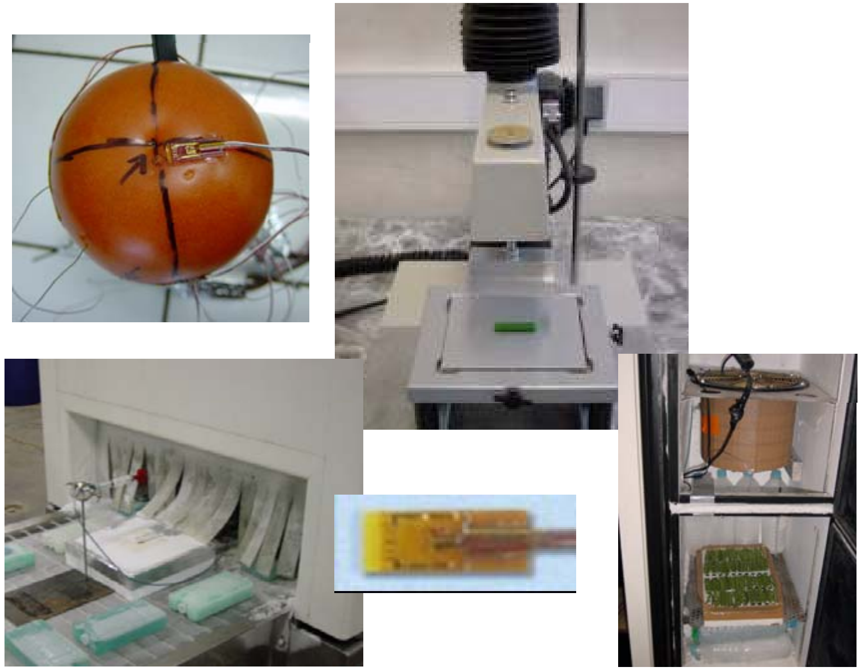
Assessment of energy efficiency in industrial freezing equipment by using heat flux sensors



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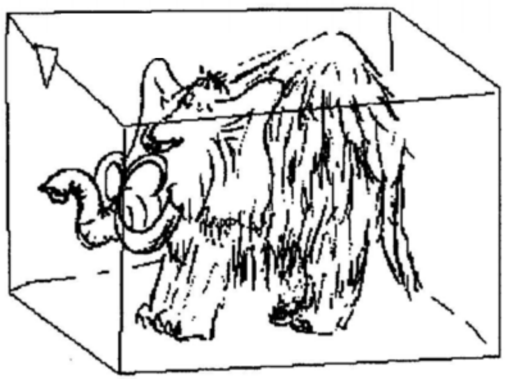
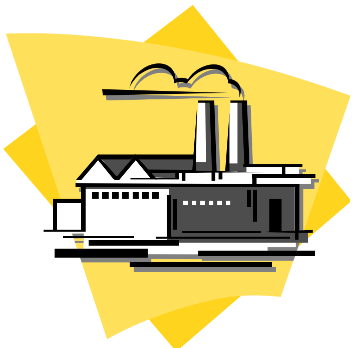
PUCPR

Outline

- **Introduction**
- **Calibration of heat flux sensors**
- **Transducers conception**
- **Application 1: Supercontact® freezing tunnel**
- **Application 2: plate freezer**
- **Application 3: fluidized bed freezer**
- **Conclusions et perspectives**

Introduction





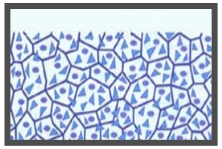
- Conservation of biological tissues by freezing has been observed for thousands of years
- The cold chain has been introduced in the market, however, only during the 30'
- Freezing is the most efficient method to preserve sensorial and nutritional food attributes over extended periods of time:
  - Little thermal degradation
  - Reduction of temperature
    - Reduction of decay reaction rates
  - Reduction of water activity (ice formation)
    - Reduction of water availability for decay reactions

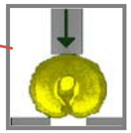
Fennema, 1977; Labuza, 1980; Leung, 1987; Cleland & Özilgen, 1998; Letang & Chourot, 2002

Introduction

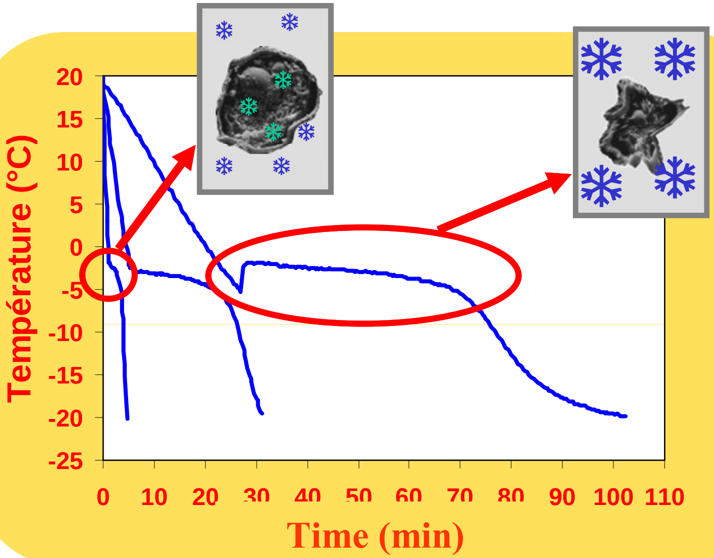
Process

Structure





Texture



Planck (1913)

$$t_c = \frac{\rho H_L}{(T_a - T_c)}\left[\frac{Pd}{h} + \frac{Rd^2}{\lambda_{ac}}\right]$$

Intrinsic factors (product):

Difficult to change

- Size: R (m)
- Area: A (m^2)
- Thermophysical properties : λ (W/m°C), c_p [J/(kg°C)], H_L (J/kg)

Key parameters

External factors (environment):

- Medium temperature : T_a (°C)
- Heat transfer coefficient : h [W/(m^2°C)]

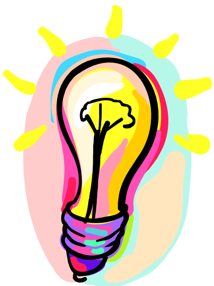
Introduction

Need for the efficient management of the freezing rate

- **Improvement of quality**
- **Optimization of energy use**

Development of methods to estimate the heat transfer coefficient (h, W/m²ºC)

- Simple and direct
- No need of extensive calculations
- Accurate
- Real time measurement
- Applicable to complex product geometries
- Not require prior knowledge of the product's thermophysical properties
- Applicable in industrial scale equipment



$$q = hA(Ts - Ta)$$

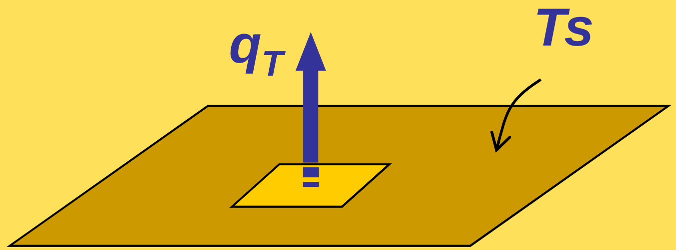
Heat transfer coefficient estimation

Some methods

- Calorimetric methods
  - Thermal balance applied to the product , inverse method
  - Exhaustive calculation
  - Heat losses
  - long response times
- Other less used and complex methods
- Heat flux sensors (potential method)
  - Short response time (< 1s)
  - Independent of the properties of the product

What is heat flux?

- Measurement of heat flux density
- Heat flux density: amount of heat transferred by surface area in the normal direction of the flux (W/m²)

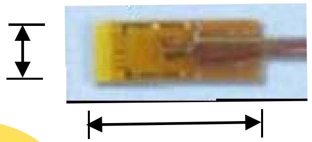


- It brings additional information to temperature data: direction and intensity of temperature change

Heat flux sensor

RdF 27036/3 (USA)

Thickness: 0,3 mm



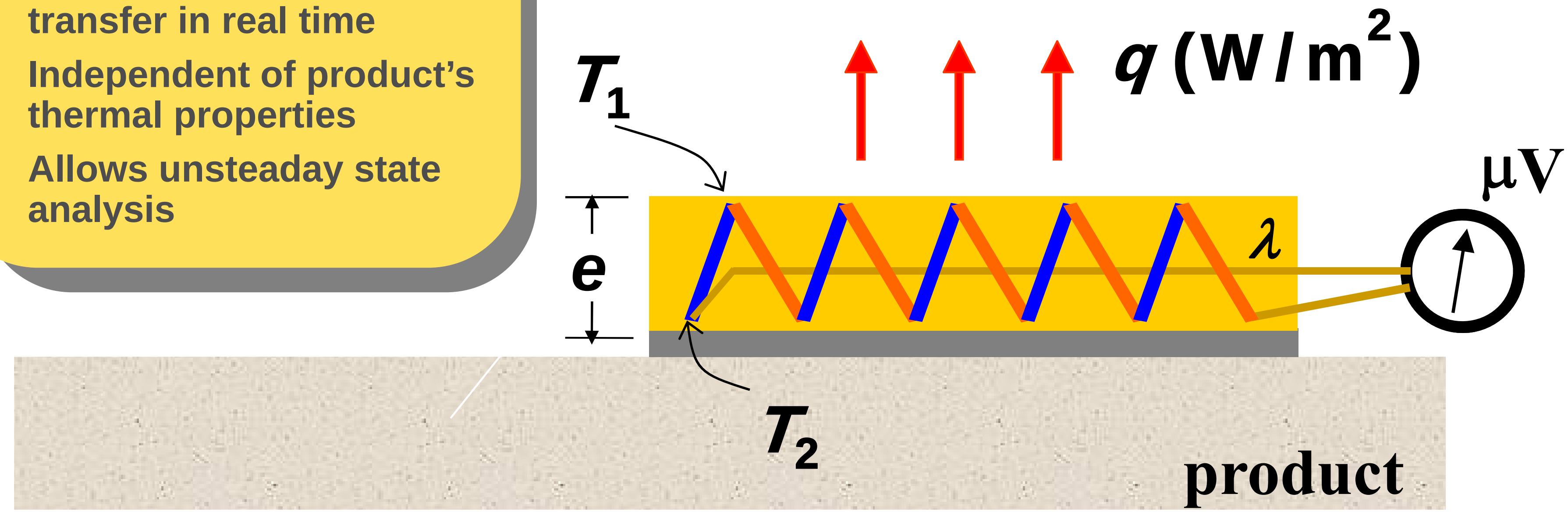
Advantages

- Low thermal mass
- Ease of measurement
- Assessment of heat transfer in real time
- Independent of product's thermal properties
- Allows unsteaday state analysis

Sensitivity [μV/(W/m²)]

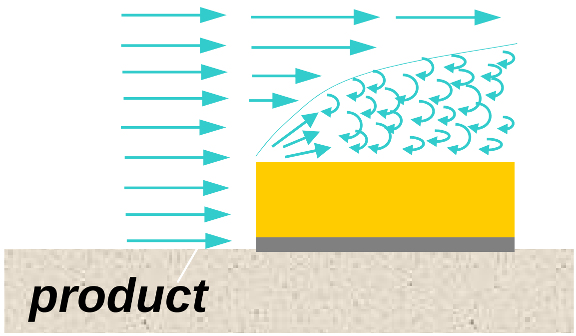
$$E(\mu V) \propto \Delta T(°C)$$

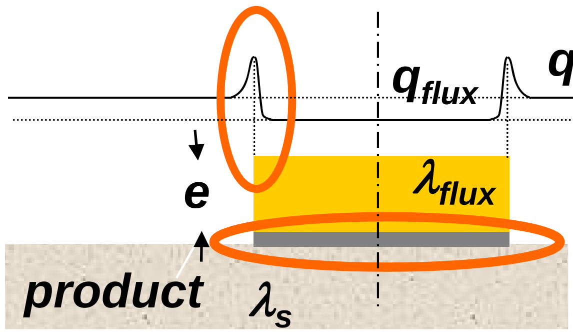
$$q = E/S \quad et \quad S = \frac{e.n.\varphi}{\lambda}$$

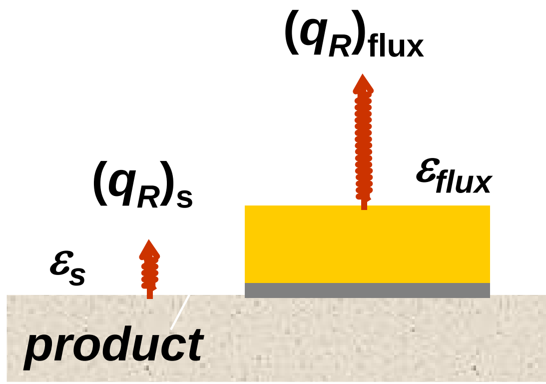


Heat flux sensor

Sources of experimental error







Convection

$Nu = CRe^a$

Flow disruption

Conduction

$$\frac{q_{flux}}{q_0} \propto \frac{R_{substrat}}{R_{substrat} + R_{flux}}$$

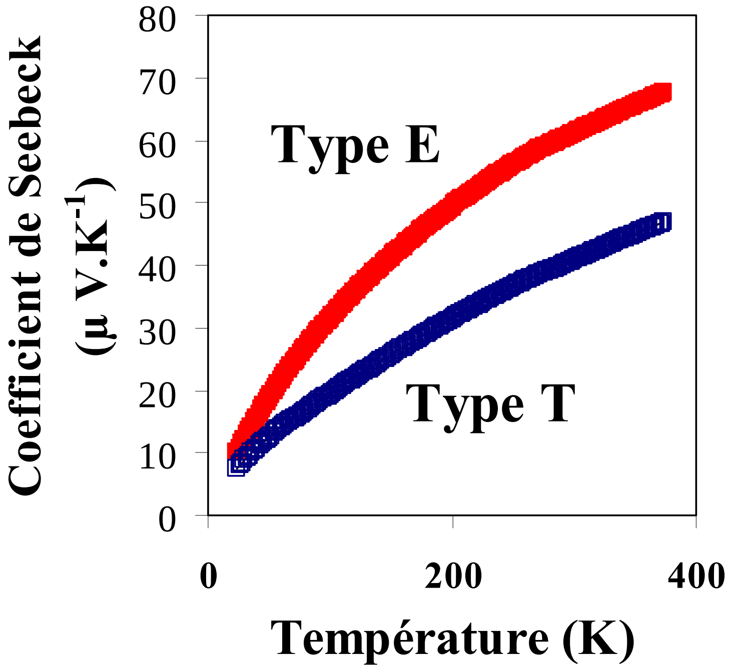
Imposed thermal resistance (m²°C/W)

Radiation

$\varepsilon_{flux} > \varepsilon_{substrat}$

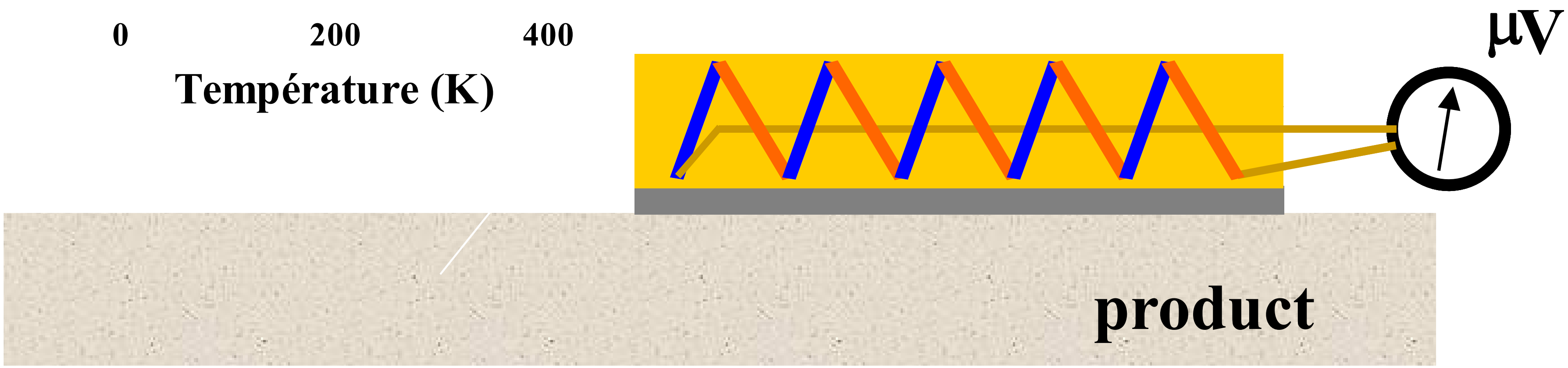
Différent Emissivities

Heat flux sensor



Thermopile – non-linear response in function of the temperature

$$S = \frac{e.n.\varphi}{\lambda}$$



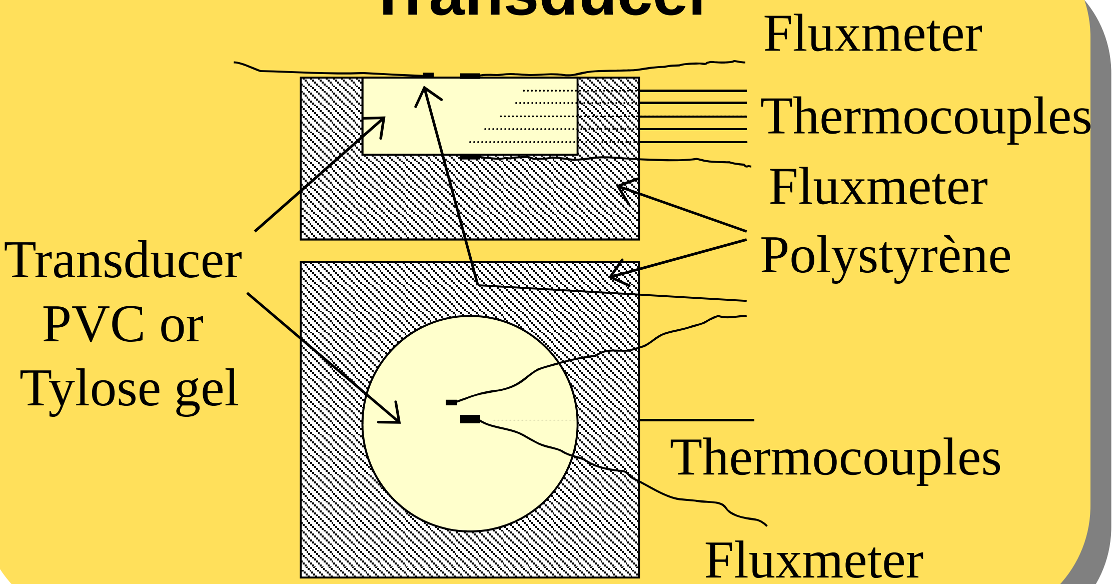
Calibration of heat flux sensors

- Steady state calibration: identification of the sensibility's variability with the temperature

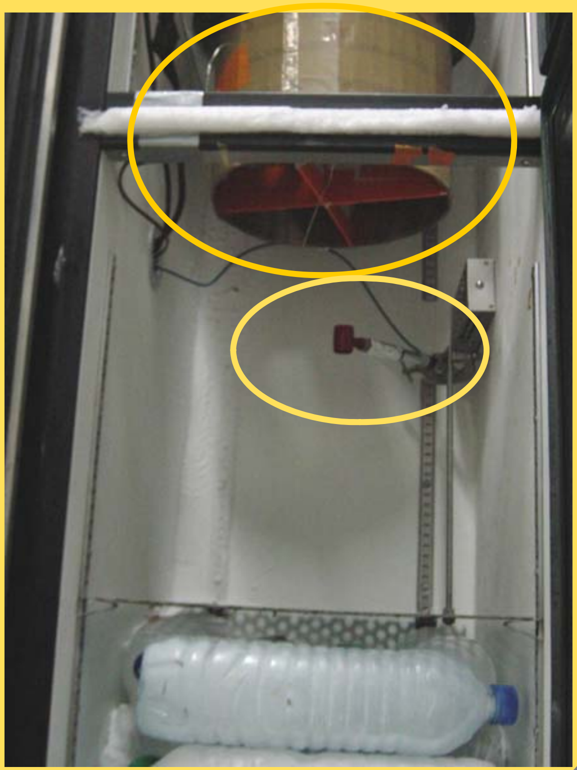
- Unsteady state calibration: determination of the sensibility at a reference temperature and under real use conditions (forced convection, low temperature)
  - On the surface of a model food (Tylose gel)
  - On the surface of a plastic transducer (PVC)

Calibration under unsteady state conditions

Transducer



Freezer



Conditions

- **Air speed 0, 1, 3, 5 et 7 m/s**
- **Chamber temperature: -40°C**

Calibration under unsteady state conditions
Calculation procedure

PVC Transducer

Adhesive tape

$$\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left[\alpha\frac{\partial T}{\partial x}\right]$$

Tylose Transducer

Heat sink paste

$$\frac{\partial H}{\partial t}=\frac{\partial}{\partial x}\left[\lambda\frac{\partial T}{\partial x}\right]$$

predicted X experimental values

Boundary conditions

$$q_s=\lambda\frac{\partial T}{\partial x}=h\left(T_a-T_s\right) \qquad \lambda\frac{\partial T}{\partial x}=q_i$$

Regression analysis

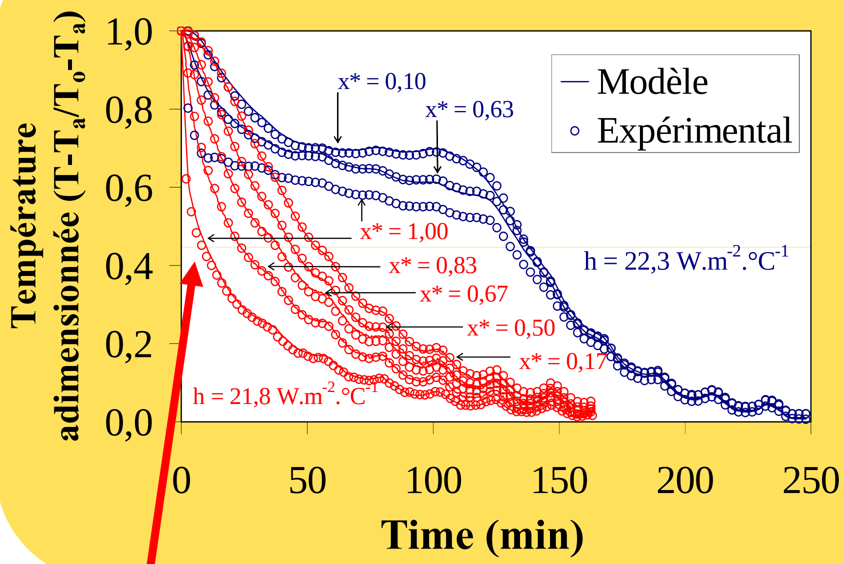
1) $SSQ_T=\frac{1}{N_l}\sum_{tout\,l}\sum_{tout\,i}\left(T_{l,i}^{exp}-T_{l,i}^{sim}\right)^2$ → h, $T_s(t)$, $q_s(t)$

2) $SSQ_q=\sum_{tout\,i}\left(\frac{V_i^{exp}F\left(T\right)}{S_{Réf}}-q_{s,i}^{sim}\right)^2$ → $S_{Réf}$

Calibration under unsteady state conditions
Results

1) Temperature gradients regression → ***h*, $T_s(t)$, $q_s(t)$**

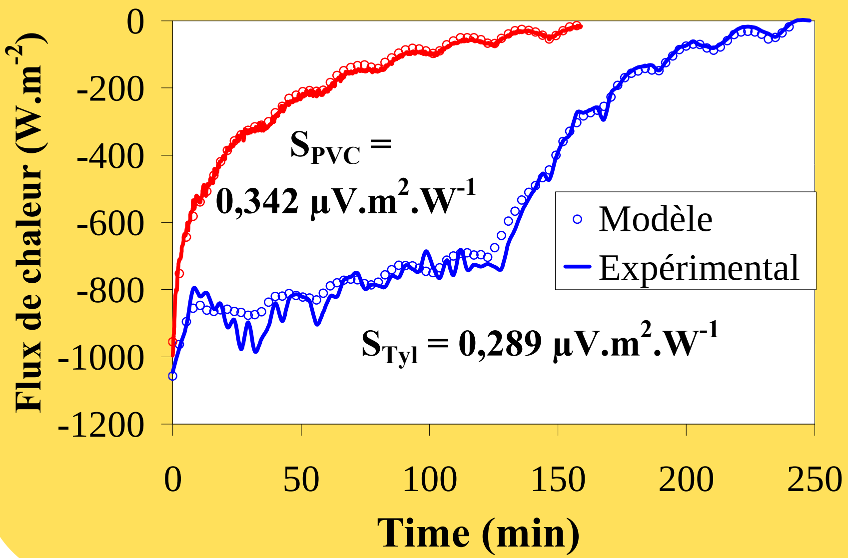
Fluxmeter 27036/3 – air speed 1 m/s



Surface thermocouple calibration

2) Heat flux regression

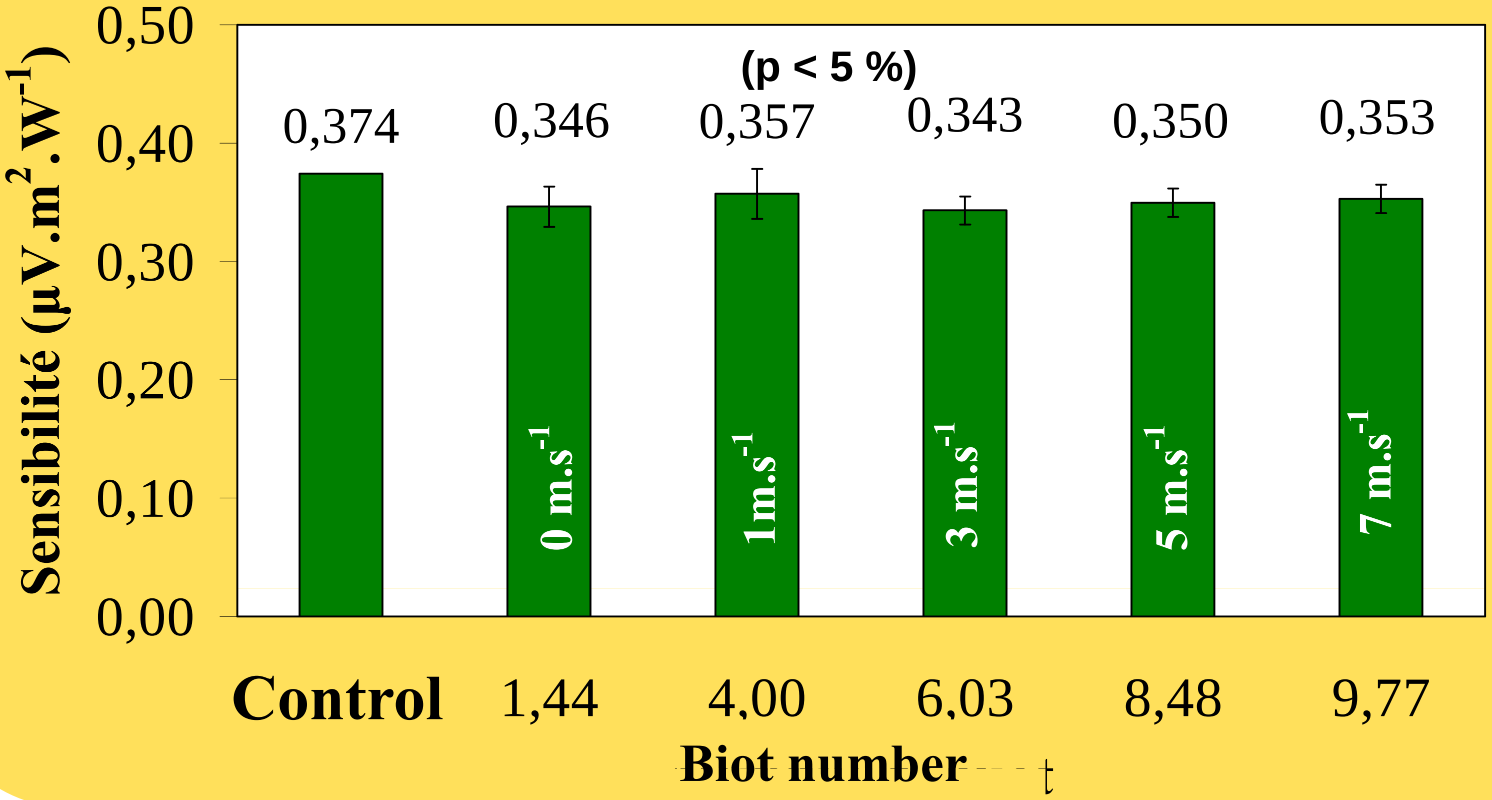
Fluxmeter 27036/3 – air speed 1 m/s



Calibration under unsteady state conditions
Results

Sensitivities on PVC

Fluxmeter 27036/3 – air speed 0 - 7 m/s; -40ºC

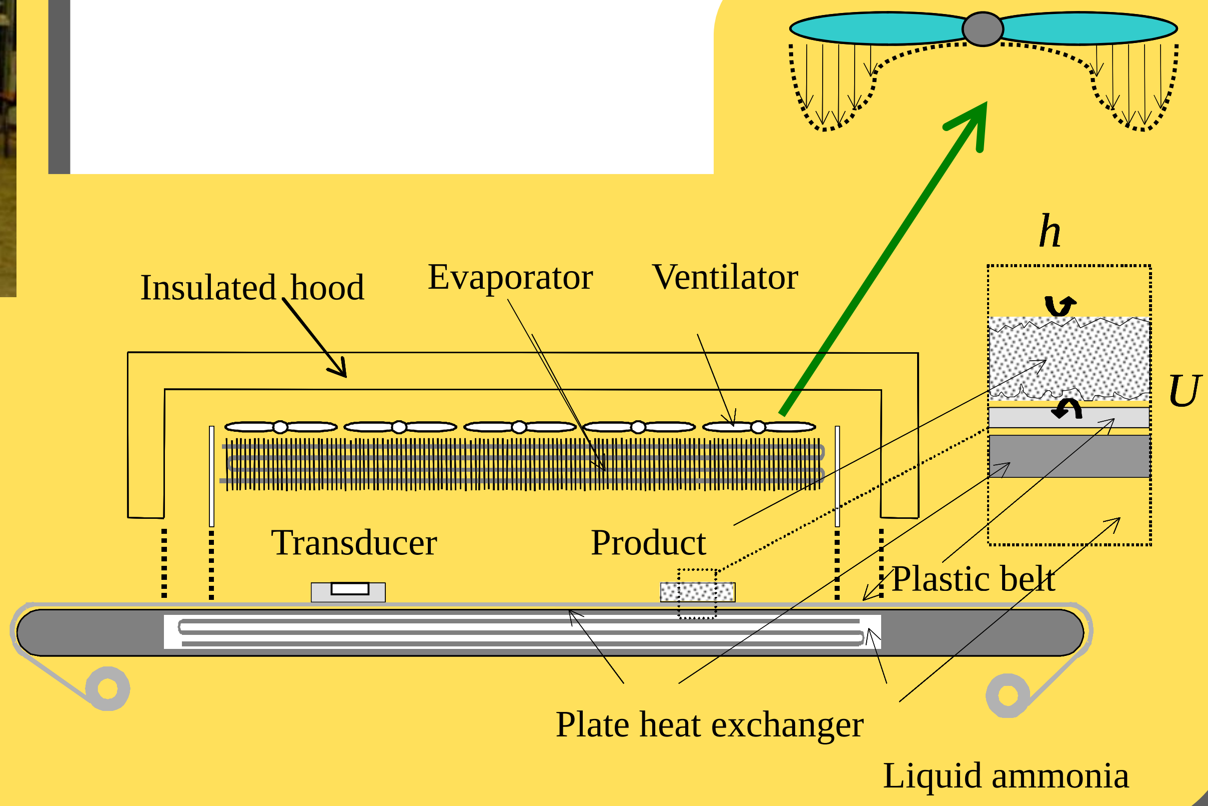


Calibration of heat flux sensors : synthesis

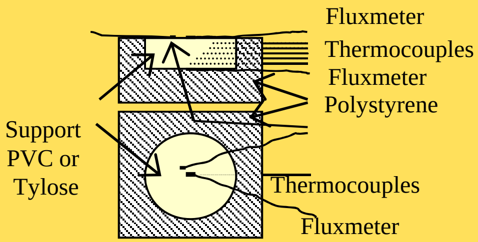
- Steady state calibration enabled the accurate determination of the variability of « S » with the temperature (results not shown)
- Unsteday state calibration enabled the accurate determination of « S » on Tylose and PVC surfaces under similar conditions as used in industrial freezers
- « S » is constant in the range of Biot numbers typically found in convective freezing (1 < *Bi* < 10)

Heat transfer coefficients in industrial freezers
Application 1: Super Contact Tunnel®

Super Contact Tunnel®
Prototype under development
(CIMS, France)

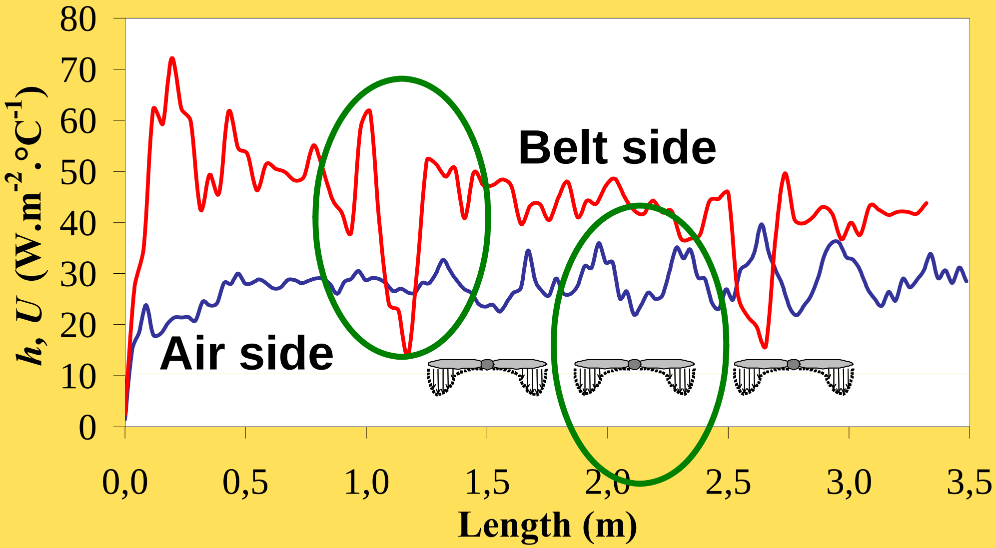


PVC Transducer

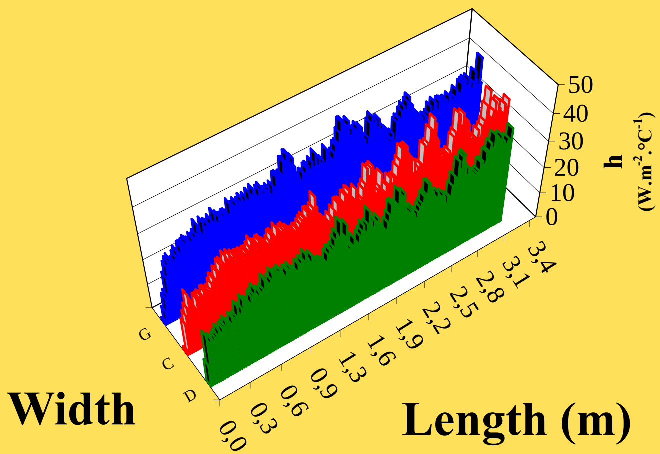


Heat transfer coefficients in industrial freezers
Application 1: SuperContact Tunnel®

Heat transfer coefficients air and plastic belt side



Cartography of heat transfer coefficients air side



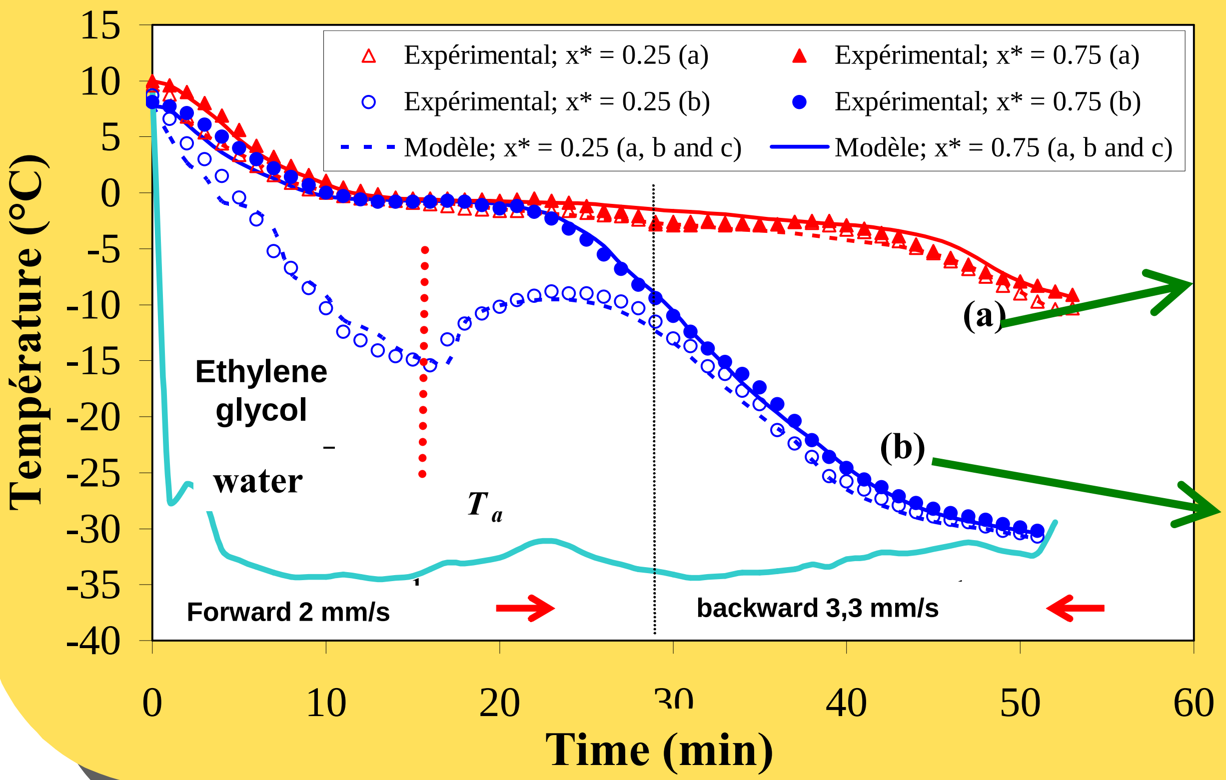
Coefficients air side – low efficiency zones as a result of the position of ventilators (high standard deviation increases ft in 5-15%)

Coefficients belt side – thermal resistance between product and plastic belt as the limiting factor for heat transfer (expected ~200 – 600 W/m^2°C)

Heat transfer coefficients in industrial freezers
Application 1: SuperContact Tunnel®

Asymmetrical freezing of Tylose

Experiments and simulation (Enthalpy model)



a) Conventional operation
h = 28 W/(m2°C) AIR
U = 40 W/(m^2°C) BELT

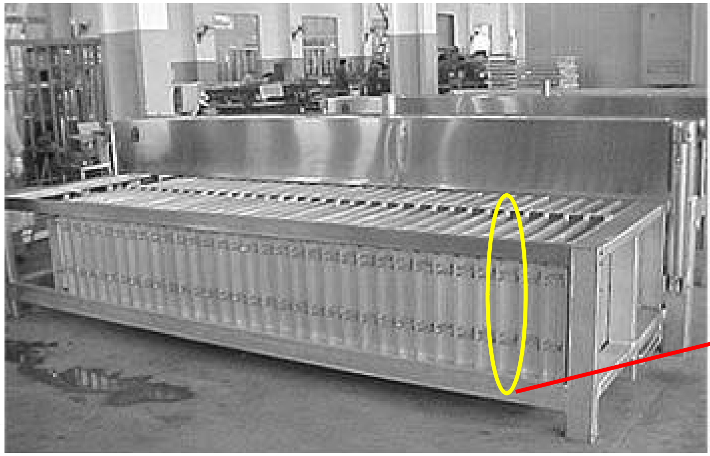
b) Moist thermal contact between belt and heat exch.

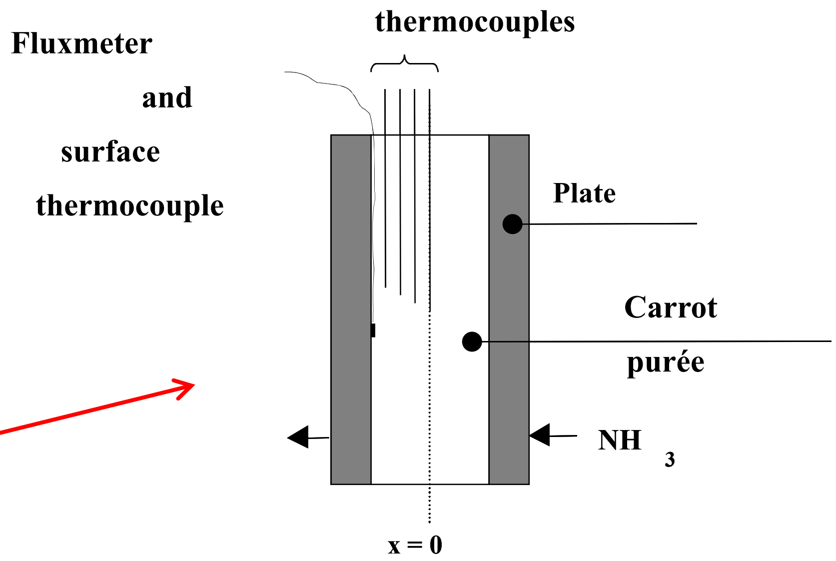
h = 28 W/(m2°C) AIR
U = 196 W/(m^2°C) BELT

Heat transfer coefficients in industrial freezers
Application 2: Plate freezer

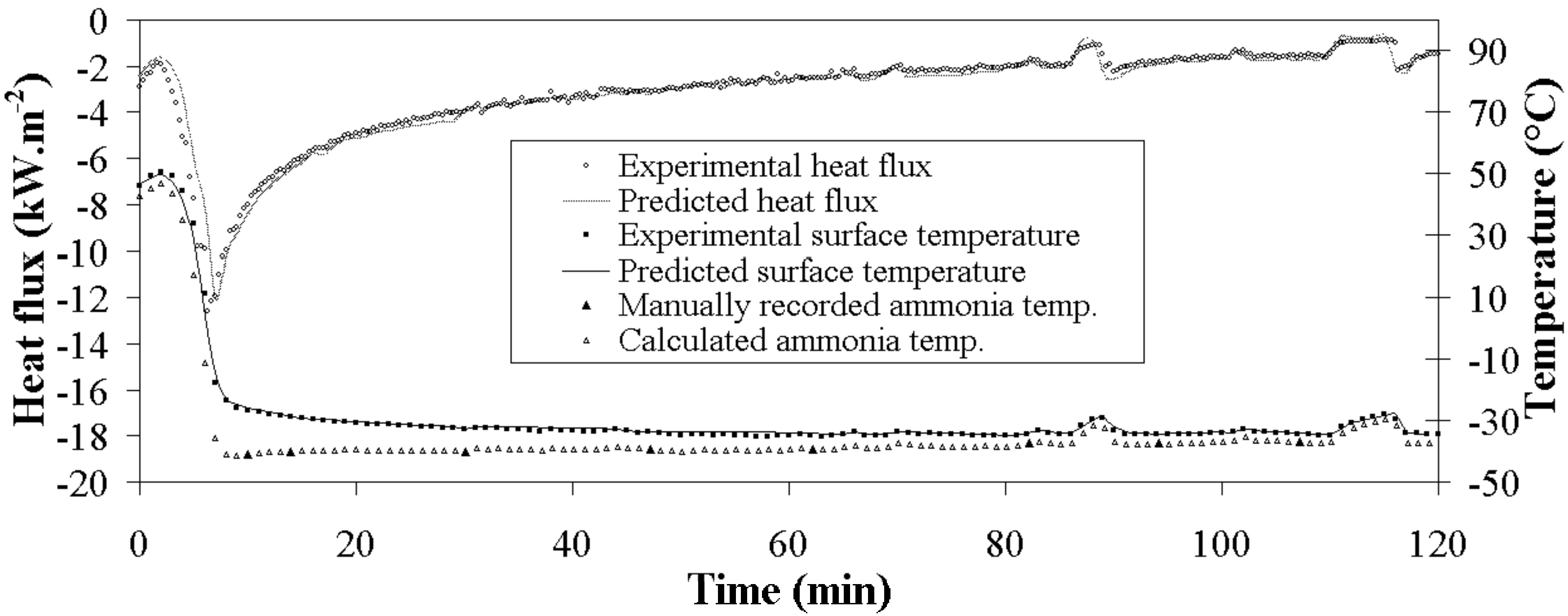
Plate freezer
(Samifi Babcock, Germany)

Carrot purée
~25 kg/cell/cycle



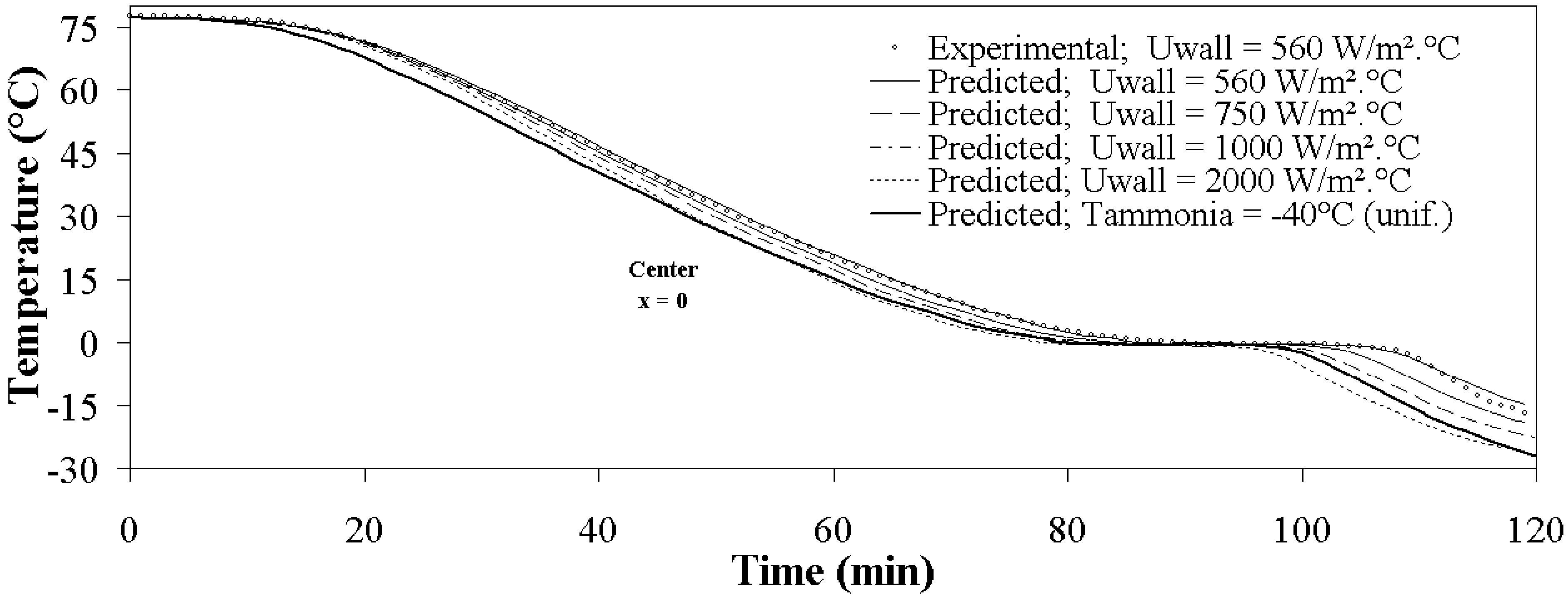


Heat transfer coefficients in industrial freezers
Application 2: Plate freezer



h = 560 W/m²ºC – compatible with contact freezing
Ammonia temperatute increases during the cycle (-40 to -35ºC)

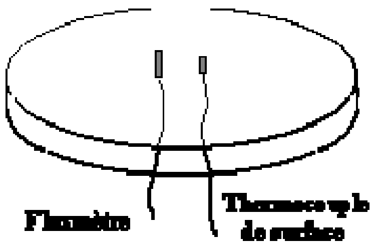
Heat transfer coefficients in industrial freezers
Application 2: Plate freezer



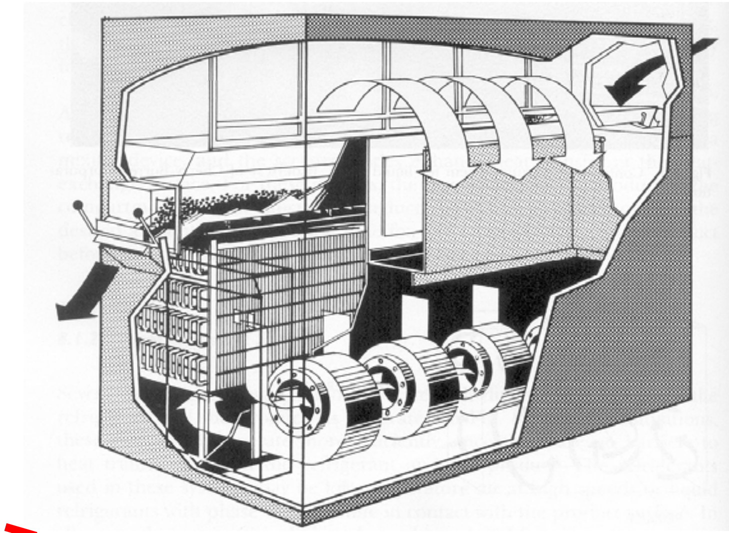
Further increase in h (costly) would not reduce significantly freezing time
Keeping ammonia temperatute constant (-40ºC) decreases freezing time by 8%
Reducing feeding temperature of purée by using a scraped surface heat exchanger would reduce significantly freezing time

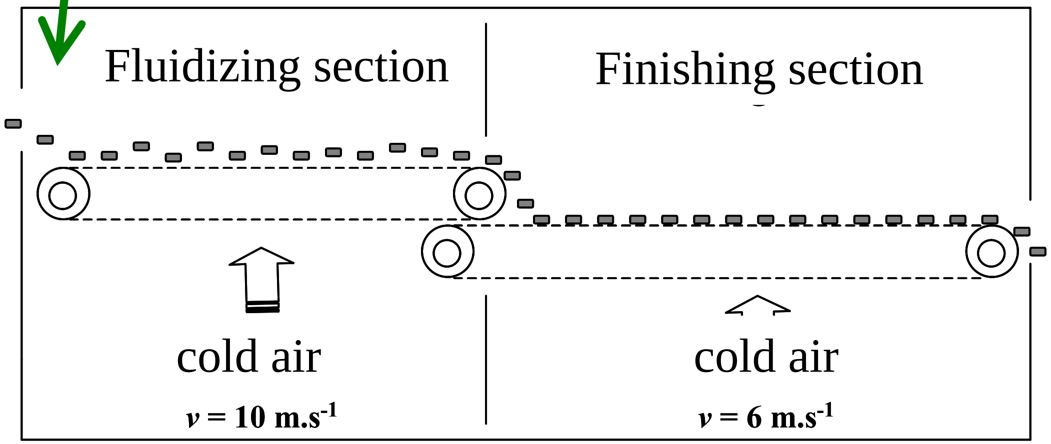
Heat transfer coefficients in industrial freezers
Application 3: Fluid bed freezer

Fluidized bed freezer (Samifi Babcock, Germany)



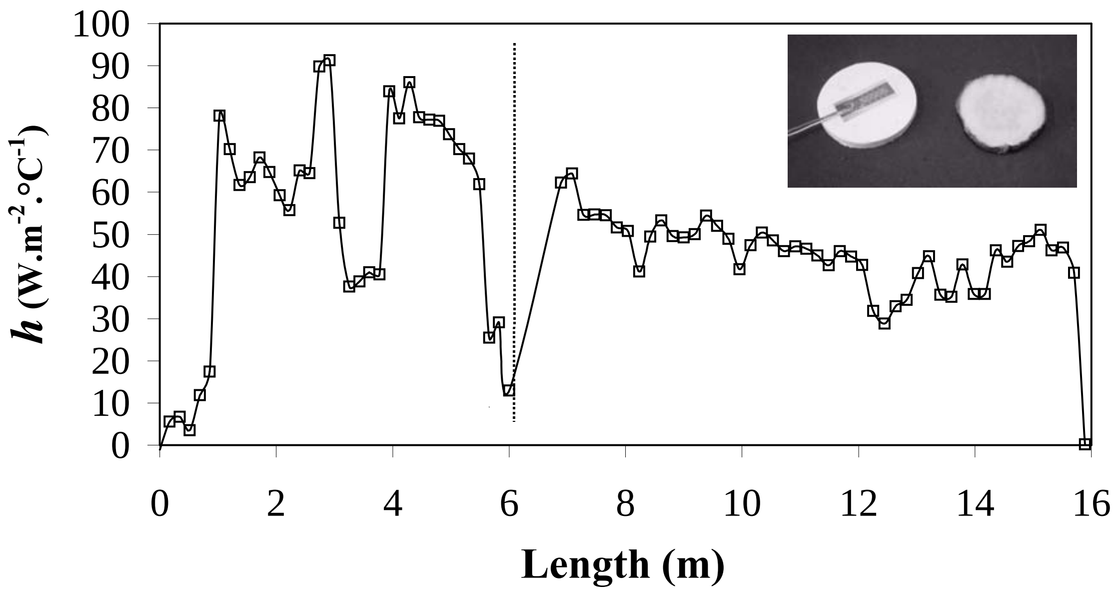
PVC microtransducer
Diameter: 50 mm
Thickness: 3 mm



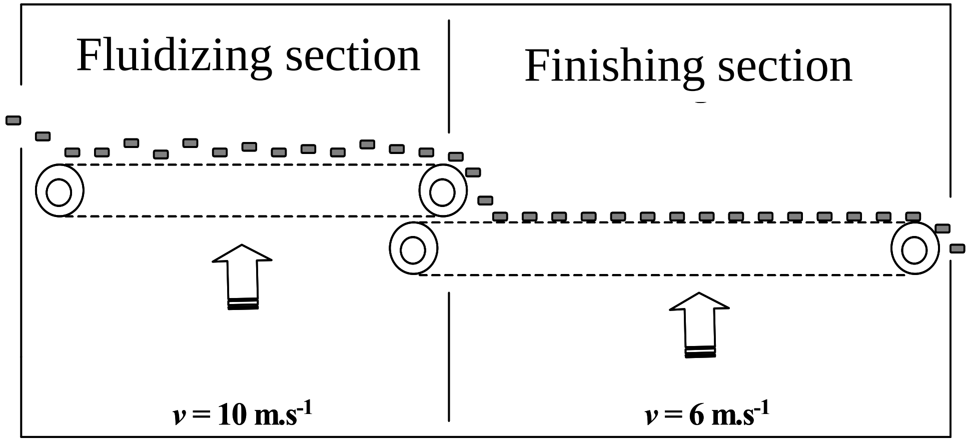


Cut zucchini 10 tons/hr

Heat transfer coefficients in industrial freezers
Application 3: Fluid bed freezer



Run # 3
Reproducible results



Conclusion and perspectives

- Heat flux sensors were accurately calibrated on different surfaces (plastic transducers and food-like material)
- Transducers equipped with heat flux sensors and thermocouples were able to measure accurately heat transfer coefficients under dynamic conditions
- The measurements allowed to diagnose energy inefficiencies and to recommend process optimization

- Use of fluxmeters to measure thermophysical properties of foods (heat capacity, thermal conductivity, enthalpy x temperature)
- Extend use to optimization of other processes (drying, cooking and other thermal processes)
- Develop new sensors and transducers (size reduction, wireless); transform into commercial product

Thank you!