Steam Sterilization -- Effect of temperature, time, number of contaminants, heat/cooling cycle, and damage to heat-labile nutrients.

Instructor: Nam Sun Wang

Equations and parameters

Some temperature definitions

$C \equiv K$

$Tk(c) \equiv c + 273.15 \cdot K$

Check: $Tk(100 \cdot C) = 373.15 \cdot K$

Steam Temperature: $T_{steam} := 121 \cdot C$

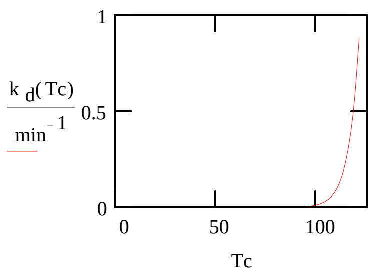
Specific Death Rate: $k_d(Tc) := \left(10^{33} \cdot min^{-1}\right) \cdot \exp\left(-\frac{30000 \cdot K}{Tk(Tc)}\right)$

Probability of survival $p(t, Tc) := \exp\left(-k_d(Tc) \cdot t\right)$

Probability of contamination: $p_c(t, Tc, N) := 1 - (1 - p(t, Tc))^N$

Part a). We can see that there is little killing power at ambient until the temperature is high (121 °C).

$Tc := 0 \cdot C .. T_{steam}$



Specific death rate at some temperatures:

$k_d(121 \cdot C) = 0.88 \cdot min^{-1}$

$k_d(100 \cdot C) = 0.012 \cdot min^{-1}$

$k_d(37 \cdot C) = 9.814 \cdot 10^{-10} \cdot min^{-1}$

Thus, heat as quickly as possible to 121 °C; one can ignore any sterilization until 121 °C. Then, hold at 121°C until the probability of contamination is 1%, or equivalently 0.01, for 1000 particles. Subsequently, cool at quickly as possible back to room temperature or 37 °C.

Initial guess of the holding time: $t_{hold} := 15 \cdot min$

Holding time to yield p=0.01: $t_{hold} := root\left(p_c\left(t_{hold}, T_{steam}, 1000\right) - 0.01, t_{hold}\right)$

$t_{hold} = 13.127 \cdot min$

Check: $p_c\left(t_{hold}, T_{steam}, 1000\right) = 0.01$

Part b). Now, if the number of particles is $N := \left(\frac{1000}{liter}\right) \cdot (1000 \cdot liter)$

probability of contamination is: $p_c\left(t_{hold}, T_{steam}, N\right) = 0.99993$ Contamination is almost certain!!

As you can see from the above numbers and the following summary, the total number of particles, or the media volume, greatly affect the probability of contamination. An acceptable level of loss at a bench-top scale can become totally unacceptable at an industrial scale. This has a serious consequence in scaling up industrial fermentations.

1 liter:	$N := 1000$	$p_c\left(t_{hold}, T_{steam}, N\right) = 0.01$
10 liters:	$N := 10000$	$p_c\left(t_{hold}, T_{steam}, N\right) = 0.092$
100 liters:	$N := 100000$	$p_c\left(t_{hold}, T_{steam}, N\right) = 0.618$
1000 liters:	$N := 1000000$	$p_c\left(t_{hold}, T_{steam}, N\right) = 1$

In addition, sterilizing at an elevated holding temperature is very important! For a given holding time, the probability of contamination increases dramatically at lower holding temperatures.:

$p_c(15\cdot min, 121\cdot C, 1000) = 0.002$ Dramatic increase even for a drop of 5°C in the temperature!

$p_c(15\cdot min, 116\cdot C, 1000) = 0.999$

$p_c(15\cdot min, 100\cdot C, 1000) = 1$ 116C is not too desirable, and 100°C is almost useless!

On the other hand, to achieve the same degree of sterility, a lower temperature requires much prolonged holding time, increasing from 13min at 121°C to 15hr at 100°C:

$p_c(13.1\cdot min, 121\cdot C, 1000) = 0.01$

$p_c(34.8\cdot min, 116\cdot C, 1000) = 0.01$

$p_c(948\cdot min, 100\cdot C, 1000) = 0.01$

Part c). A heat labile component (e.g., vitamin) has a different expression of specific heat death rate.

1. Holding Phase

$k_d(Tc) := \left(10^4\cdot min^{-1}\right)\cdot \exp\left(-\frac{5000\cdot K}{Tk(Tc)}\right)$ $p\left(t_{hold}, T_{steam}\right) = 9.619\cdot 10^{-6}$ ...survial for particles

$p(t, Tc) := \exp\left(-k_d(Tc)\cdot t\right)$ $p\left(t_{hold}, T_{steam}\right) = 0.66607$ ...survival for vitamin

$p_{hold} := p\left(t_{hold}, T_{steam}\right)$

2. Heat-Up Phase

Heating Rate: $r_{heat} := 20\cdot C\cdot min^{-1}$

Temperature profile: $T(t) := 25\cdot C + r_{heat}\cdot t$

Time needed: $t_{heat} := \frac{T_{steam} - 25\cdot C}{r_{heat}}$ $t_{heat} = 4.8\cdot min$

specific death rate $k_d(t) := \left(10^4\cdot min^{-1}\right)\cdot \exp\left(-\frac{5000\cdot K}{Tk(T(t))}\right)$

Probability of survival: $p(t) := \exp\left(\int_{0\cdot min}^{t_{heat}} -k_d(t)\, dt\right)$ $p_{heat} := p\left(t_{heat}\right)$

3. Cool-Down Phase

Cooling Rate: $r_{cool} := 10\cdot C\cdot min^{-1}$

Temperature profile: $T(t) := T_{steam} - r_{cool}\cdot t$

Time needed: $t_{cool} := \frac{T_{steam} - 25\cdot C}{r_{cool}}$ $t_{cool} = 9.6\cdot min$

specific death rate $k_d(t) := \left(10^4\cdot min^{-1}\right)\cdot \exp\left(-\frac{5000\cdot K}{Tk(T(t))}\right)$

Probability of survival: $p(t) := \exp\left(\int_{0\cdot min}^{t_{cool}} -k_d(t)\, dt\right)$ $p_{cool} := p\left(t_{cool}\right)$

4. Overall survival

$p_{hold} = 0.666$ ⟵ Most death

$p_{heat} = 0.959$ ⟵ Some death

$p_{cool} = 0.92$ ⟵ Some death

Overall fraction of vitamin surviving: $p_{hold} \cdot p_{heat} \cdot p_{cool} = 0.588$

When the heating and cooling rate is low -- say, 1°C/min (e.g., for a large fermentor), the probability of vitamin surviving during both heat-up and cool-down, p_{heat} and p_{cool}, dropped to 0.436, yielding an overall surviving fraction of only 0.127. This could mean a significant loss of expensive nutrients. Thus, it is better to heat/cool quickly.
When the same calculation was done by changing T_{steam} at the beginning of this file, the resulting longer holding time dropped the overall fraction of vitamin surviving from 0.588 at T_{steam}=121°C, to 0.361 at T_{steam}=116°C, and merely 5.67×10^{-7} at T_{steam}=100°C. These conclusions are also applicable to everyday cooking.