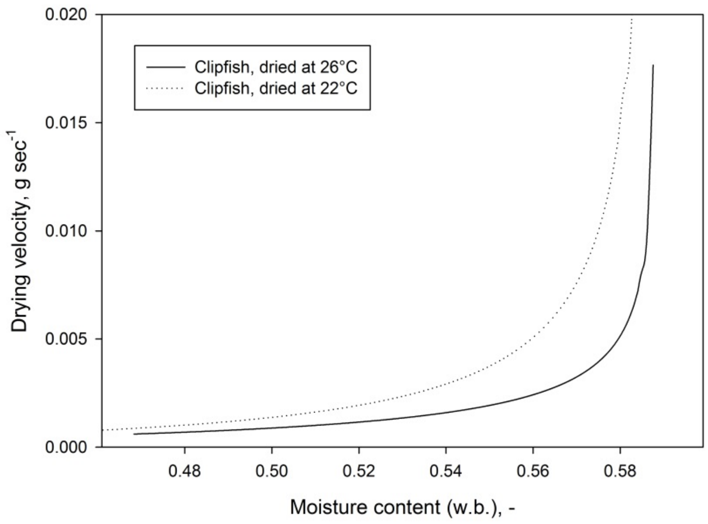


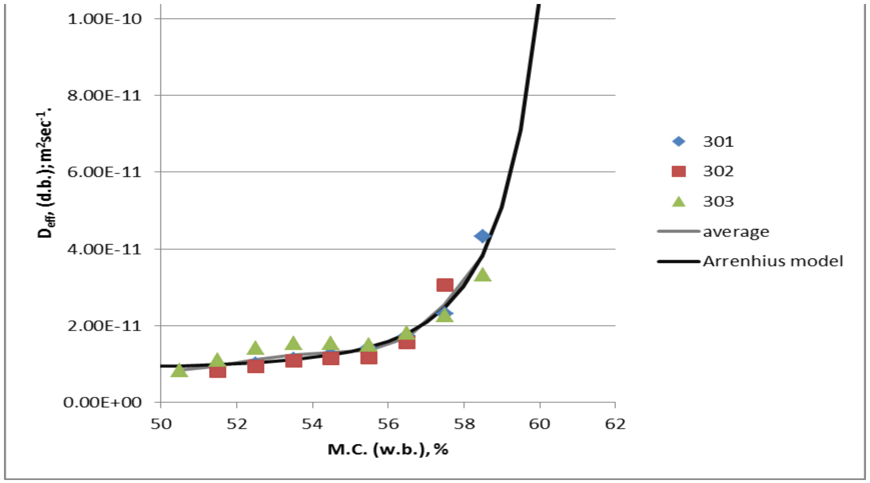
- Length of the tunnel is built by connecting the rows together
  - Drying air out of row one is input to row 2, etc.

- Assumptions:
  - Concentration gradient force for diffusion
  - Diffusion resistance is a function of salt crystallization (M.C.)
  - Homogeneous material
  - One dimensional mass transport
  - No shrinkage
  - Solid is inactive
  - No secondary heat or mass transfer
  - Uniform drying air distribution

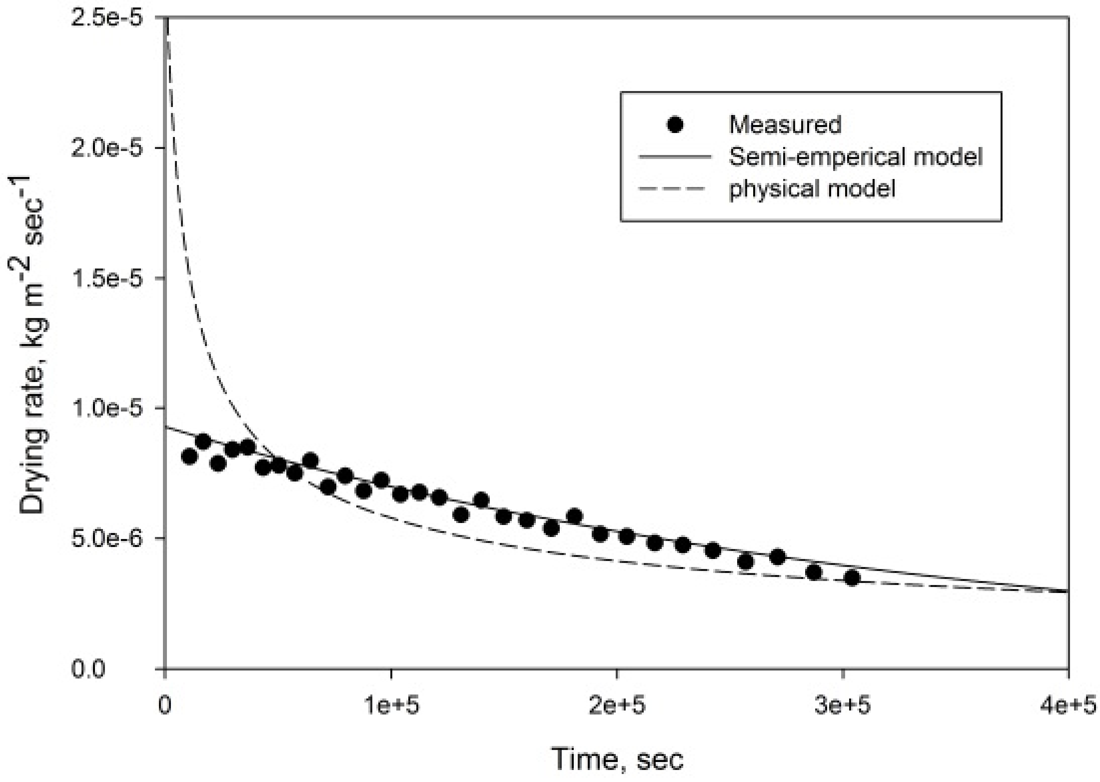
2.3 Modelling of drying systems: clipfish



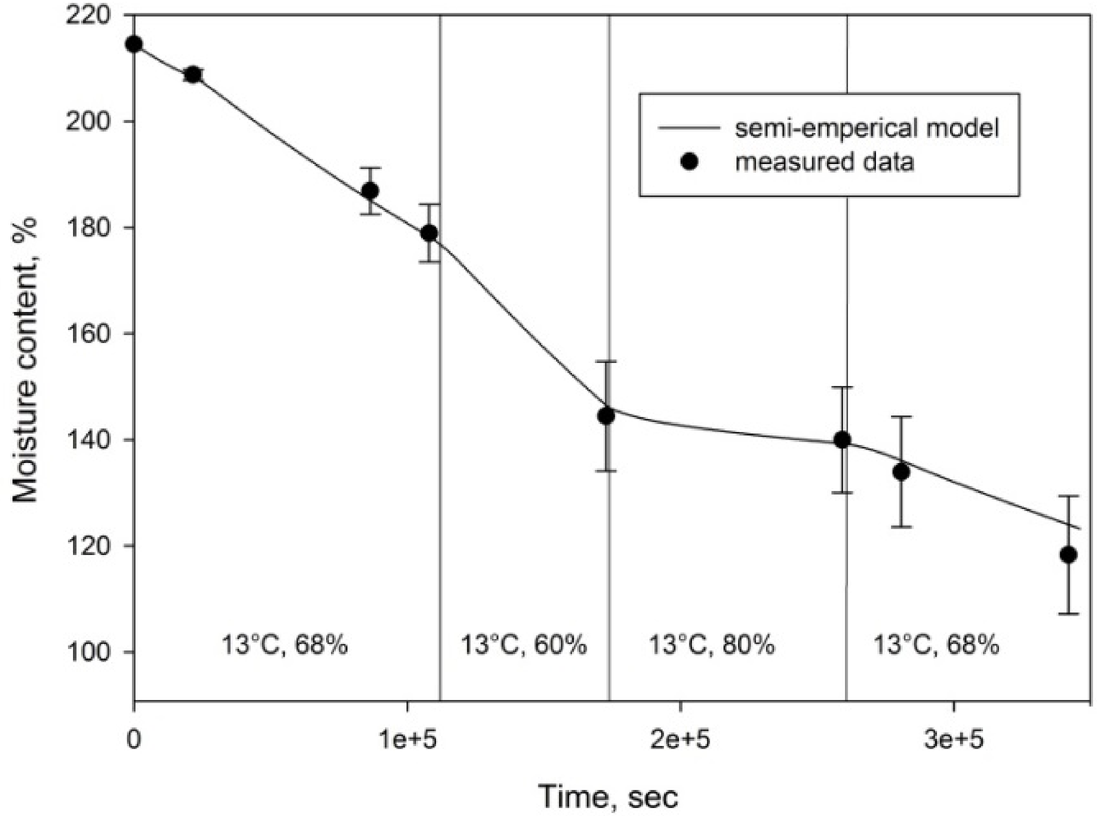




2.3 Modelling of drying systems: ham



2.3 Modelling of drying system: ham



2.3 Modelling of drying systems:

- Physical models
  - Not as precise as empirical models
  - What is the smallest drying volume
  - Upscaling is easier compared to empirical models
  - Varying drying parameters can be included without separate experiments (?)
- Changing product properties → problematic

→ Can we couple heat and mass transfer of a drying system into other processes

→ How is the interaction (in a closed loop)

→ What kind of control strategy

→ Are we interested in the absolute "error" of one model or in the "relative" error when comparing two different systems

3.1 Clipfish drying

- "Klippfisk" is codfish, disembowelled , cut open along the backbone and unfolded into on piece

- Stored in salt or brine (osmotic dehydration) for 3-4 weeks, moisture content of 55% to 60%

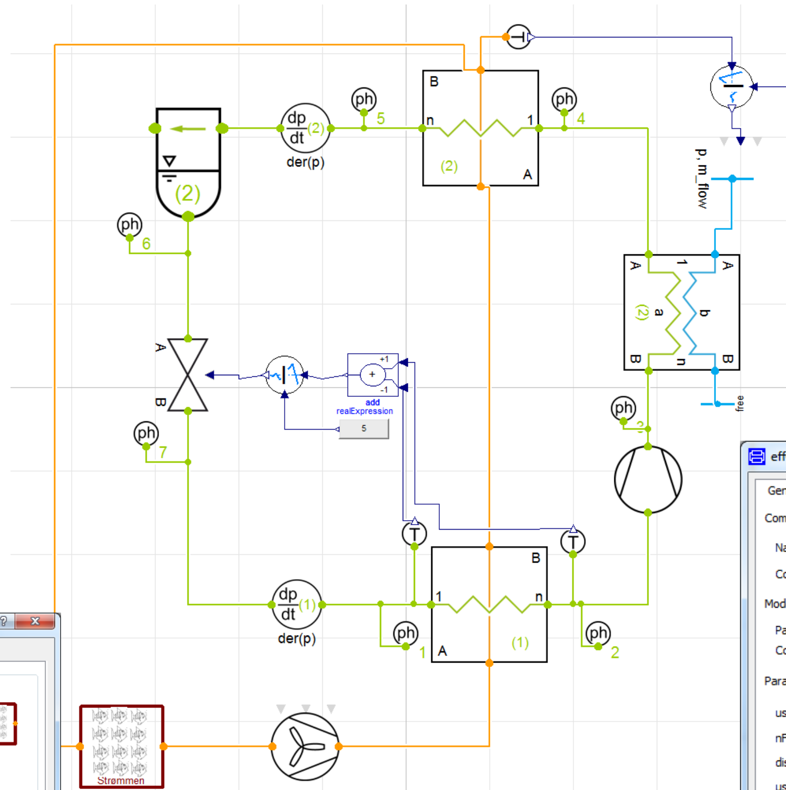
- Convective drying for 3-7 days until moisture content is reduced to 43%-48%
  - Temperature 20-26°C, humidity ≈40%, velocity 1.5 m/sec

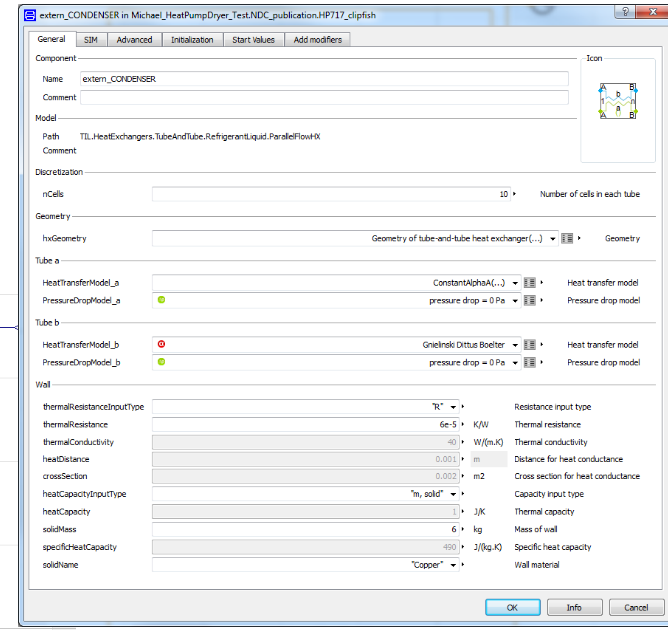
2. Heat Pump Drying of Clipfish

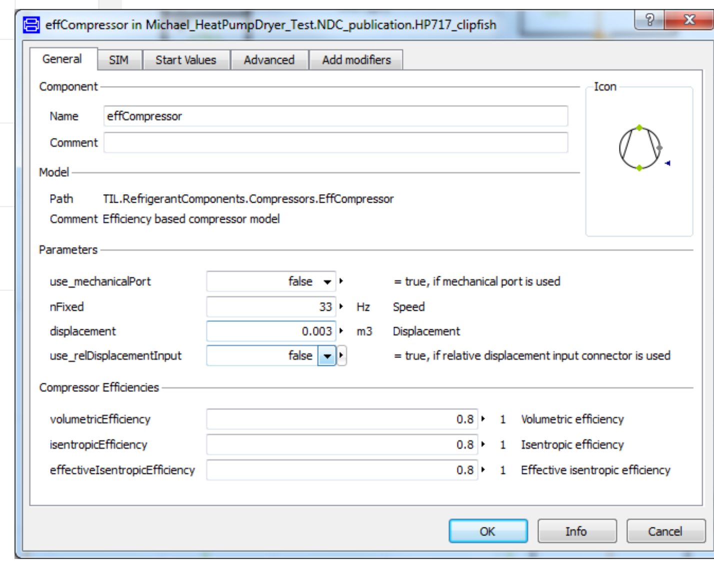
3.1 Model of HPD of clipfish

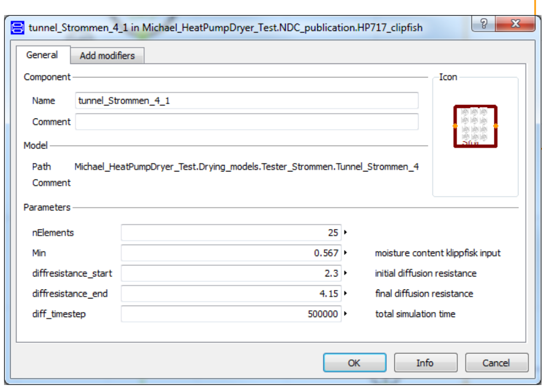
Design for

- 250kW HP system
- 40 ton drying tunnel (5*2*25 meter)
- based on industrial plant

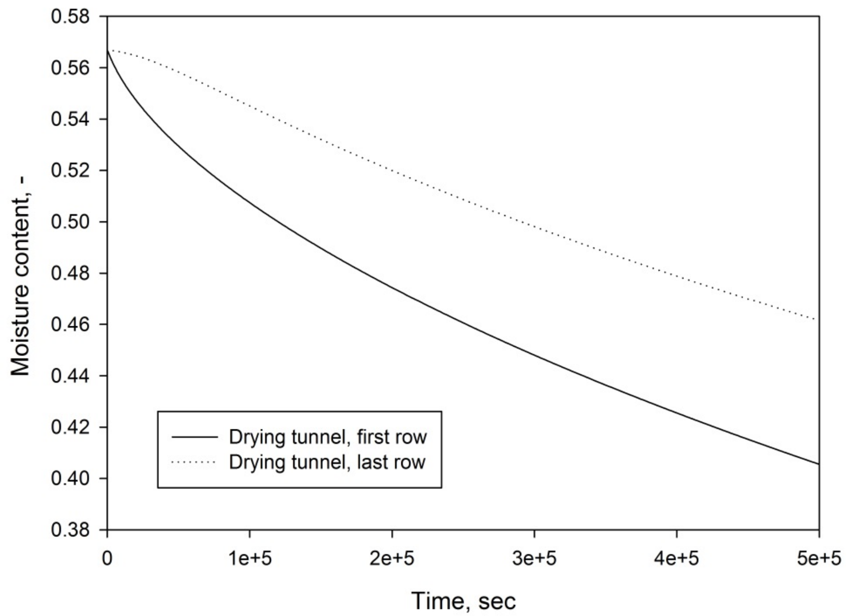






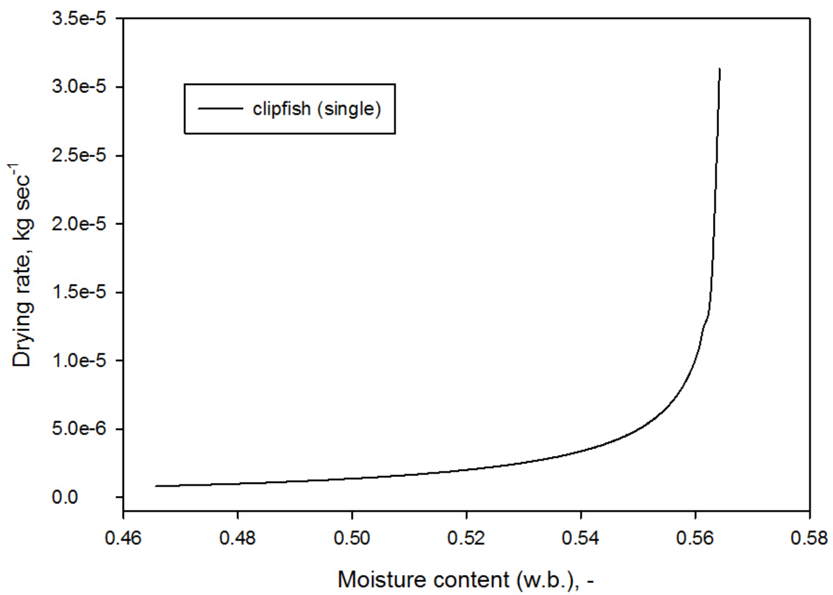


4. Results: Moisture profile in the tunnel



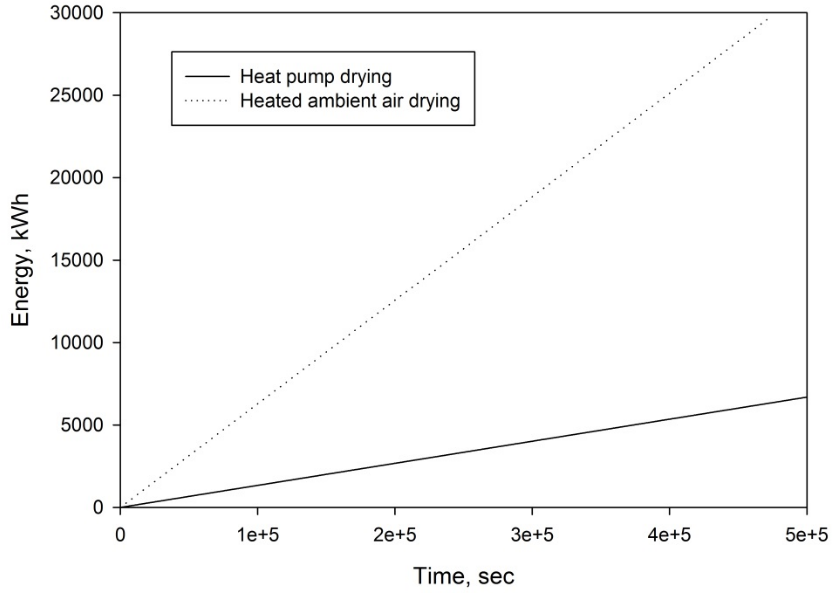
- Last row is drying very slow
  - Model can answer when each tray is dried enough
  - Constructive changes (wider tunnel, shorter tunnel, cross flow tunnel,...)

4. Results: Drying rate



- Drying rate is fast in beginning and low towards the end
  - Long drying times and large drying units
  - Inefficient and expensive process towards the end of drying

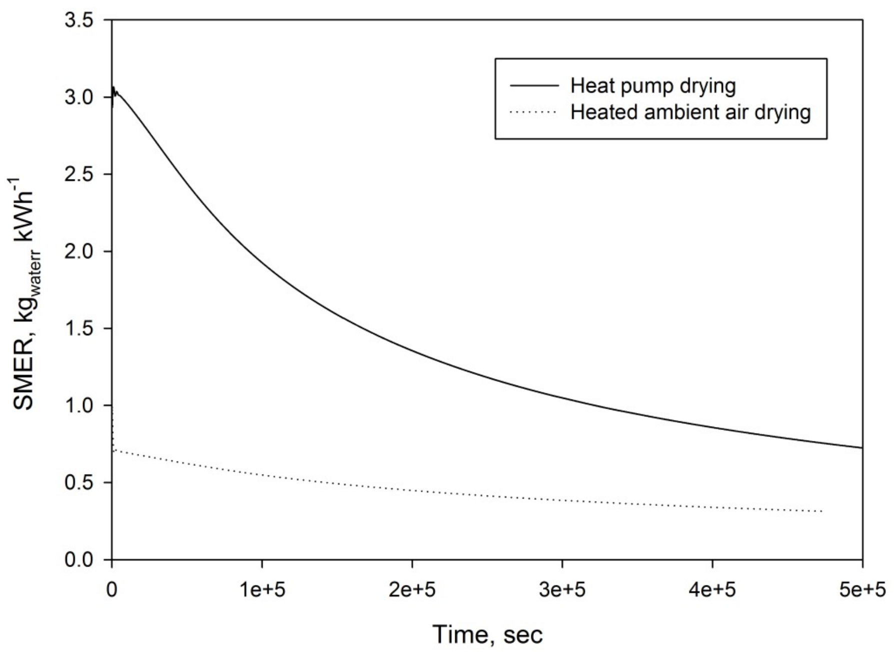
4. Results: Energy consumption for one batch



- Heat pump drying
  → 195.5 kWh/ton
- Heated ambient air drying
  → 973.8 kWh/ton

- Heat pump drying is more economic
  - HPD approximately 25% of HAAD
  → Significant for the production costs

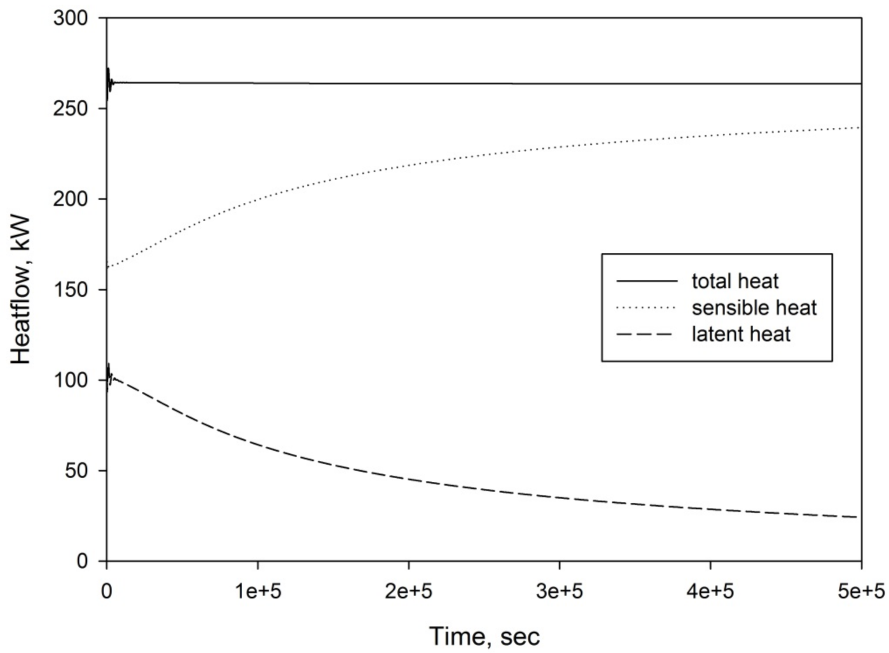
4. Results: SMER for HPD of clipfish



$$SMER = \frac{m_{water,evaporated}}{energy_{input}}$$

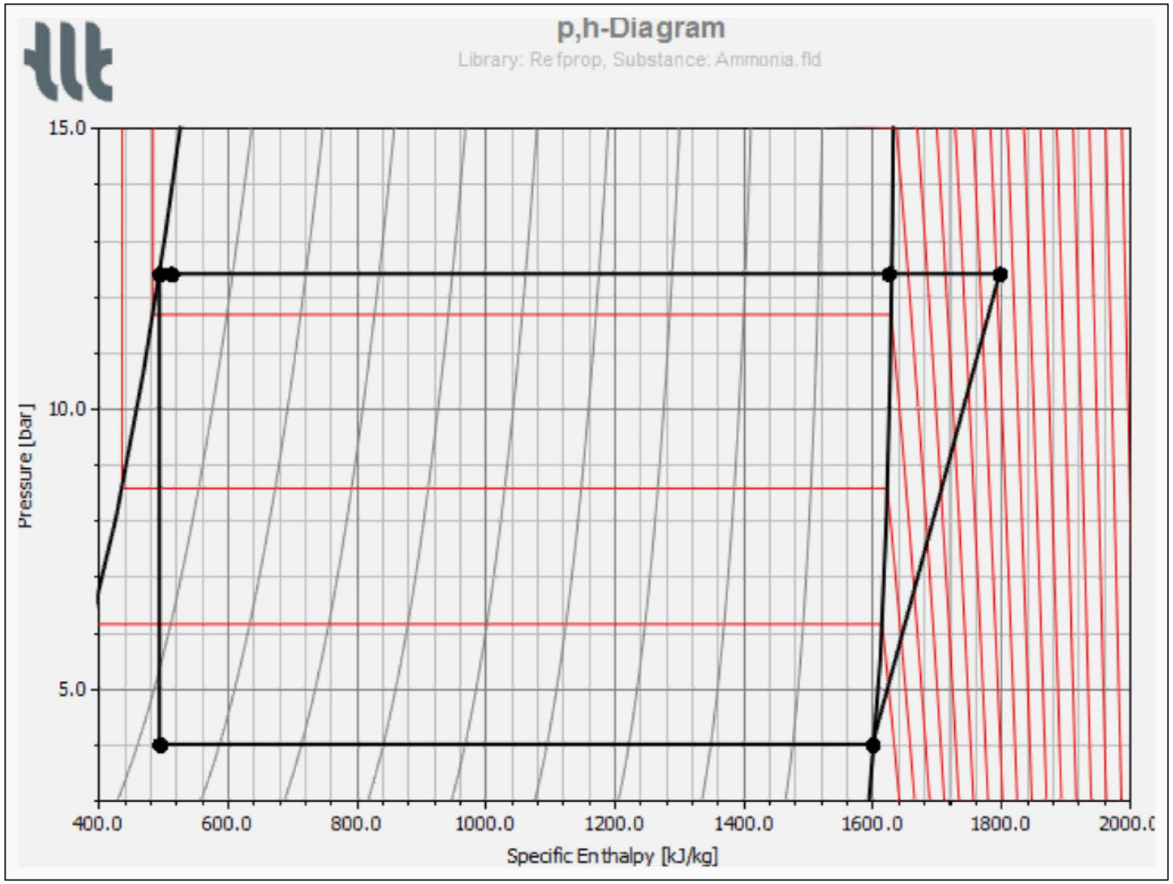
- Falling SMER for both processes
  - more significant for HPD
- Develop control strategy for ventilation and compressor in order to increase efficiency of batch process

4. Results: Heat flow in evaporator



- With on-going drying less latent heat and more sensible heat is transferred.
- Total amount of transferred heat is stable
  - This is what reduces the SMER

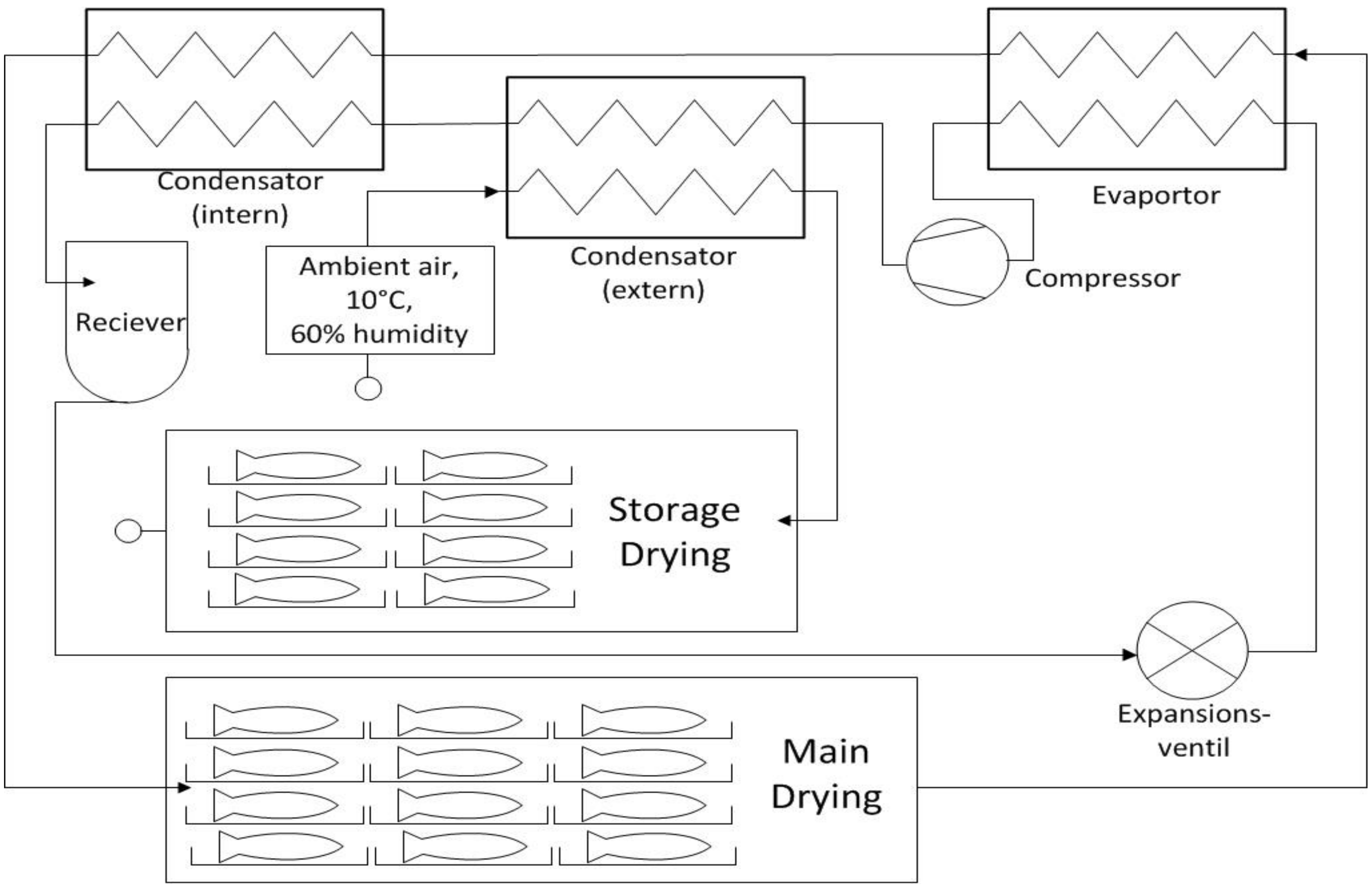
4. Results: HPD in log-ph diagram



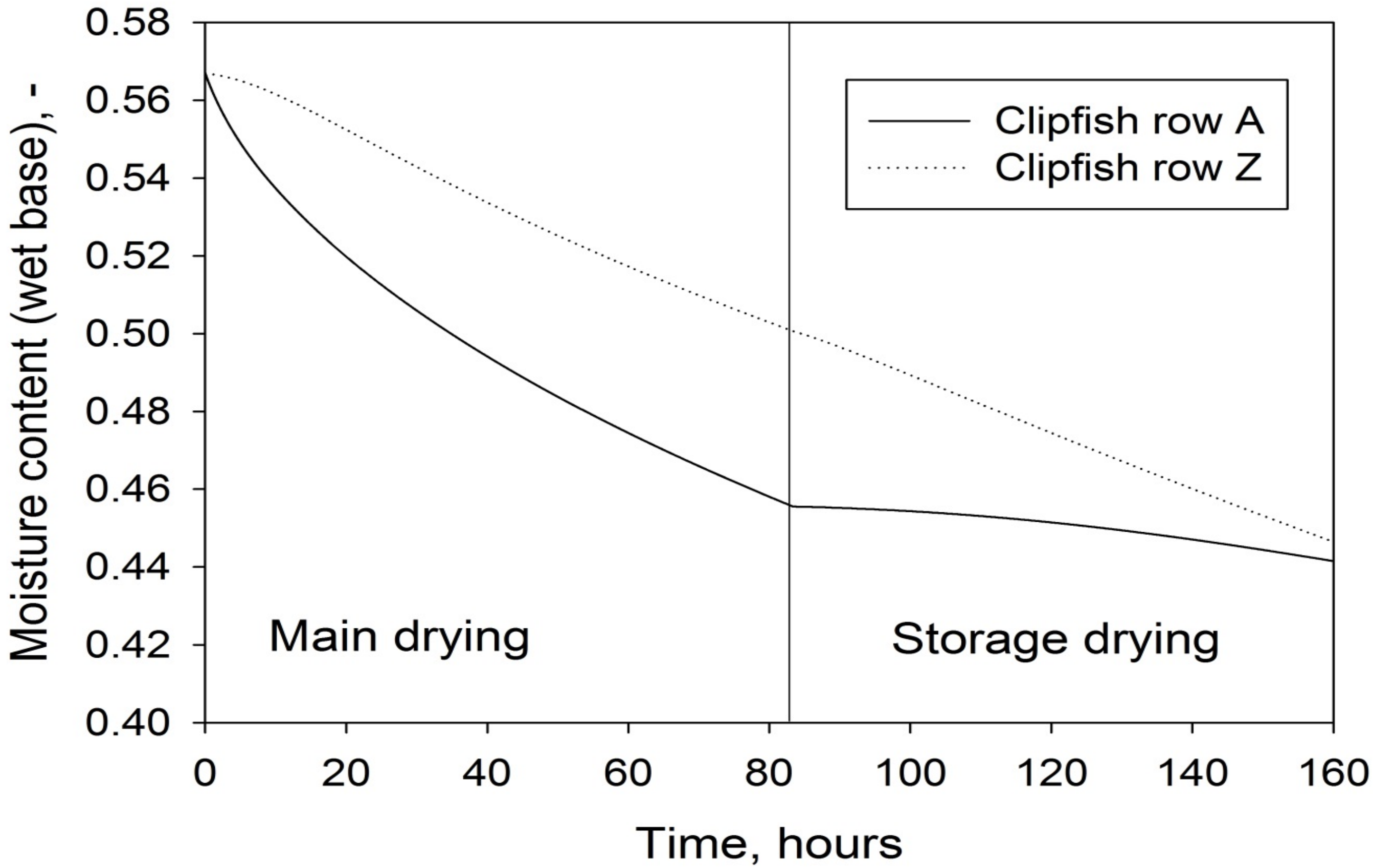
3.2 Heat Pump Drying with Storage drying

- Product quality is defined during the first 1-2 days of drying
- Drying rate is high in the beginning and low at the end of the drying period
- Drying efficiency is also high in the beginning and low in the end
    - Depends on control strategy
    - In industrial systems temperature, humidity and air flow is normally kept constant
- Excess energy available from the secondary condenser
- Moisture profile through the tunnel
    - Varying product quality (over-dried at one end and not-dried-enough at the other end
    - Need to run the (batch) tunnel longer (increased drying time)

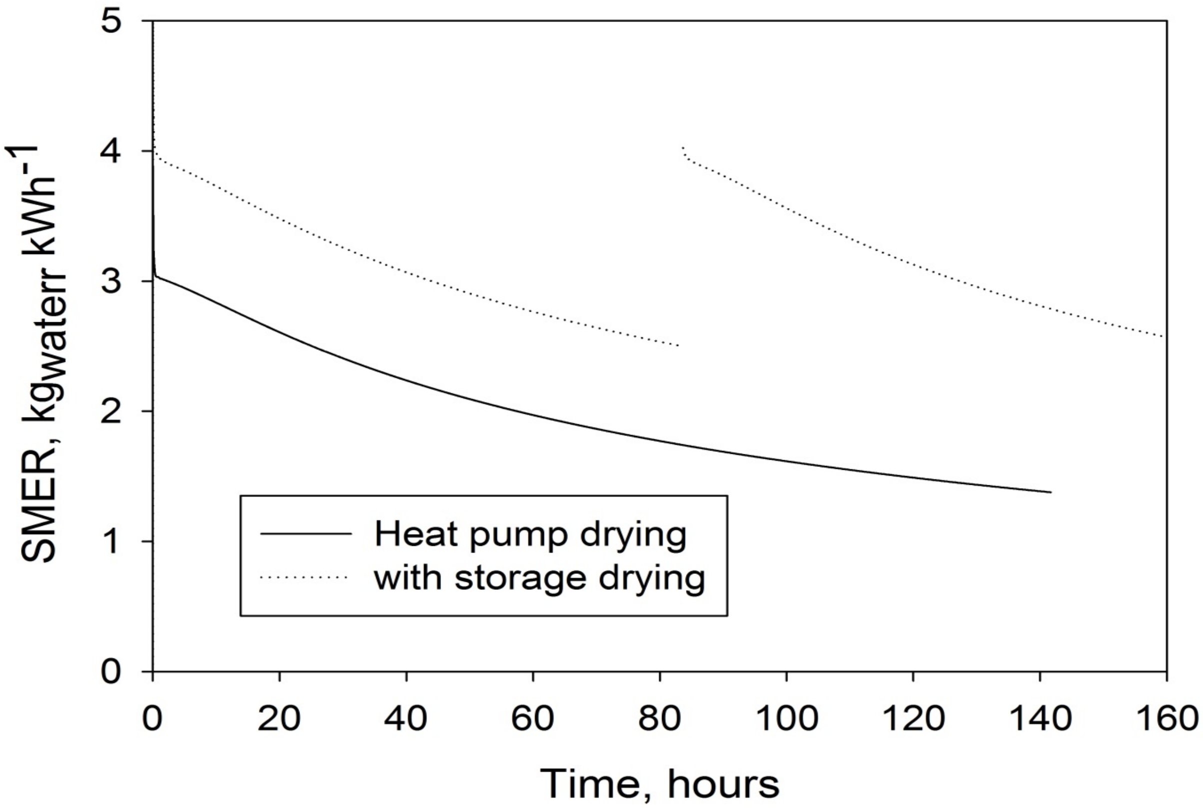
3.2 Heat Pump Drying with Storage drying



3.2 Heat Pump Drying with Storage drying



3.2 Heat Pump Drying with Storage drying



3.2 Results HPD vs. HPD+storage

- Effective drying time reduction of 40% (effective)
- Increase of productivity of the system by 40%
- Drying time per fish is increase from 6 to 7 days
- SMER is increased by 1 kg water per kWh

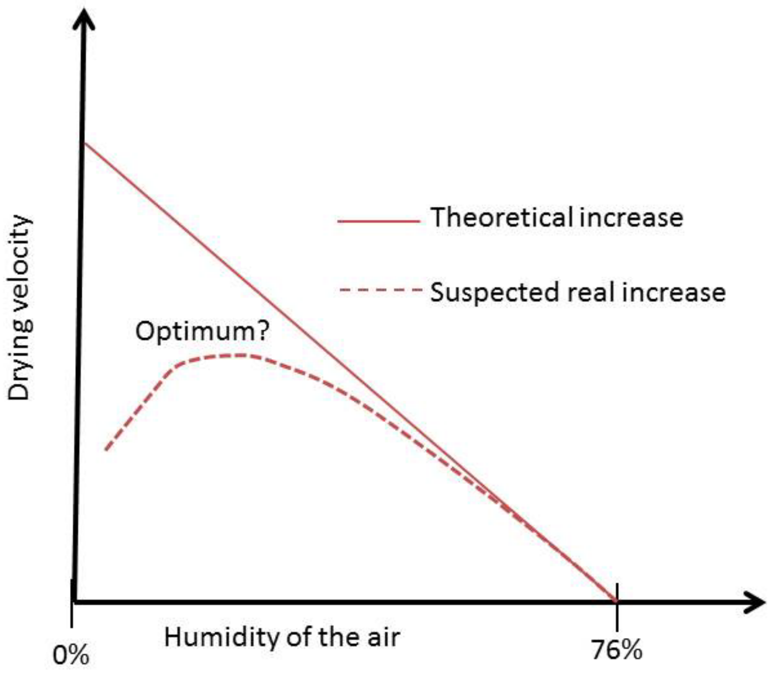
	Production costs
Main + Storage Drying	133.6 kWh
HPD	222.8 kWh per ton
HAAD	973.8 kWh per ton

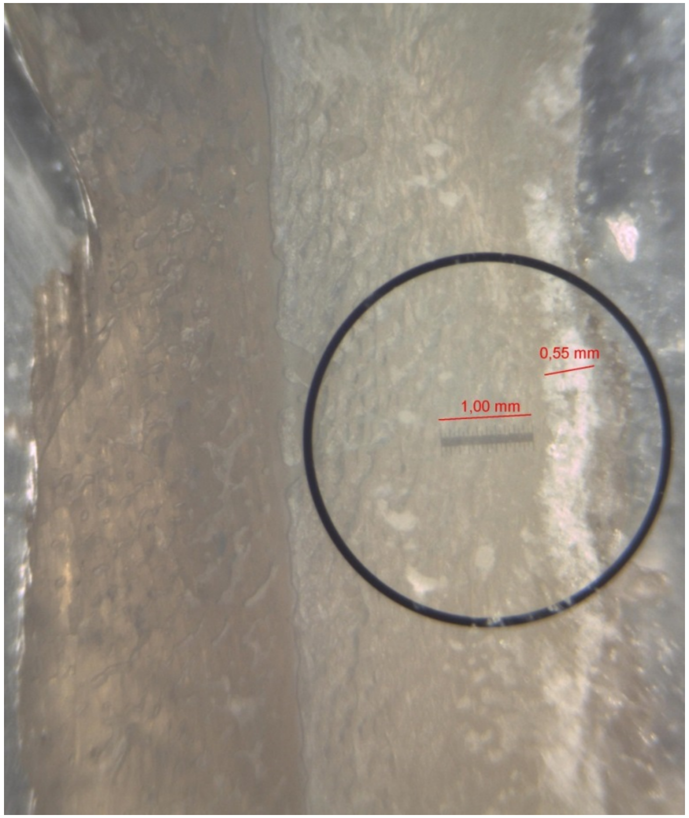
3.2 Results HPD vs. HPD + storage

- R717 can be applied in HPD
- Heat pump drying can reduce energy consumption by 80%(□future technology?)
- Sectioning the drying process with respect to drying progress and available heat/refrigeration □40% energy saving
- Main and storage drying concept can be applied on existing processing plants
- Model can also be used to optimize drying process with respect to refrigeration system

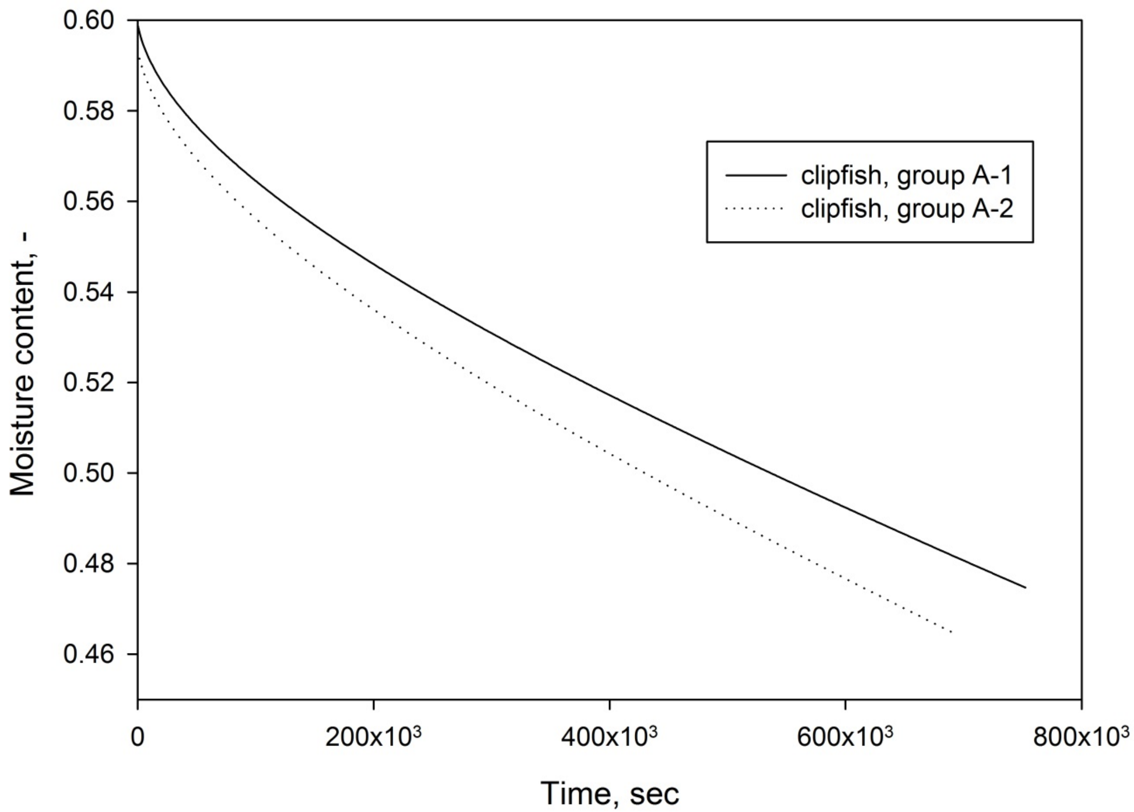
3.3 Intermitted drying

- During drying a dry layer is build up
  - Growing barrier for mass transfer through the produt
  - Growing barrier for heat transfer
  - Depends on the drying conditions



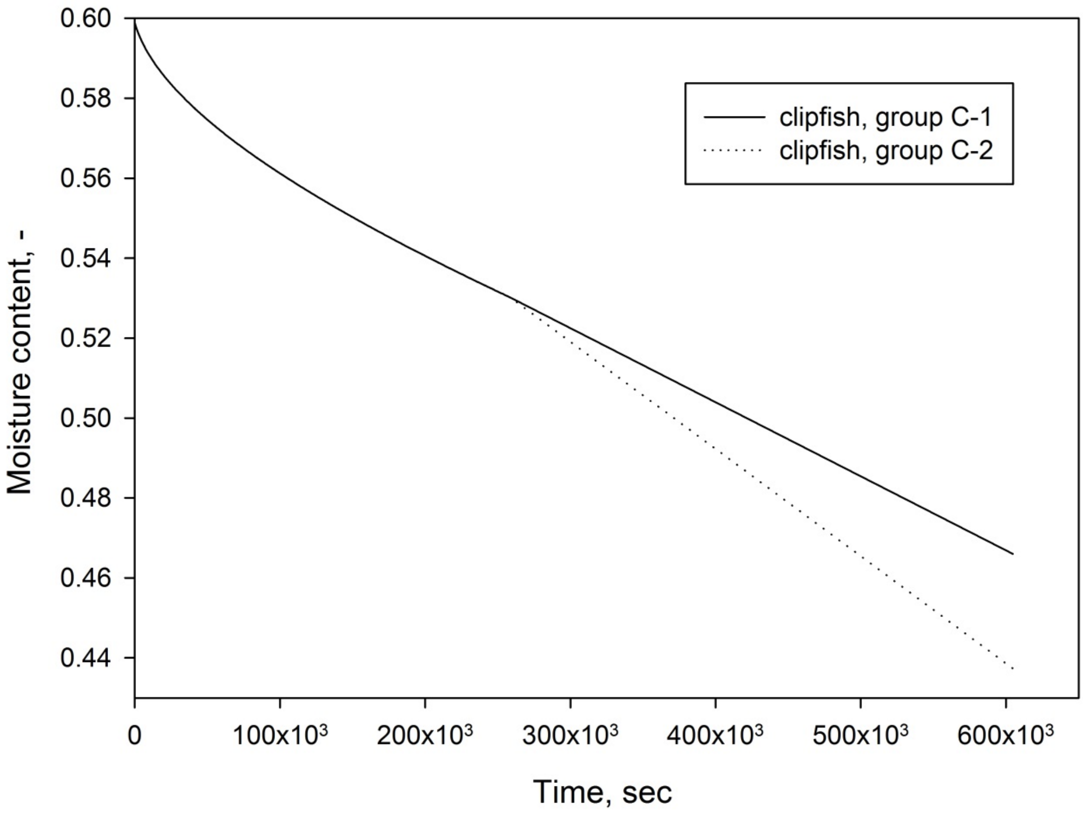


3.3 Intermitted drying



Groups:
A1: initial temperature of 4°C
A2: tempered for 17h at 22°C (room temperature)

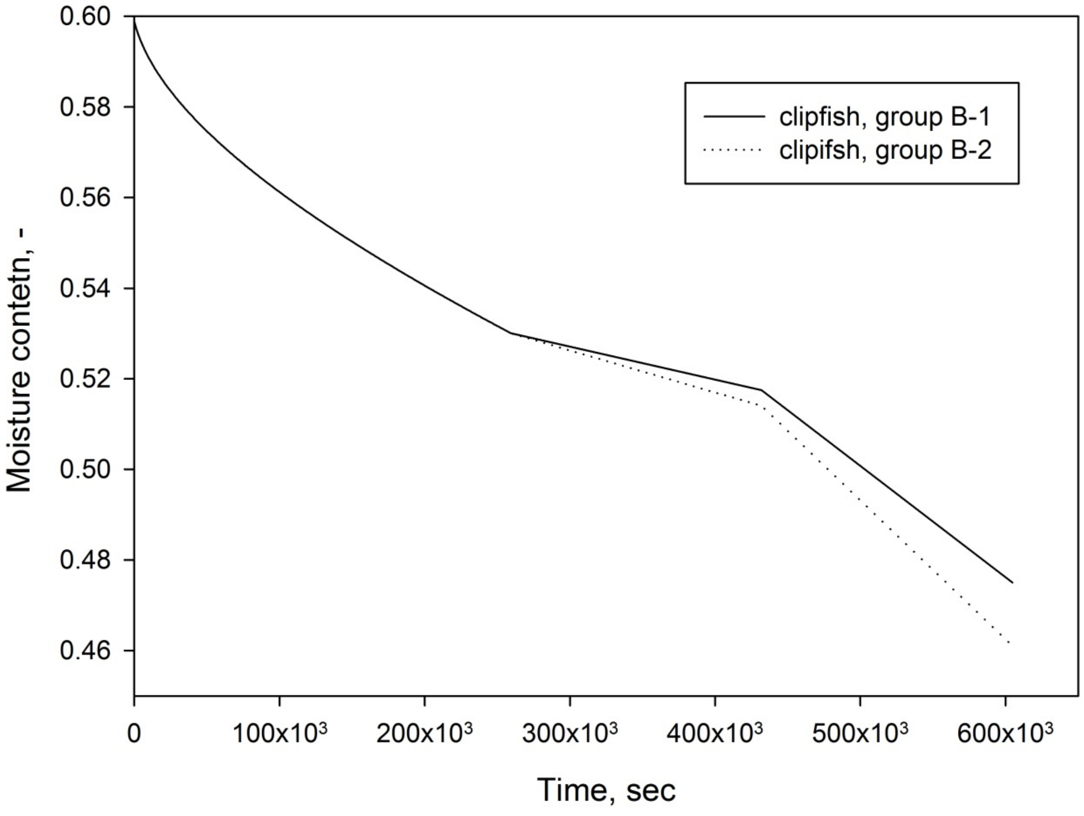
3.3 Intermitted drying



Groups:

C1: no treatment (standard drying)
C2: bended after 3 days, no intermediate storage

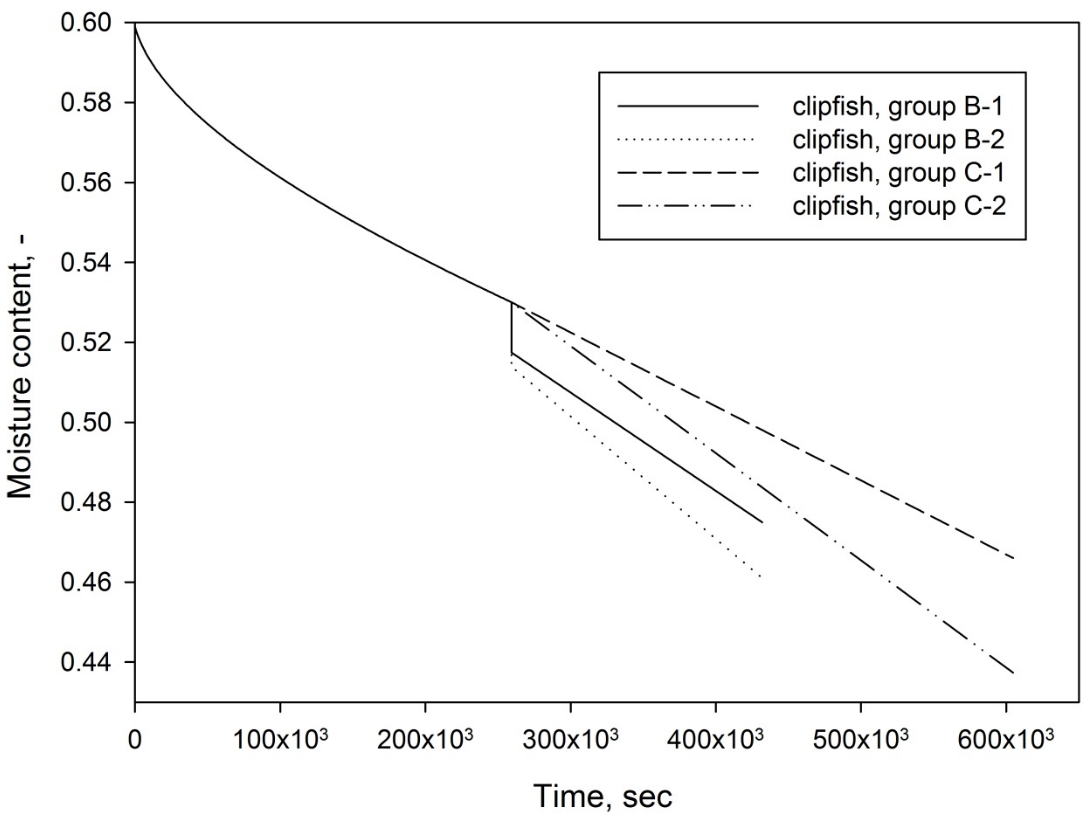
3.3 Intermitted drying



Groups:

B1: after 3 days intermediate storage at room temperature for 2 days
B2: after 3 days intermediate storage at room temperature for 2 days and bended

3.3 Intermitted drying



B1: after 3 days intermediate storage at room temperature for 2 days
B2: after 3 days intermediate storage at room temperature for 2 days and bended

C1: no treatment (standard drying)
C2: bended after 3 days, no intermediate storage

3.3 Intermitted Drying: Results

- Drying time reductions of up to 35 % can be achieved with the proposed measures.
- The capacity and productivity of existing plants can be increased without constructive changes of the drying system.
- Reduced drying layer due to moisture diffusion and a higher specific surface area are identified as cause for the higher heat and mass transfer.
- Further work will focus on applying the proposed measure in industrial drying systems.

4. Conclusions

- Increasing demand for:
  - High-quality food and feed
  - Reliable, "green" energy

  → Increased prices (?)
- Meat/Fish industry is associated with high amount greenhouse gases (~energy)
- Better usage of available food (and feed) sources

  → **Food preservation (=Drying)** will be a key element
- Use of "new" technology which is more energy efficient
  - Heat Pump Drying
  - Food/feed industry is quite conservative towards innovations
  - Payback time should be short (→ problematic)
- Food processing demands thermal energy

  → Heat pumps (European directive on use of renewable energy) for upgrade to premium energy

4. Conclusions

- Faster drying is not automatically more energy efficient
  - Smaller drying system
- Industrial application: drying technology and process technology should interact in a better way
  - Optimisation of the drying process and the energy system (production costs)
  - Hybrid drying systems (microwave/ultrasound/…)
- Dynamic process simulation
  - Heat transfer
  - Mass transfer
  - Biological changes (quality)
- Energy prices will influence future developments
- Legislative/Regulations will limit process technology

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