Modeling adiabatic heating for optimization of high pressure processing

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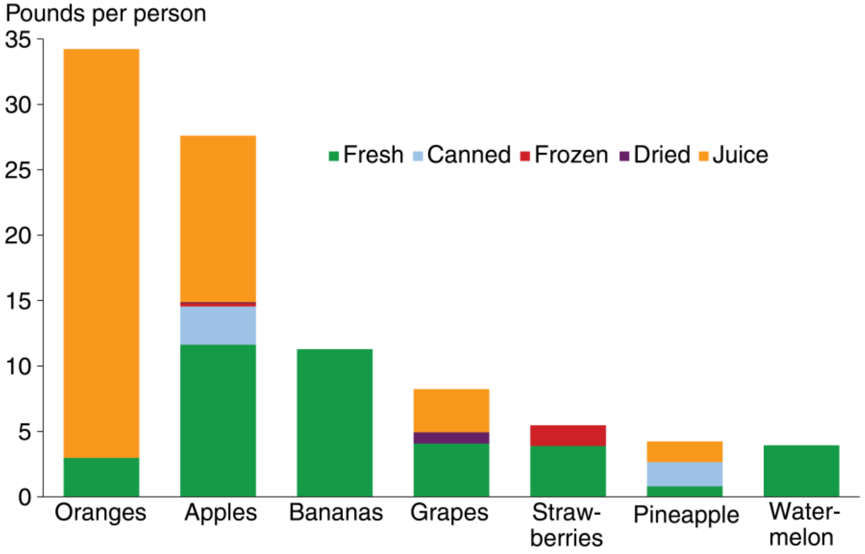
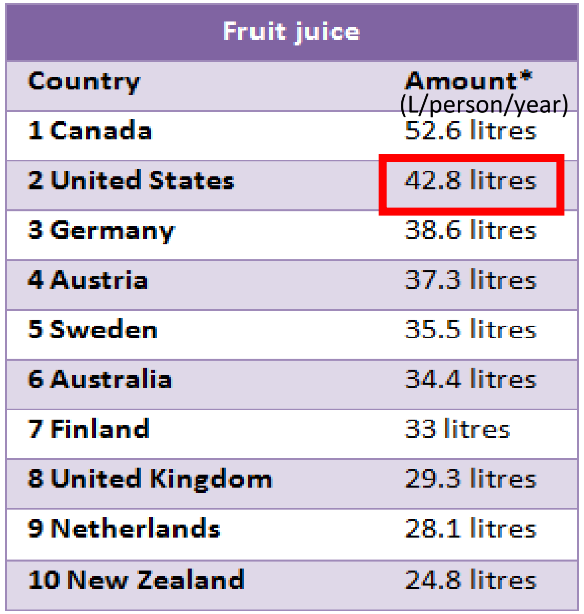
Background and Motivation

- Fruit juice is a good source of vitamins and antioxidants.
- World produced 12,840,318 tonnes of citrus fruit juices in 2012 (FAO).
- U.S. produced 607,000 metric tons of orange juice in 2012 (USDA).
- Juice is very susceptible to microorganisms due to its high water content, therefore must be undergo decontamination process to ensure the public health safety.

Most commonly consumed fruits among U.S. consumers, 2014



Loss-adjusted food availability data are proxies for consumption.
Source: USDA, Economic Research Service, Loss-Adjusted Food Availability Data.



Fruit juice	
Country	**Amount*** (L/person/year)
1 Canada	52.6 litres
2 United States	42.8 litres
3 Germany	38.6 litres
4 Austria	37.3 litres
5 Sweden	35.5 litres
6 Australia	34.4 litres
7 Finland	33 litres
8 United Kingdom	29.3 litres
9 Netherlands	28.1 litres
10 New Zealand	24.8 litres

Orange Juice Nutrition Facts

Nutrition Facts

Serving Size 1 cup 248 g

Amount Per Serving
Calories 112 Calories from fat 4

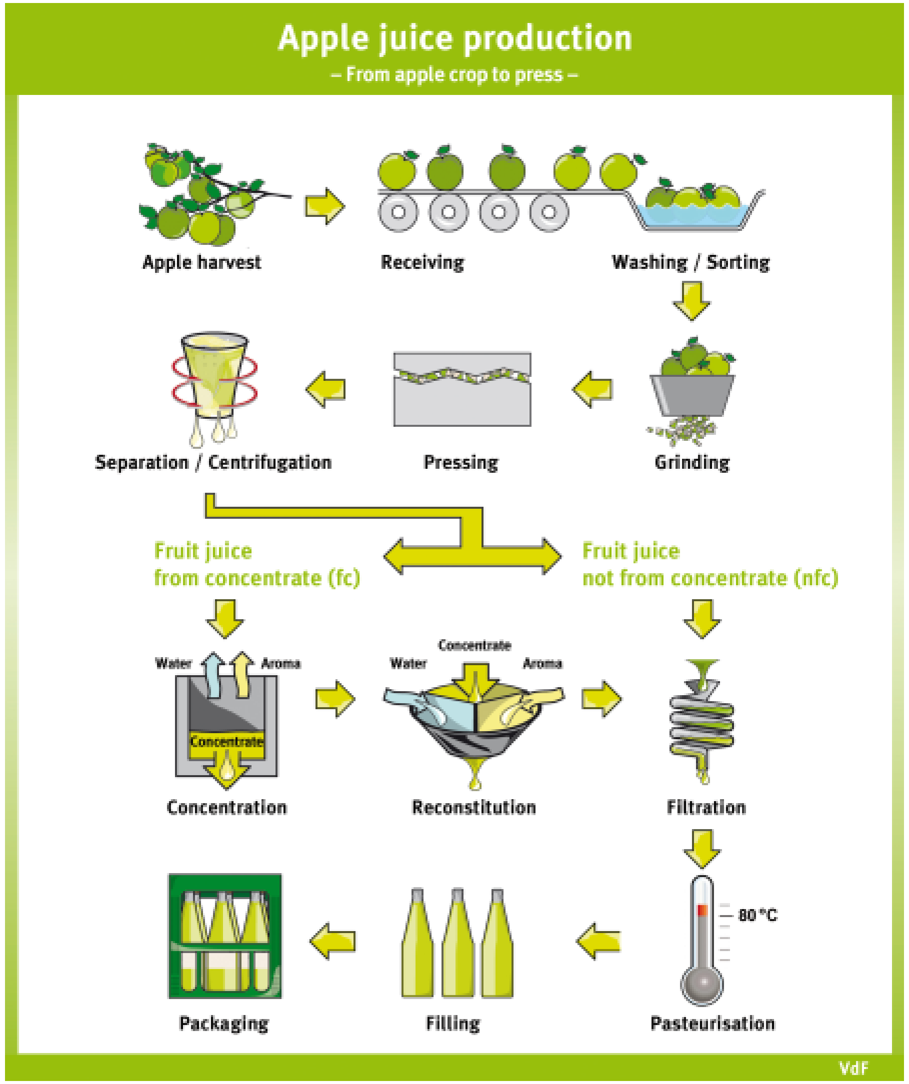
% Daily Value*

Total Fat 0g	1%
Saturated Fat 0g	0%
Trans Fat 0g	
Cholesterol 0g	0%
Sodium 2mg	0%
Total Carbohydrate 26g	9%
Dietary Fiber 0g	2%
Sugars 21g	
Protein 2g	
Vitamin A	10%
Vitamin C	207%
Calcium	3%
Iron	3%

*Percent Daily Values are based on a 2,000 calorie diet. Your daily values may be higher or lower depending on your calorie needs.

Juice Production

1. Cultivation and Preparation
2. Juice Extraction and Filtration
3. Concentration and Reconstitution
4. Pasteurization
    a. Microbial inactivation
    b. Extend shelf life
5. Packaging



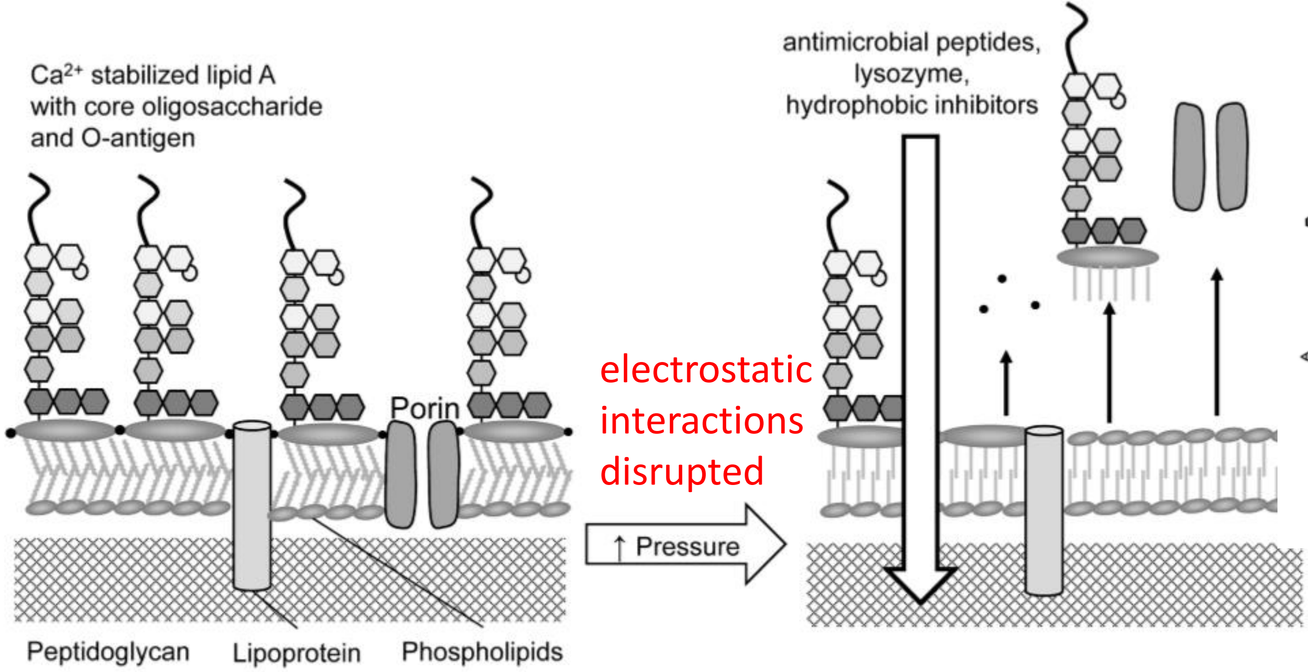
Juice Regulation

- FDA juice regulation: 5-log pathogen reduction.
  - Thermal treatment: at least 80C for 30 seconds.
    - Cons: nutritional value, taste, and color break down.
  - Non-thermal treatments: radiation, chemical treatment, or high pressure processing.
    - HPP: sensorial and nutritional properties remained.

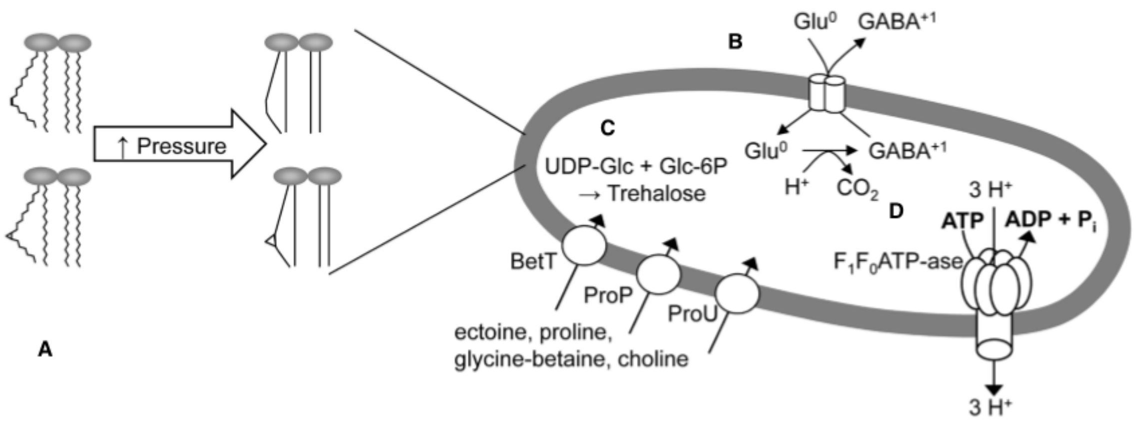
FDA. Juice Guidance Regulation.

Problem

- Although HPP at 400-800MPa is good for extent shelf life and improve food safety, not all bacteria can be inactivated.
    - Pressure resistance bacteria.
    - During HPP and post-pressure survival.



electrostatic interactions disrupted



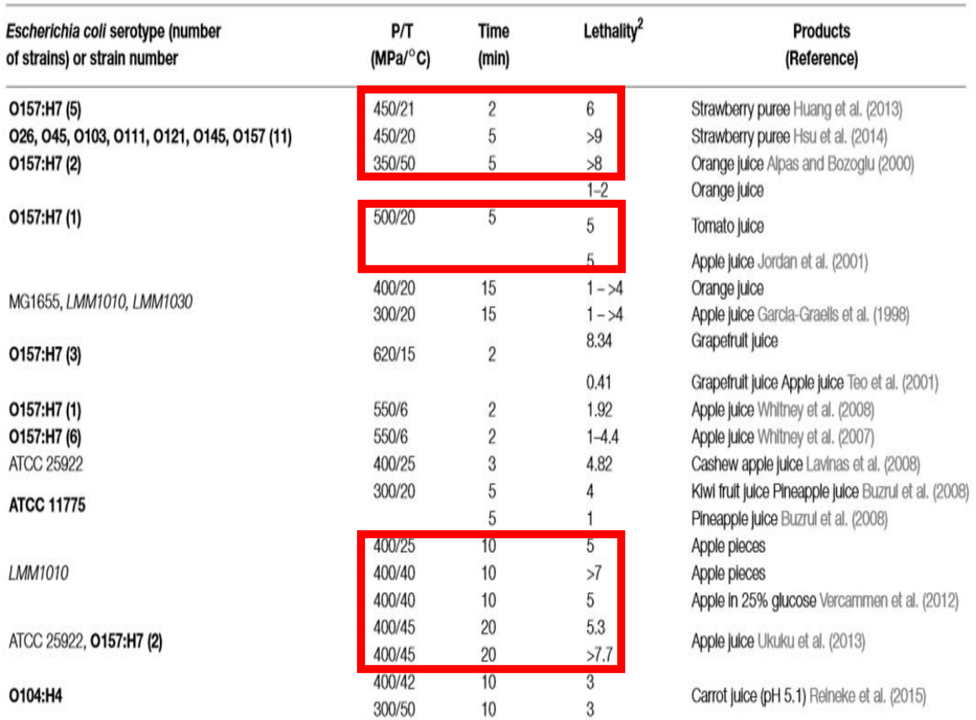
Ganzle, M. 2015. Mechanisms Of Pressure-mediated Cell Death And Injury In Escherichia Coli: From Fundamentals To Food Applications.
Ardia, A. 2004. Adiabatic Heat Modelling For Pressure Build-up During High-pressure Treatment In Liquid-food Processing.

Objectives

- Determine the optimal HPP with adiabatic heating parameters to microbial reduction.
- Explore potential cost analysis for HPP with adiabatic heating.

Hypothesized inactivation mechanisms

- Studies found that high pressure treatment at moderately elevated temperature could greatly enhance microbial inactivation and eliminates even pressure-resistance strains.
- Optimal process parameters for 6-log reduction of B. subtilis (melon juice):
    - 464 Mpa, 54.61C, and 12.8 mins.



Escherichia coli serotype (number of strains) or strain number	P/T (MPa/°C)	Time (min)	Lethality[2]	Products (Reference)
O157:H7 (5)	450/21	2	6	Strawberry puree Huang et al. (2013)
O26, O45, O103, O111, O121, O145, O157 (11)	450/20	5	>9	Strawberry puree Hsu et al. (2014)
O157:H7 (2)	350/50	5	>8	Orange juice Alpas and Bozoglu (2000)
			1–2	Orange juice
O157:H7 (1)	500/20	5	5	Tomato juice
			5	Apple juice Jordan et al. (2001)
MG1655, *LMM1010*, *LMM1030*	400/20	15	1 – >4	Orange juice
	300/20	15	1 – >4	Apple juice Garcia-Graells et al. (1998)
O157:H7 (3)	620/15	2	8.34	Grapefruit juice
			0.41	Grapefruit juice Apple juice Teo et al. (2001)
O157:H7 (1)	550/6	2	1.92	Apple juice Whitney et al. (2008)
O157:H7 (6)	550/6	2	1–4.4	Apple juice Whitney et al. (2007)
ATCC 25922	400/25	3	4.82	Cashew apple juice Lavinas et al. (2008)
ATCC 11775	300/20	5	4	Kiwi fruit juice Pineapple juice Buzrul et al. (2008)
		5	1	Pineapple juice Buzrul et al. (2008)
LMM1010	400/25	10	5	Apple pieces
	400/40	10	>7	Apple pieces
	400/40	10	5	Apple in 25% glucose Vercammen et al. (2012)
ATCC 25922, **O157:H7 (2)**	400/45	20	5.3	Apple juice Ukuku et al. (2013)
	400/45	20	>7.7	
O104:H4	400/42	10	3	Carrot juice (pH 5.1) Reineke et al. (2015)
	300/50	10	3	

Chen, J. 2015. Optimization of effective high hydrostatic pressure treatment of Bacillus subtilis in Hami melon juice.
Ganzle, M. 2015. Mechanisms Of Pressure-mediated Cell Death And Injury In Escherichia Coli: From Fundamentals To Food Applications.

Process Parameters

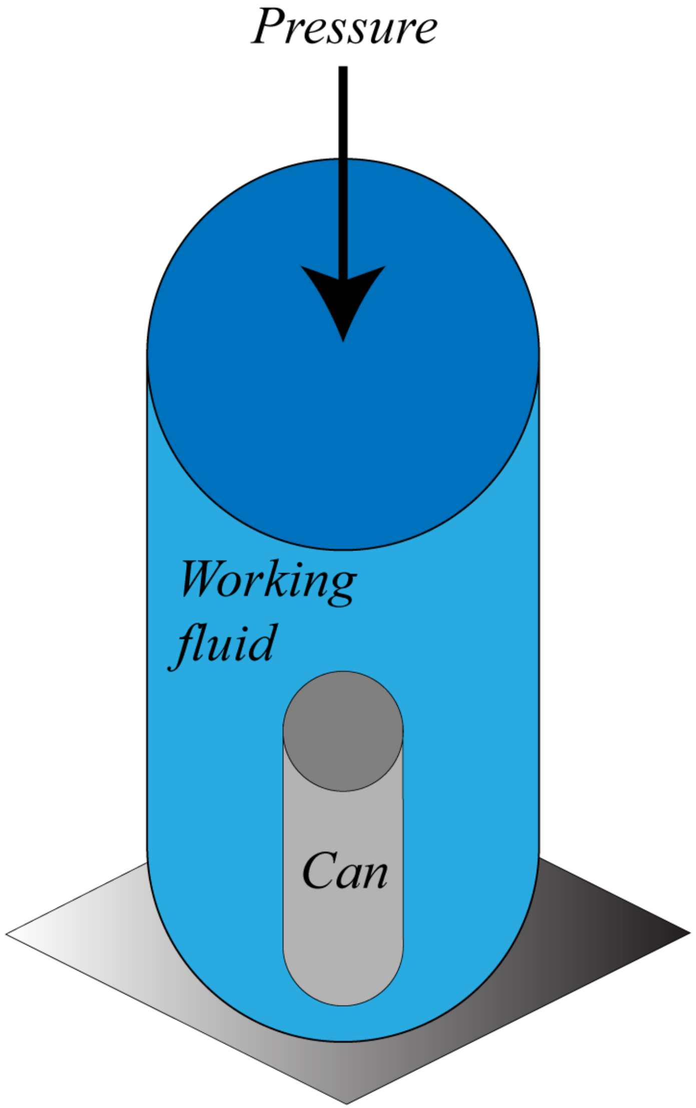
- Critical HPP + adiabatic heating processing parameters:
  - Process time
  - Pressure
  - Temperature

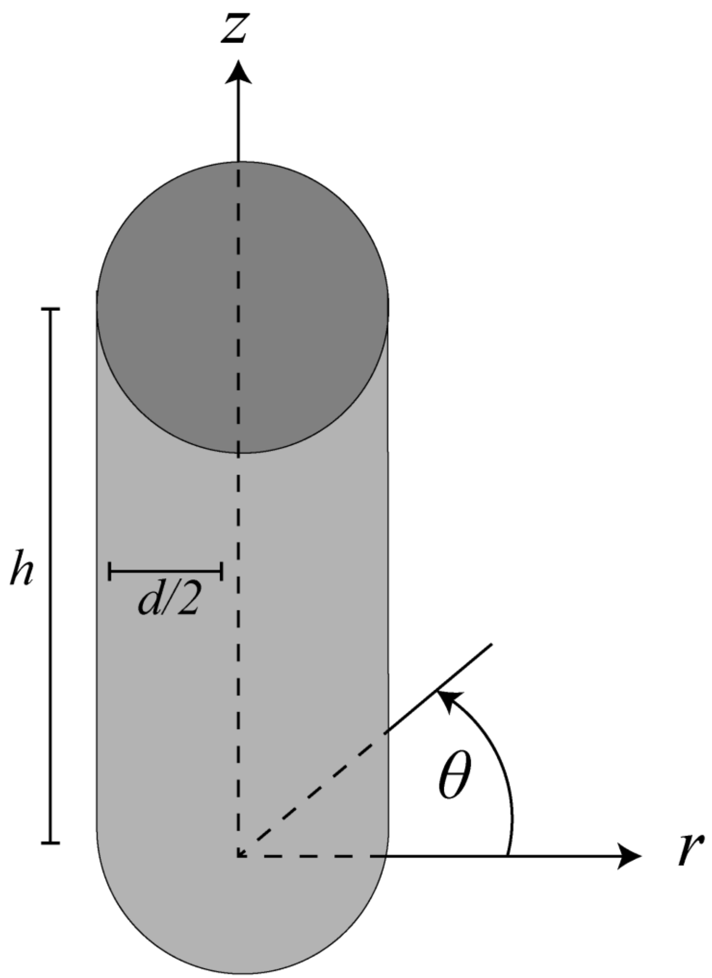
Ganzle, M. 2015. Mechanisms Of Pressure-mediated Cell Death And Injury In Escherichia Coli: From Fundamentals To Food Applications.

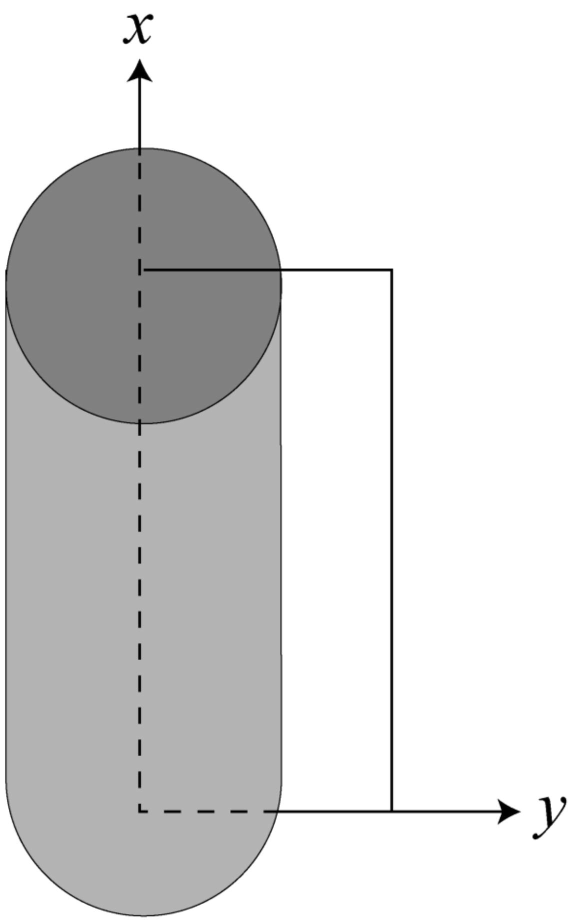
How Adiabatic Heating Works

- $H \equiv U+PV$
- $U \equiv Q+PV$
- “Constant” volume due to rigid container
- Increase in internal energy becomes heat

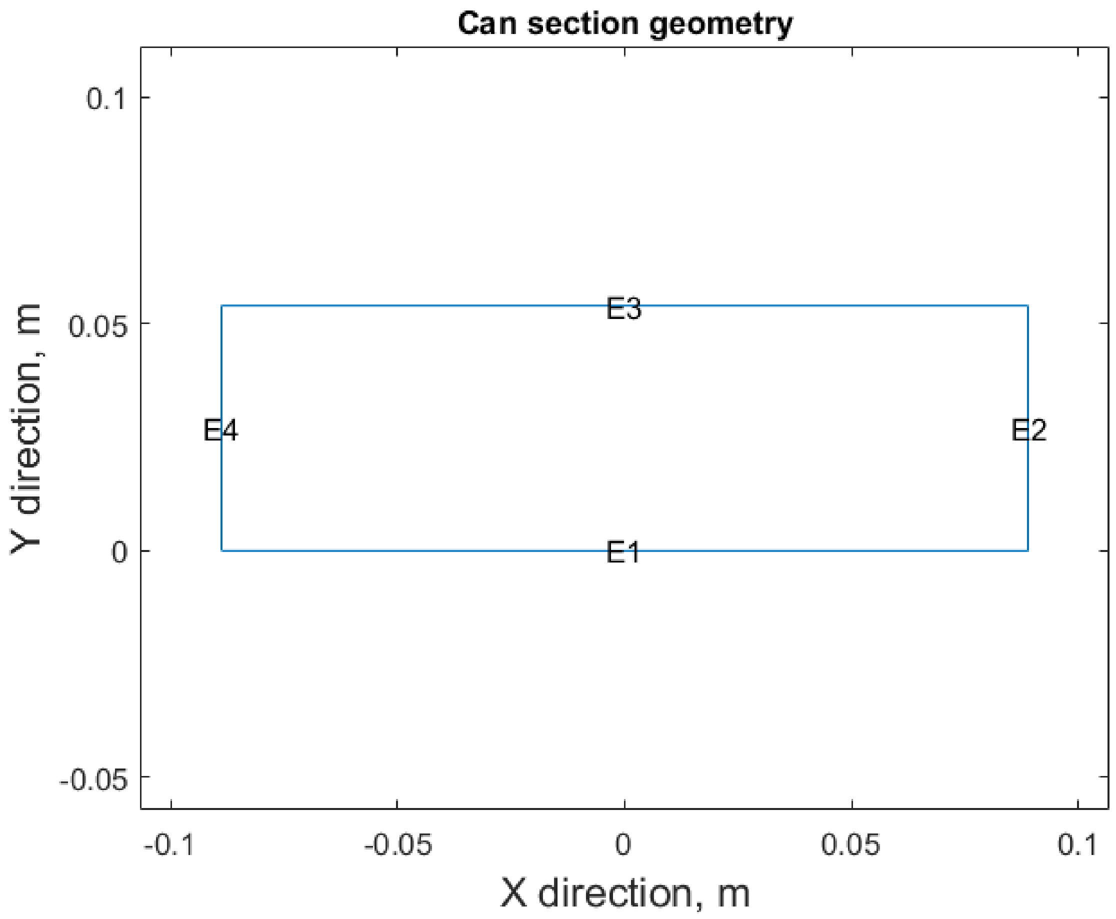
Juice container in high pressure chamber

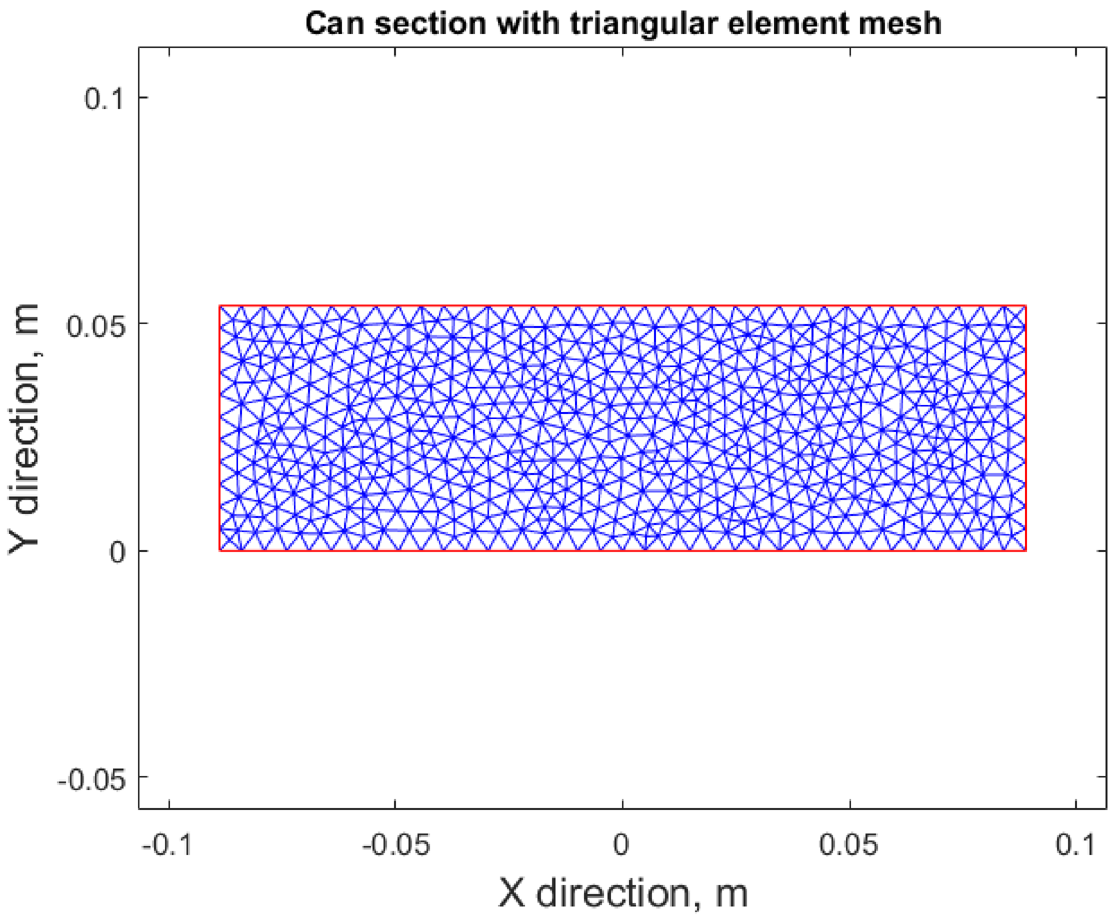






Problem reduced from T(t,r,θ,z) to T(t,x,y)





Heating problem formulation

- Heat conduction equation $$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k\nabla T) + q$$
- Where
  - T = temperature [°C]
  - ρ = mass density [kg/m^3]
  - C_p = specific heat [J/kg-°C]
  - k = conductivity [W/m-°C]
  - t = time [s]
  - ∇ is the gradient operator = $\left(\frac{\partial}{\partial x} e_x + \frac{\partial}{\partial y} e_y + \frac{\partial}{\partial z} e_z\right)$
  - q is heat generation term [W/m^3]
  - $\cdot$ indicates the dot product

- For constant conductivity $$\frac{\partial T}{\partial t} = \alpha \nabla^2 T$$
- Where

  α = thermal diffusivity [m^2/s]

Telis-Romero, etl al. (1998). Journal of Food Engineering 28: (27-40)

Heat equation “big picture”

- Time derivative of temperature $\frac{\partial T}{\partial t}$
- Proportional to the second spatial derivative of temperature at that point $= \alpha \nabla^2 T$
- Plus heat generated inside from pressure increase $+ q$
  - “adiabatic heating”

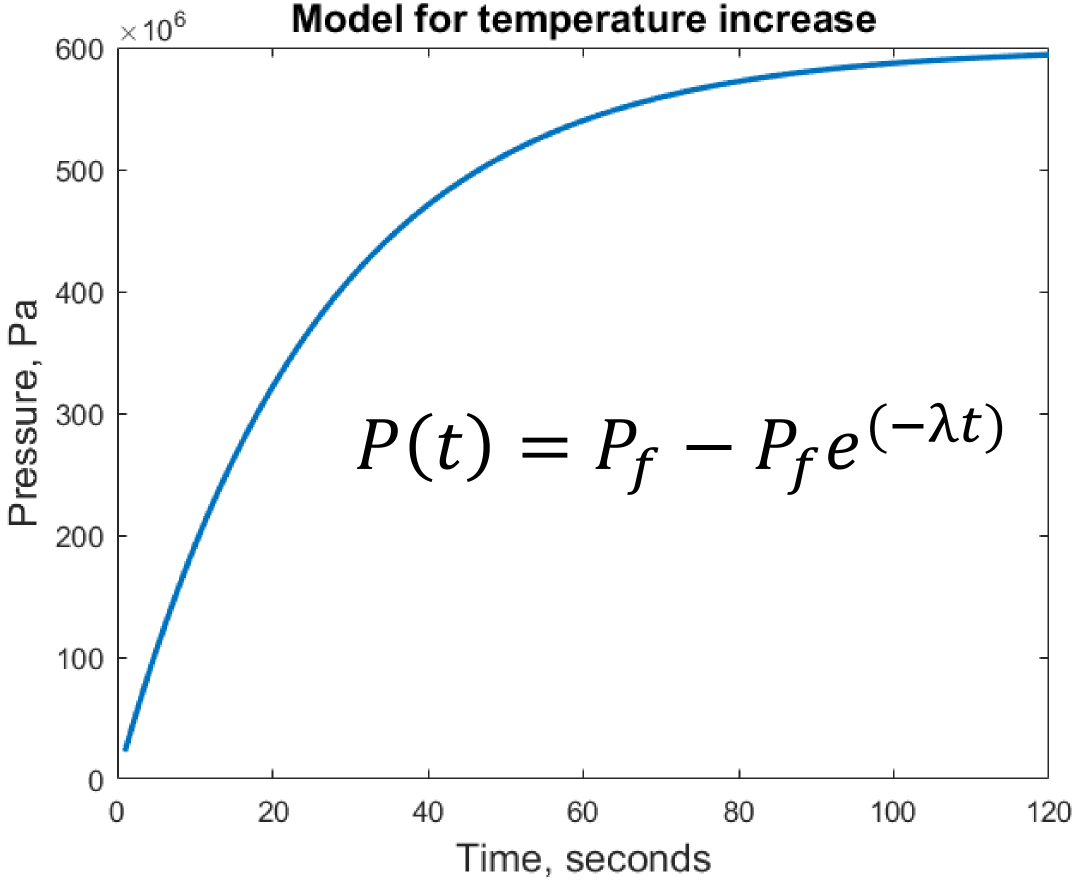
- Can find the temp at any point in the can
  - At any time

Modeling adiabatic heating

$$\frac{\partial T}{\partial P} = \frac{\beta}{\rho C_P} T \quad [=] \quad \frac{\frac{1}{{}^\circ C}}{\frac{kg}{m^3}\frac{J}{kg{}^\circ C}} {}^\circ C \; [=] \frac{{}^\circ C}{Pa}$$

$$\frac{\partial T}{\partial t} = \frac{\partial T}{\partial P}\frac{\partial P}{\partial t}$$

$$\frac{\partial T}{\partial t} = \left(\frac{\beta}{\rho C_P} T\right)\frac{\partial P}{\partial t}$$



$$P(t) = P_f - P_f e^{(-\lambda t)}$$

- Where
  - β= compressibility [1/°C]
  - λ = decay constant, chosen so pressure increase happens in 2min

Ardia, A. Knorr, D. Heinz, V. (2004) Trans IChemE, Part C, Food and Bioproducts Processing, 82(C1):89-95

Modeling adiabatic heating

$$\frac{\partial T}{\partial t} = \left(\frac{\beta}{\rho C_P} T\right) \frac{\partial P}{\partial t}$$

$$P(t) = P_f - P_f e^{(-\lambda t)}$$

$$\frac{\partial P}{\partial t} = \lambda P_f \, e^{(-\lambda t)}$$

$$\frac{\partial T}{\partial t} = \left(\frac{\beta}{\rho C_P} T\right) \lambda P_f \, e^{(-\lambda t)}$$

$$q(t) = \rho C_P \frac{\partial T}{\partial t}$$

$$q(t) = (\beta T) \lambda P_f \, e^{(-\lambda t)}$$

Ardia, A. Knorr, D. Heinz, V. (2004) Trans IChemE, Part C, Food and Bioproducts Processing, 82(C1):89-95

Final model formulation

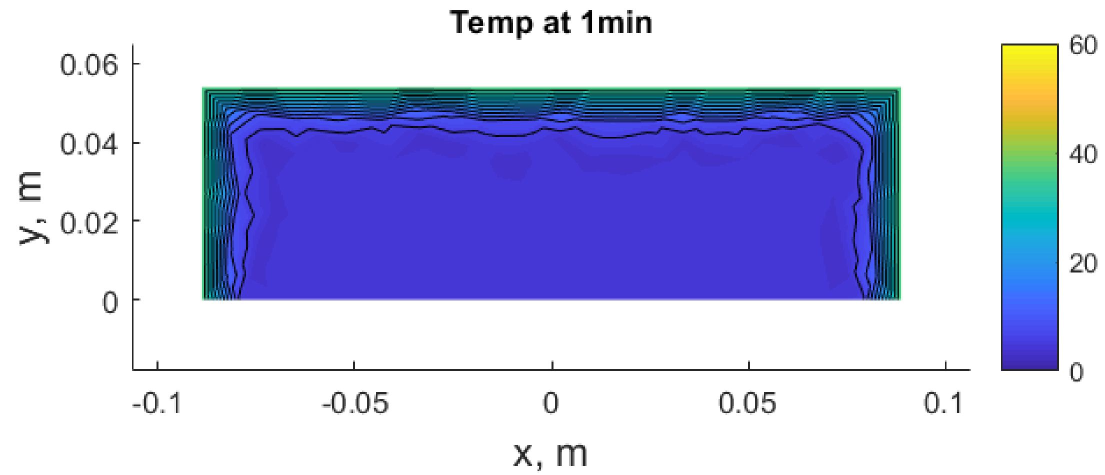
$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + q$$

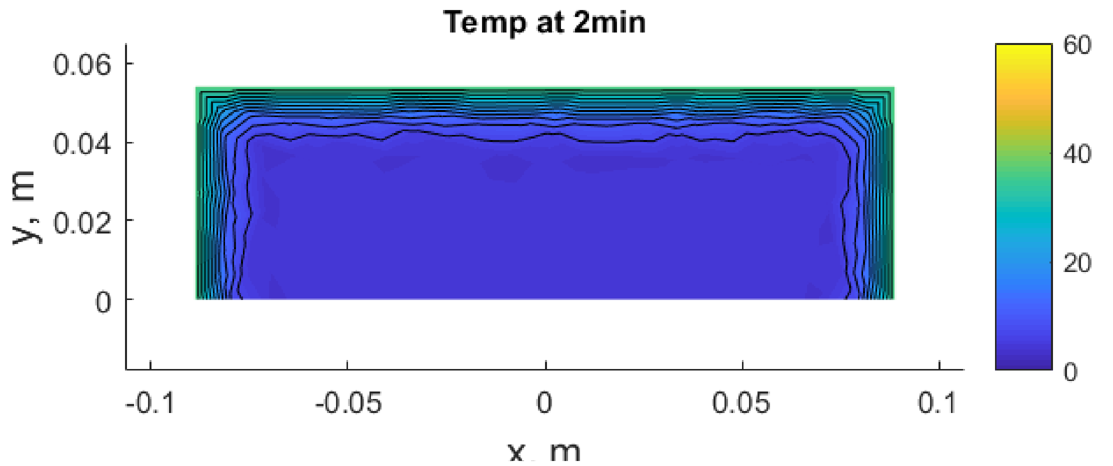
$$q(t) = (\beta T)\lambda P_f \, e^{(-\lambda t)}$$

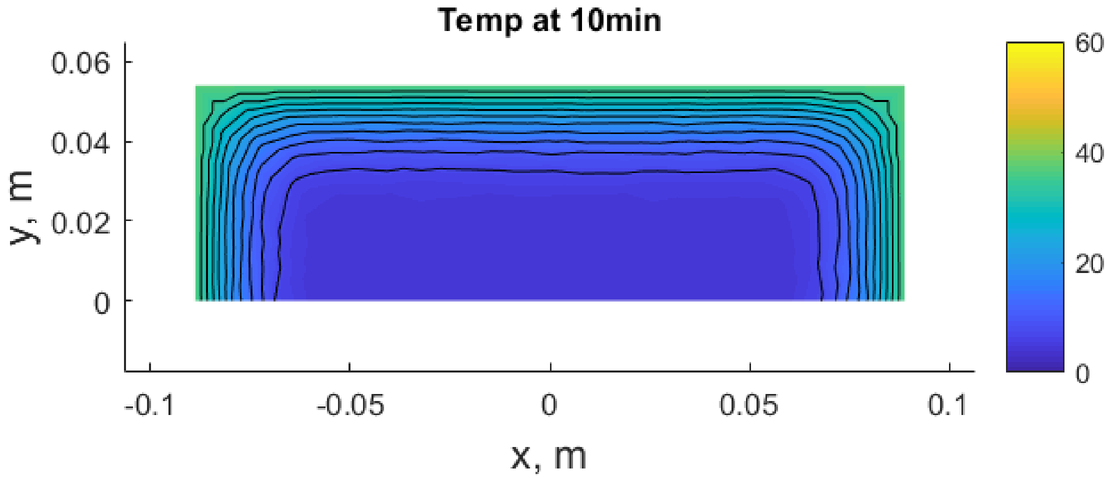
$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + (\beta T)\lambda P_f \, e^{(-\lambda t)}$$

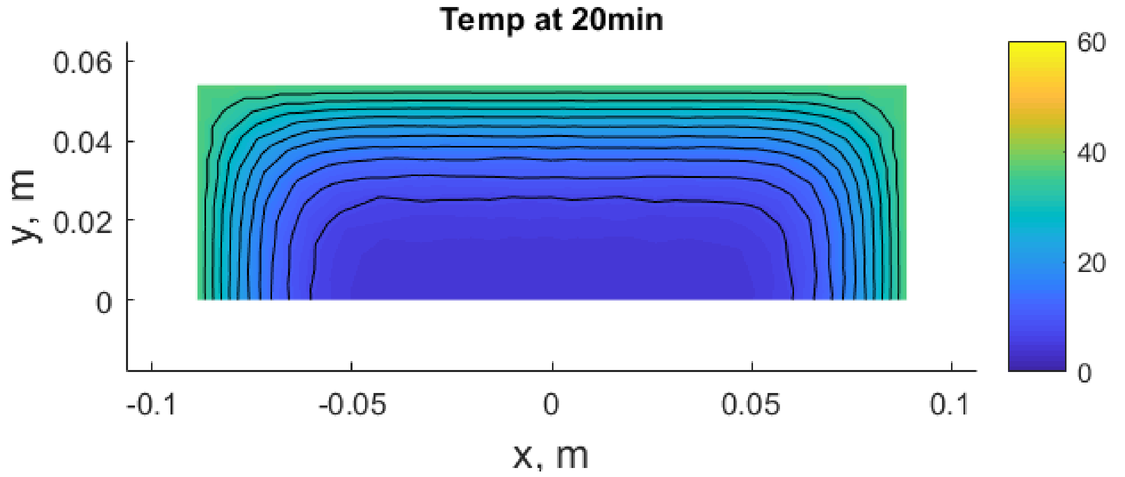
- **Limitations**
  - Properties are considered constants
  - Assume temperature on the edge of the can = temperature of bulk fluid
  - Assume temperature bulk fluid constant

Results: Constant bulk fluid temp = 37C, Initial juice temp 4C

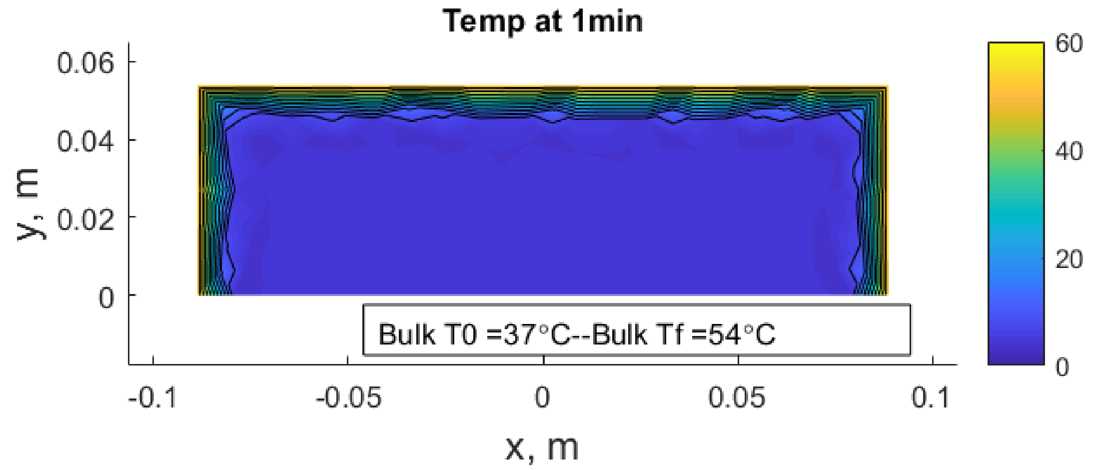


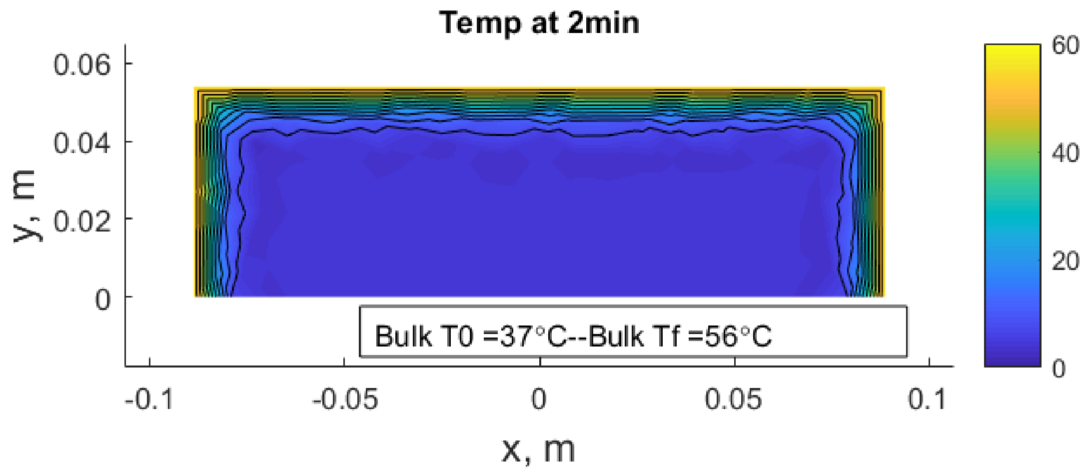


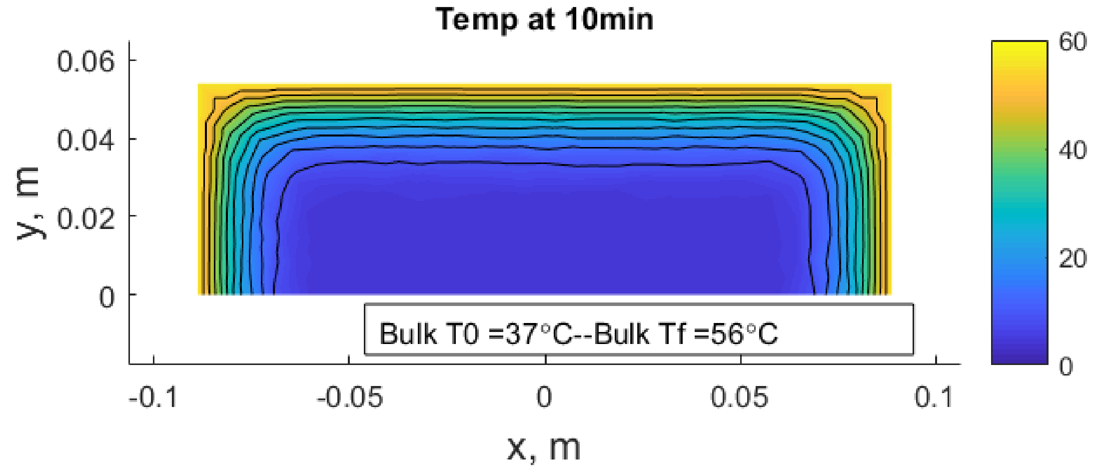


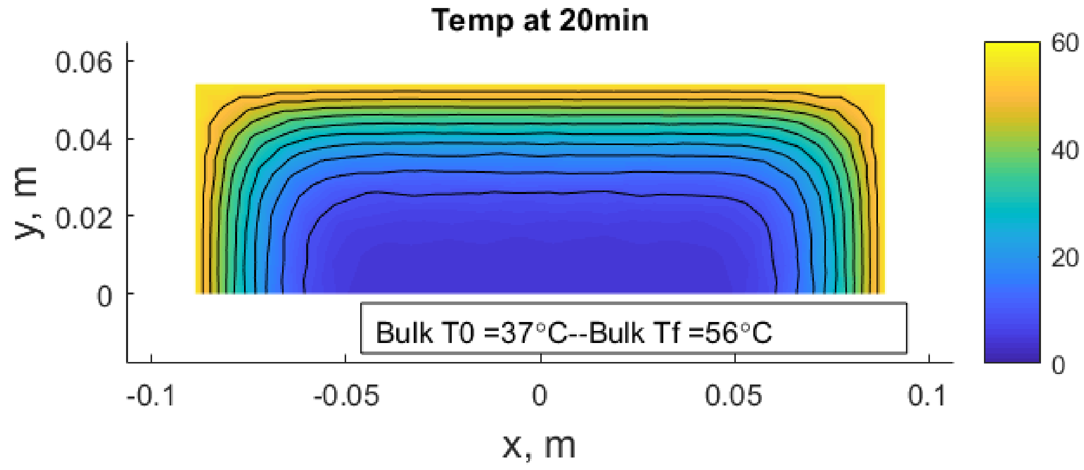


Results: Initial bulk fluid temp 37C, with adiabatic heating Initial juice temp 4C

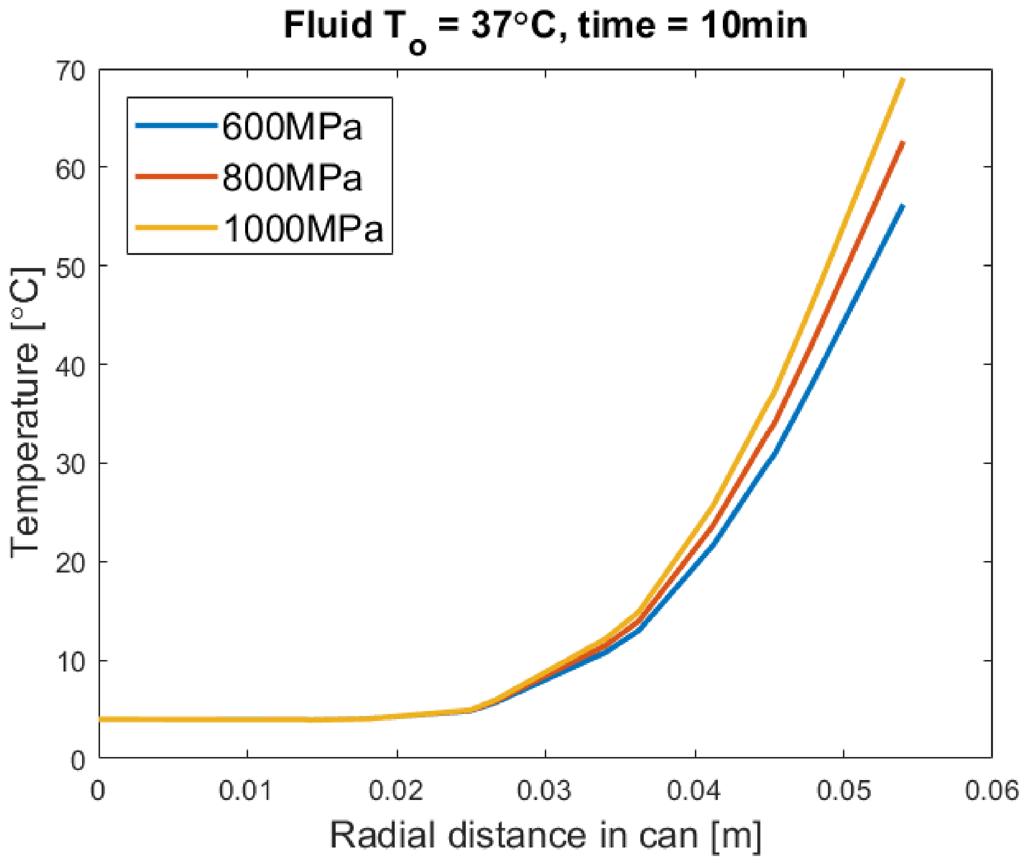

Temp at 1min

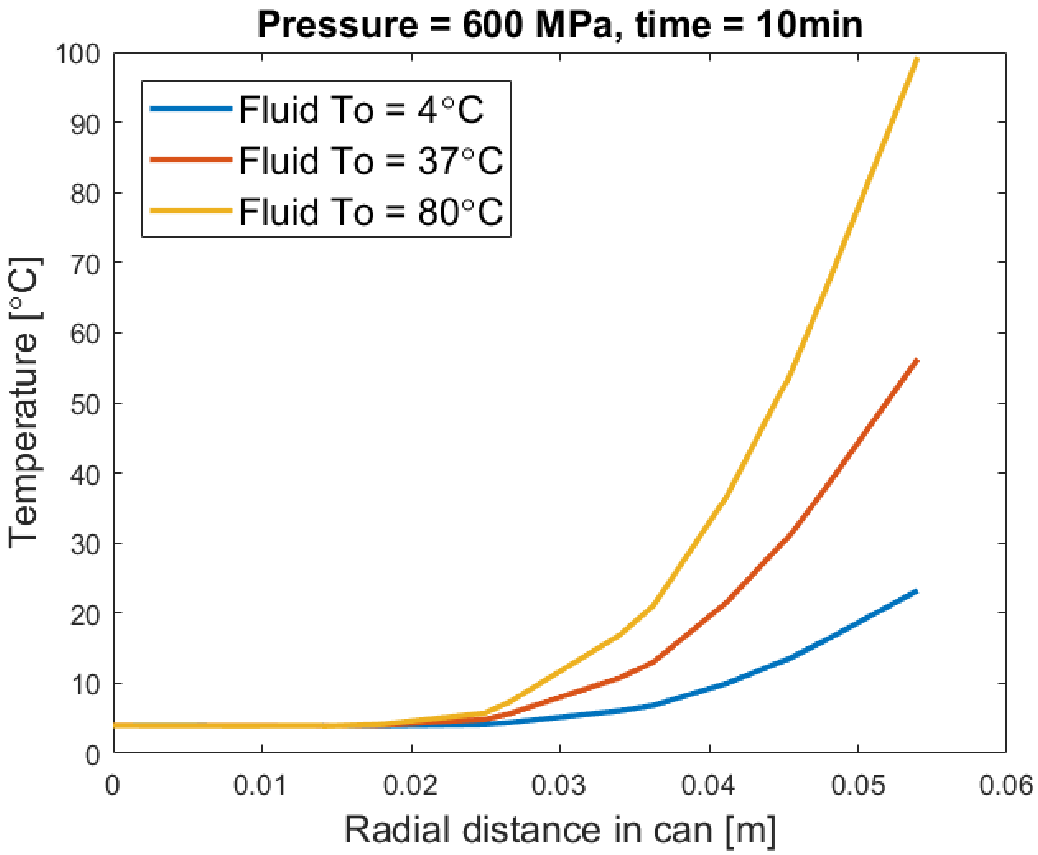

Temp at 2min


Temp at 10min

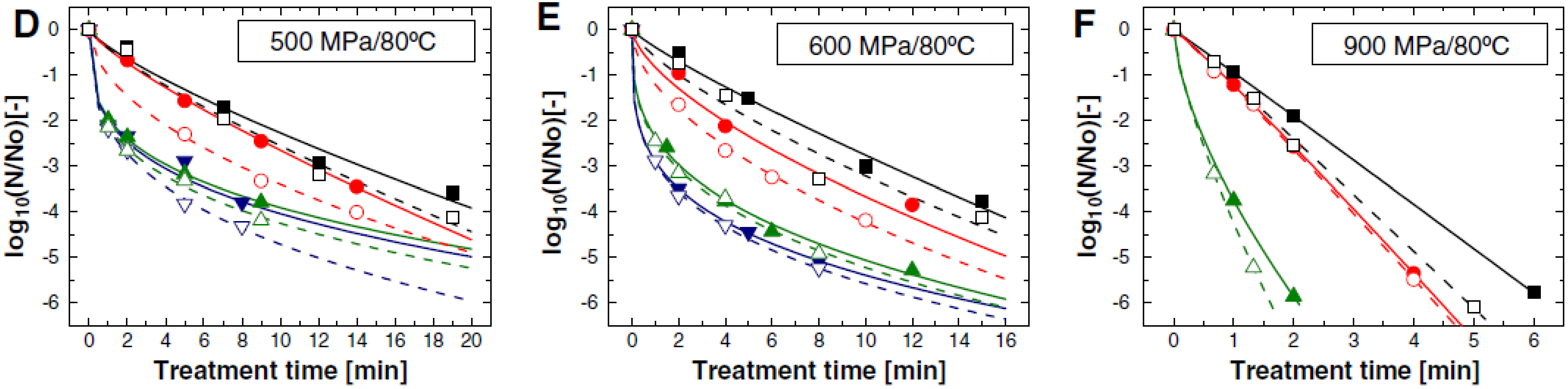

Temp at 20min

Results: Can temperature has weak dependence on final pressure; stronger dependence on working fluid temp





Pressure dependent inactivation of a model organism



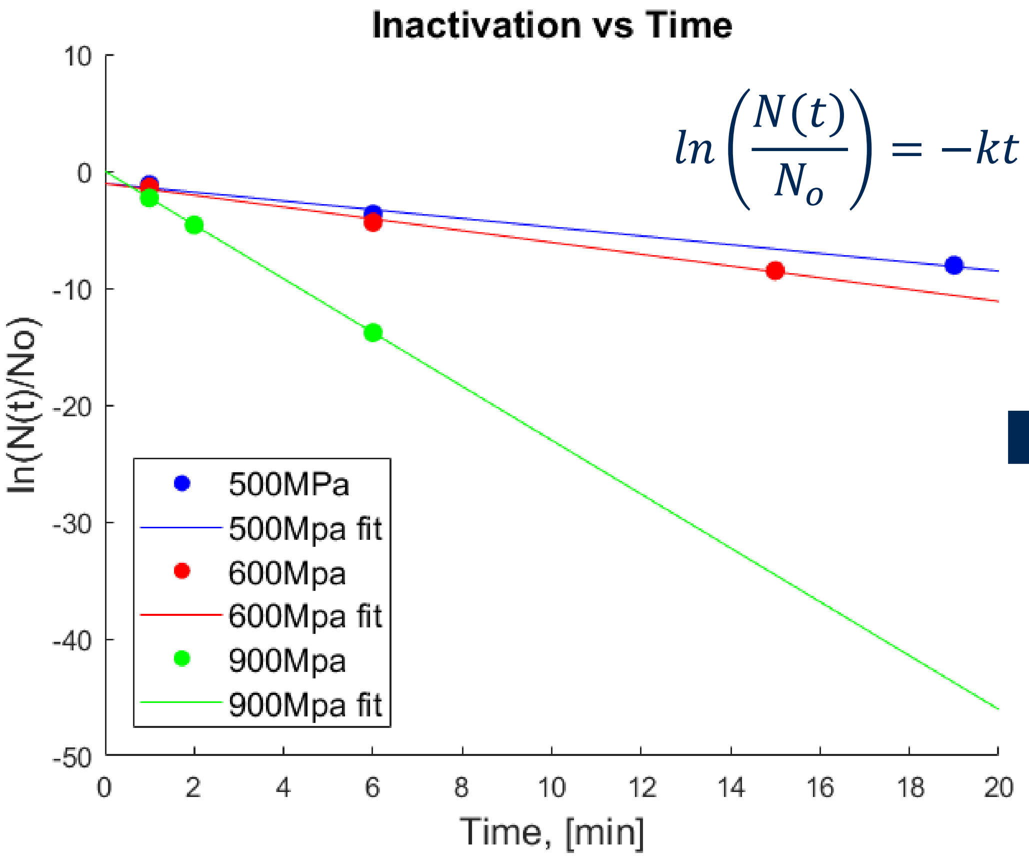
$$\frac{dN}{dt} = -kN$$

$$N = N_o e^{-kt}$$

$$ln\left(\frac{N(t)}{N_o}\right) = -kt$$

Mathys, et. al. (2008) Food Control 19: 1165-1173.
Melo Silva, et. al. (2013) Food Control 29: 76-81.

Pressure dependent inactivation of a model organism



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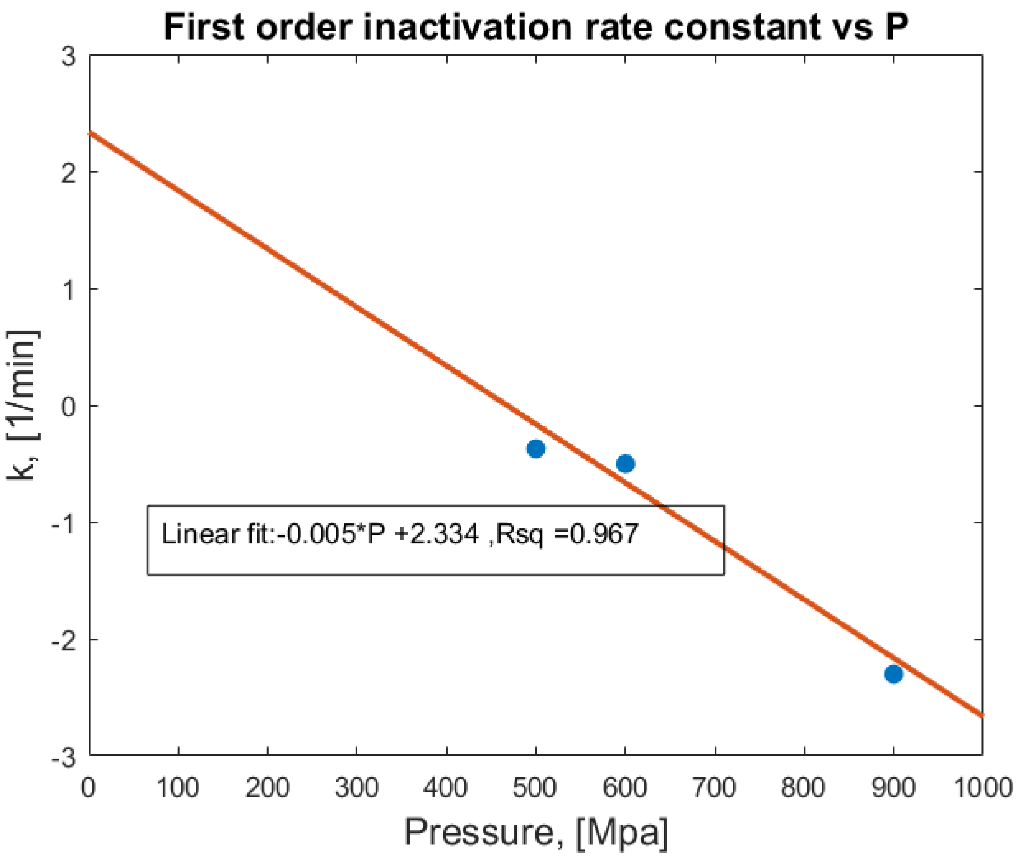
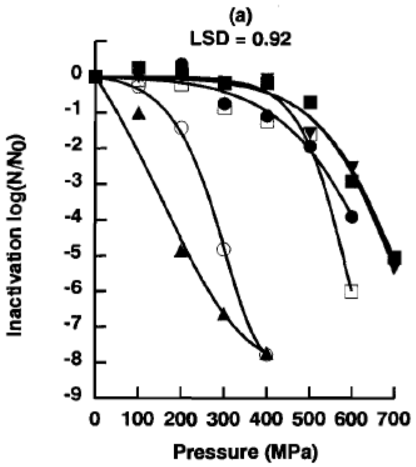


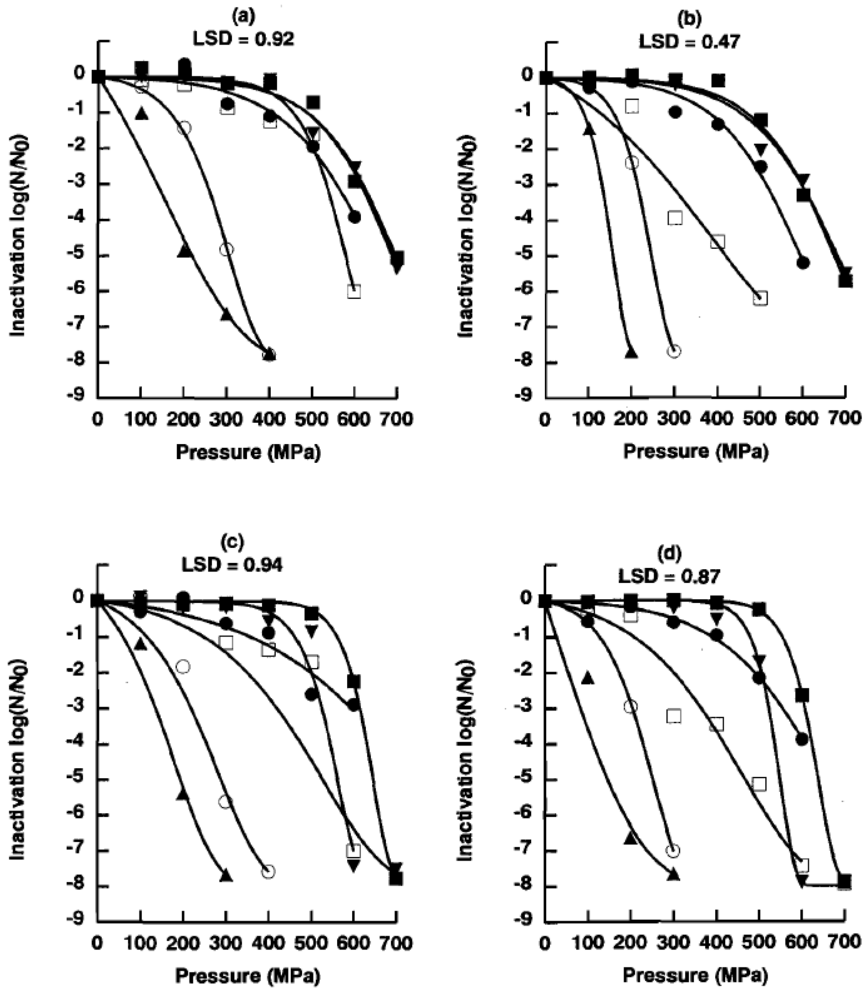
Mathys, et. al. (2008) Food Control 19: 1165-1173.

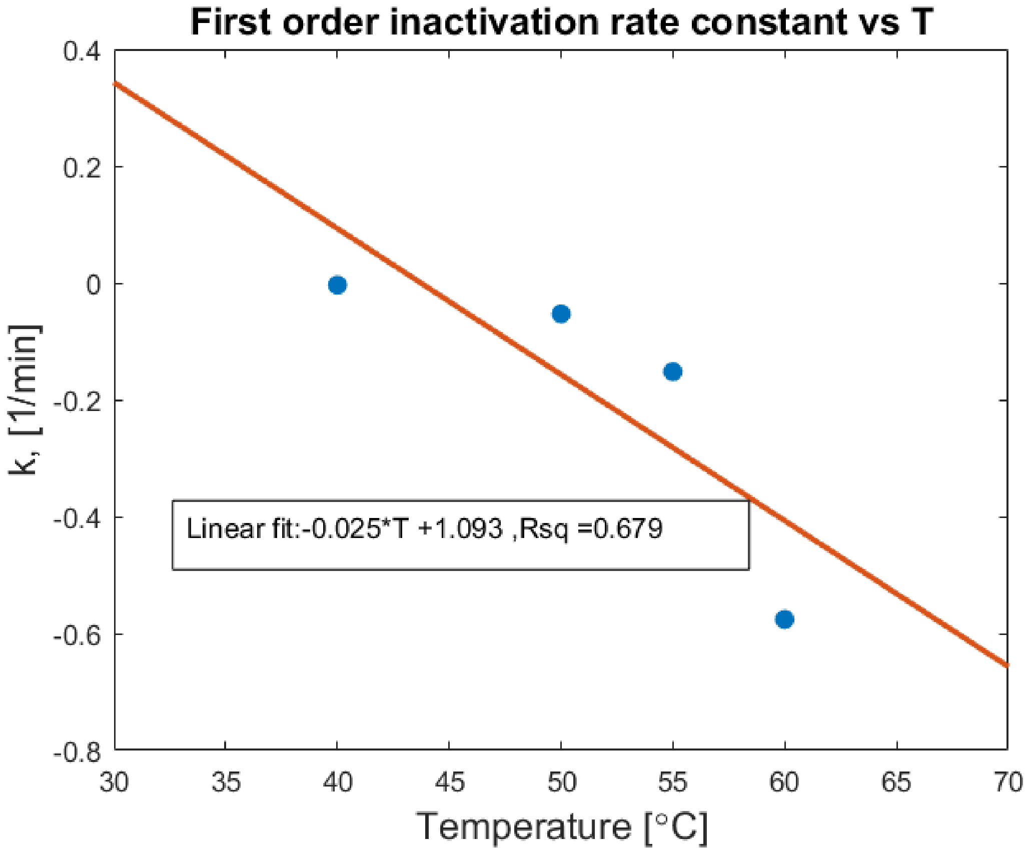
Including the contribution of temperature…



- **Researchers measured inactivation as function of Temperature as well as Pressure**

Including the contribution of temperature…



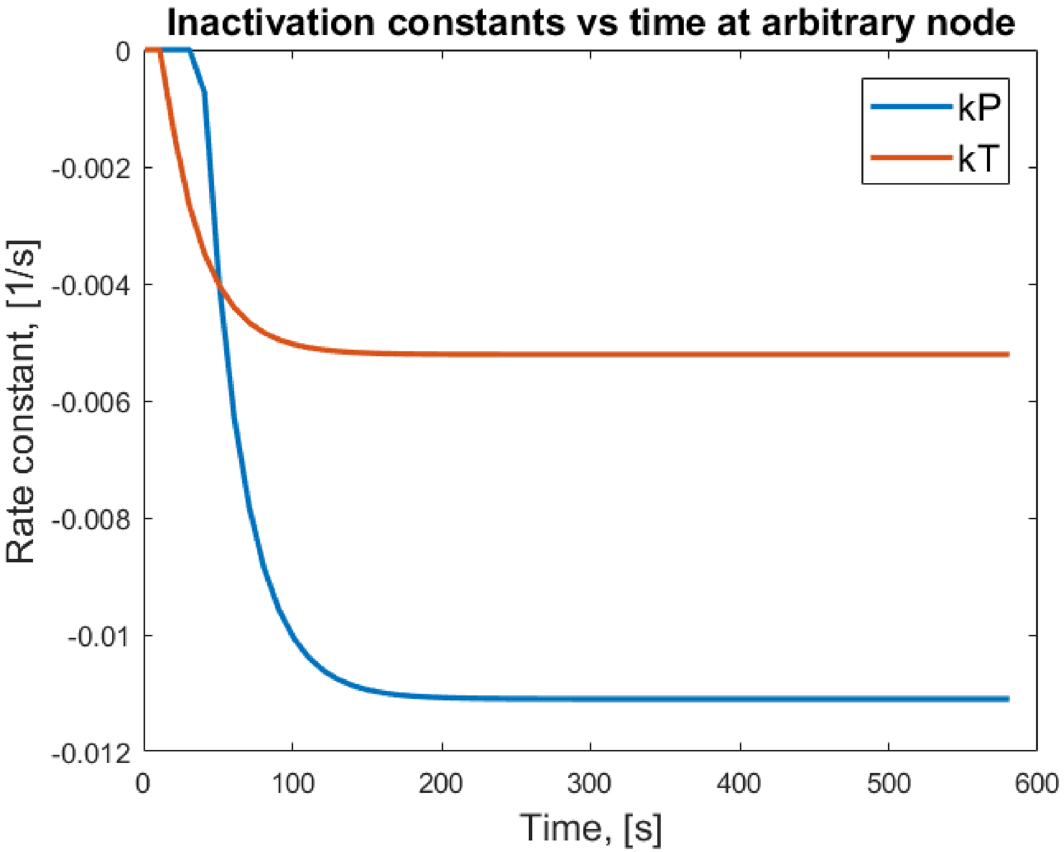


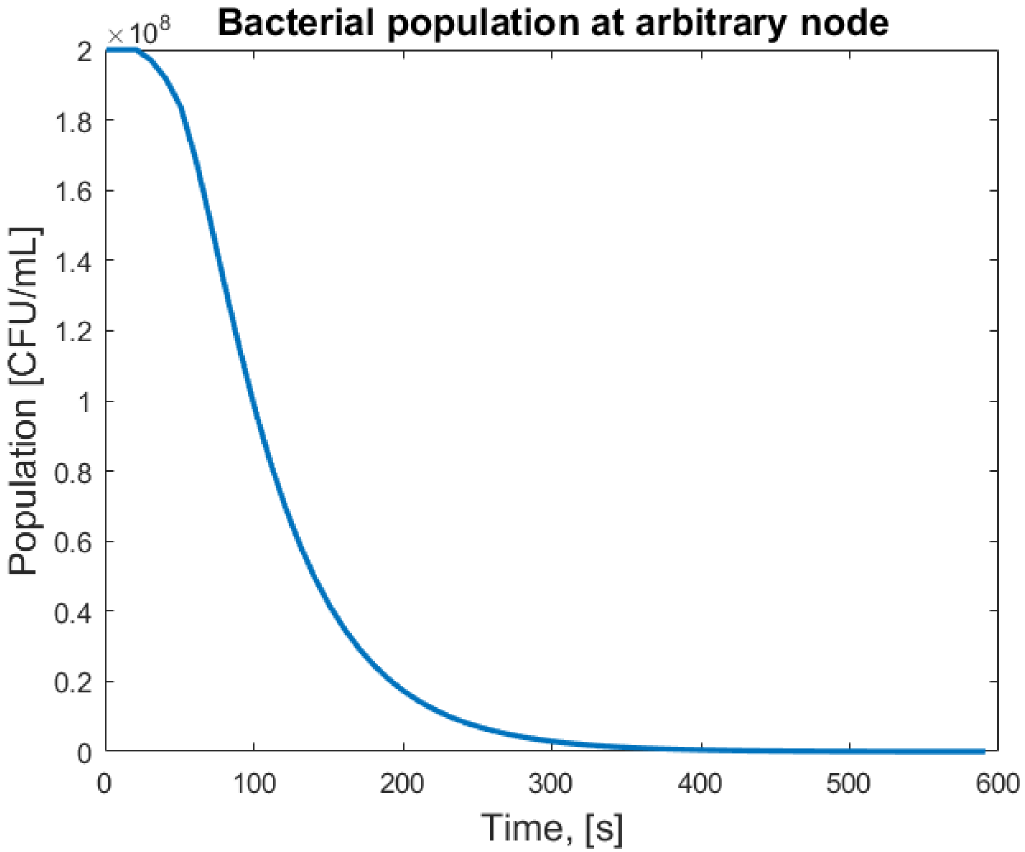
Patterson et. al. (1998). Journal of Food Protection 61:4:432-436

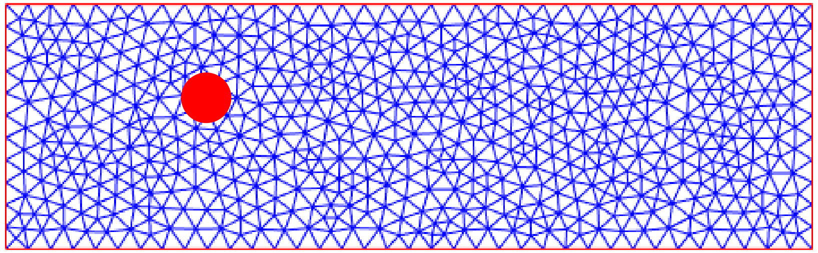
Total inactivation = sum of temperature and pressure effects

$$\frac{dN}{dt} = -k_P N - k_T N, \qquad where\ k_P, k_T < 0$$

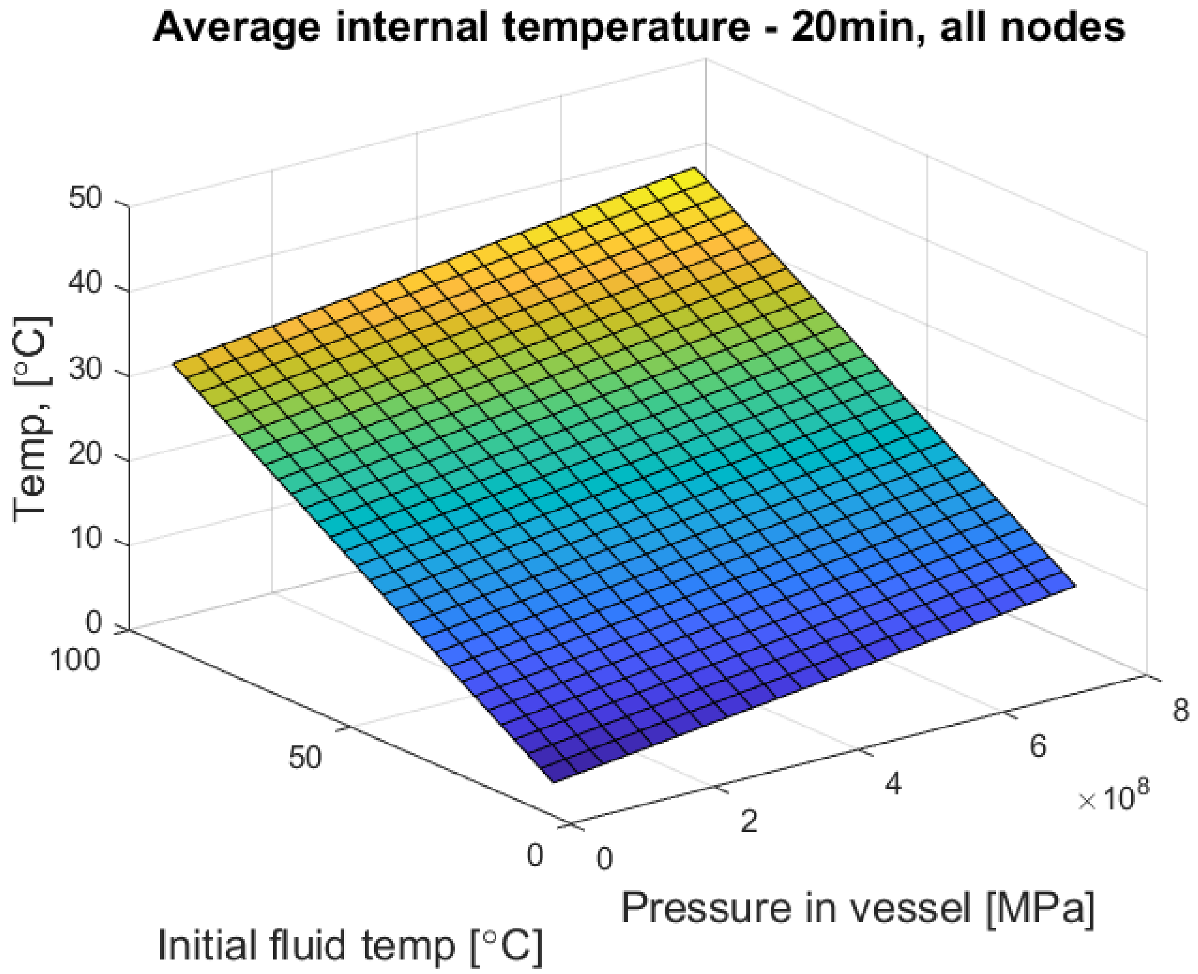
```
dt = mean(diff(t)); %time step
for i = 1:1:length(t)-1
    kP = -(-0.0050*P(i) + 2.3340)/60;  %pressure inactivation rate constant [1/s]
    kT = -(-0.025*T(i) + 1.0930)/60;   %temperature inactivation rate constant [1/s]
    dNdt = kP*N(i) + kT*N(i);          %change in microbial population
    N(i+1) = N(i) + dNdt*dt;           %new microbial population
end
```

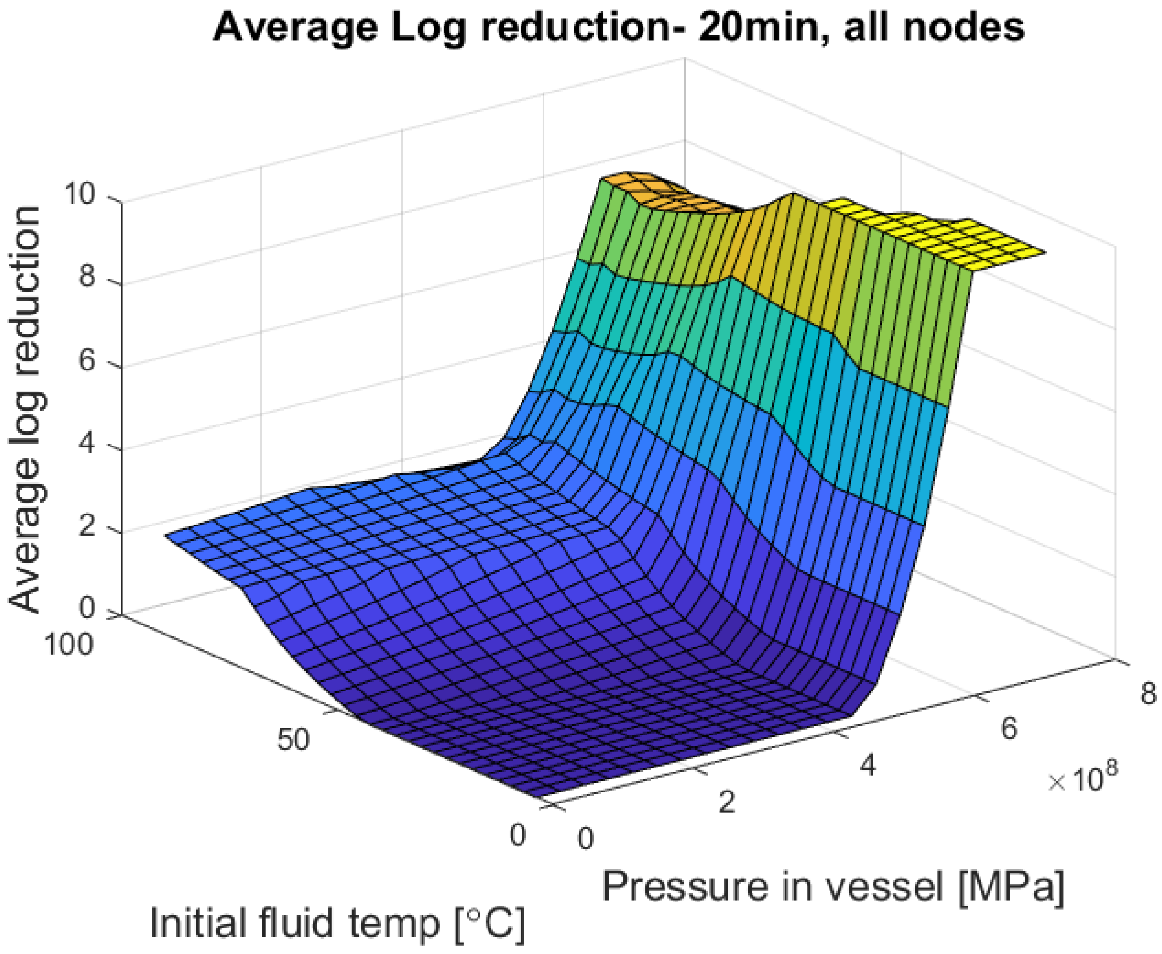

Inactivation constants vs time at arbitrary node


Bacterial population at arbitrary node



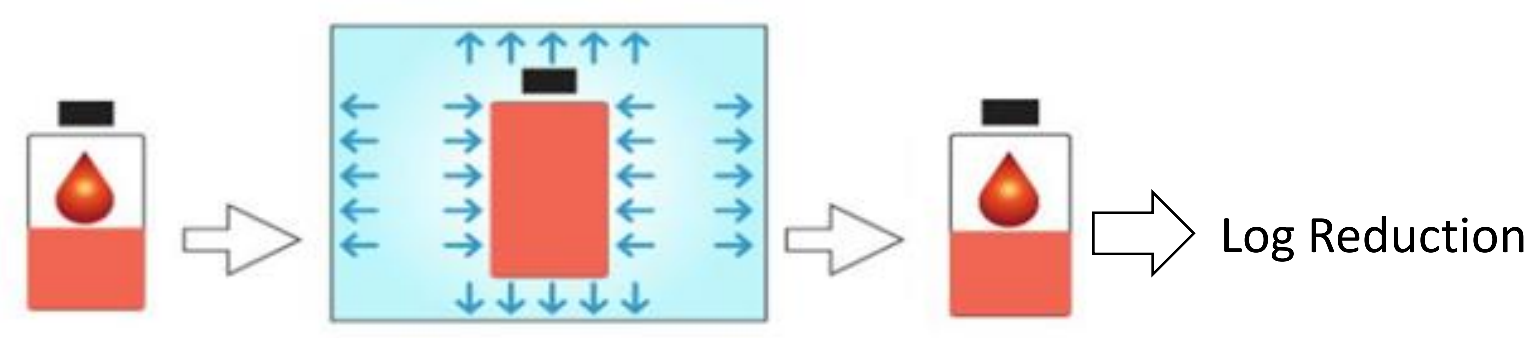
Model used for process design


Average internal temperature - 20min, all nodes


Average Log reduction- 20min, all nodes

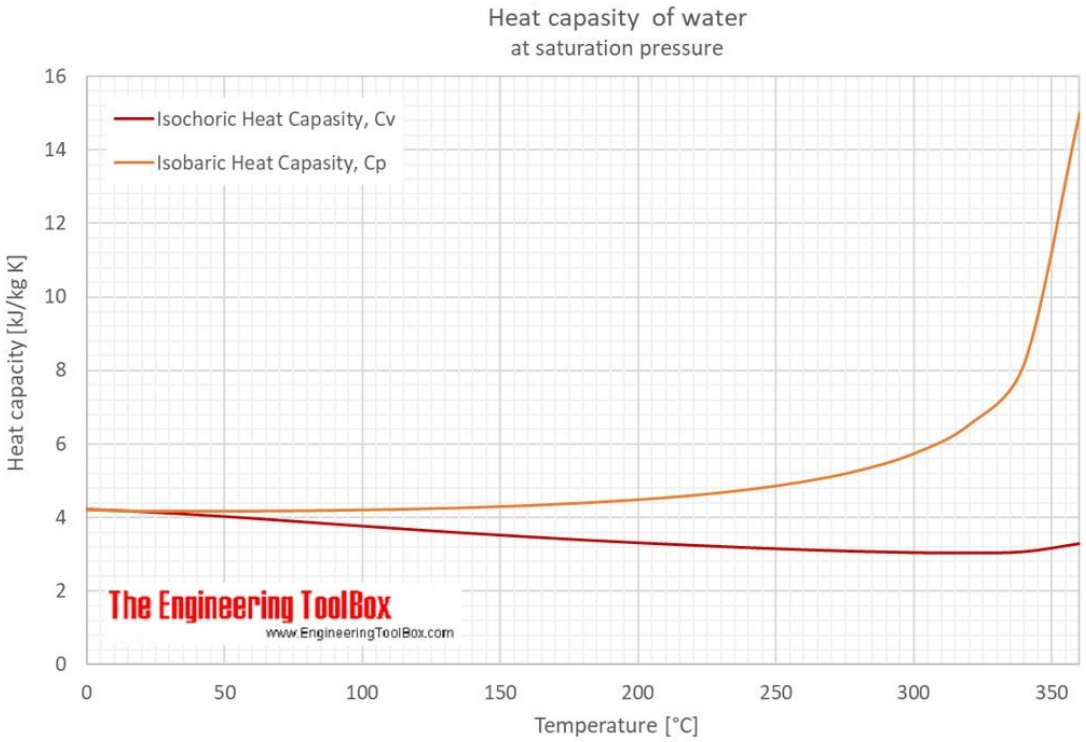
Testing Plan

- Initial bulk fluid temp, with adiabatic heating initial juice temp 4C.
- Experiment at different initial fluid temp and different pressure conditions.



1. Different initial fluid temp
2. Different pressure

The Costs of Heating



- Inherent inefficiency in heating systems
  - Electric ~90-95% efficient
  - Gas ~60%
  - $Q = \rho C_p \triangle T$ (Assuming "constant" heat capacity regime)
- Pipe losses vary by system
  - $Q = (t_i - t_o) / [(\ln(r_o / r_i) / 2 \pi k L) + (\ln(r_s / r_o) / 2 \pi k_s L)]$

Costs of Heating Cont.

- CA average 18.77 cents per kWh (electricity)
- Can integrate across different timescales for each type of energy input
  - Potential differences in time for HPP
  - Normalized to same level of bacterial death
- Cost benefit analysis possible

Other Cost Considerations/Impact

- Processing time impact on throughput?
- Heat exchangers?
- HPP Unit packing density?
- Small % savings large numerically
- Improve PATS/TAPS processes