Heat Transfer Modeling of Solid-State Fermentation Bioreactors to Produce Medicine in Space Habitats

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Background

Motivation

- Need for cost-effective/sustainable way to produce antibiotics and other medicine during long-term space missions, where resources are scarce
- Need for optimal forced aeration design to prevent overheating from fungal growth in a contained system [1]

Solid-State Fermentation

- Require less water, generate less wastewater, and reduce processing costs than submerged fermentation (SmF) [2]
- Higher product yield in shorter time periods [3]

Bioreactors

- Apparatus that allows for bioprocesses to occur [4]
- SSF bioreactors have a lower demand on sterility due to lower water requirement and activity [4]

Penicillin

- Secondary metabolite of *Penicillium chrysogenum* fungi (filamentous) [5]
- Antibiotic for gram-positive bacteria [6]
- Used to treat pneumonia, sepsis, strep throat, etc. [7]
- Fungal growth produces heat; fungi can overheat/die [6]

Theory for Mathematical Modeling

- Derived Contois equation for filamentous microorganism growth (fungal growth kinetics) to find biomass formation (heat generation) [8]
- $\frac{dX}{dt} = \mu_{max} * X$ [8]
- $X = X_0 * e^{\mu_{max}*t}$ [8]
- $\frac{dX}{dt} = \mu_{max} * (X_0 * e^{\mu_{max}*t})$
- $\frac{dQ}{dt}$ = (heat per biomass)$*\frac{dX}{dt}$ [8]
- Maximum growth rate μ_{max} = 0.1 h^{-1} [8]
- Initial value X_0 = 1000 g/m³ [8]
- Heat per biomass = 10,000 J/g at 25°C [7]

Objectives

1. Model heat produced by penicillin growth
2. Optimize a penicillin-producing bioreactor by modeling heat transfer varying tray length and air inlet velocity

Research Methods

- Mathematical manipulation
  - Derivation of equations
- COMSOL Multiphysics Software
  - Used to model heat transfer and air inlet velocity
  - 2 models: laminar flow (air) and heat transfer (solid-substrate inoculated with *P. chrysogenum* as heat source)
  - Varying tray length and inlet velocity
- Bioreactor 3D Modeling
  - Three evenly-spaced out solid-substrates ("trays") in tray bioreactor
  - Sample length at 10 cm as seen in Figure 2

Results

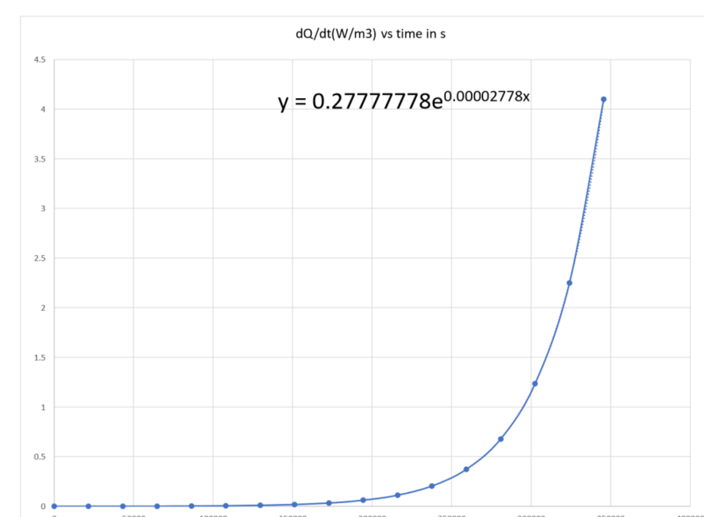


Figure 1. Mathematical model of heat produced (W/m³) over time (s) by *P. chrysogenum* as it produces spores, which produce penicillin as a secondary metabolite. No heat production when T > 45 °C to account for cell death.

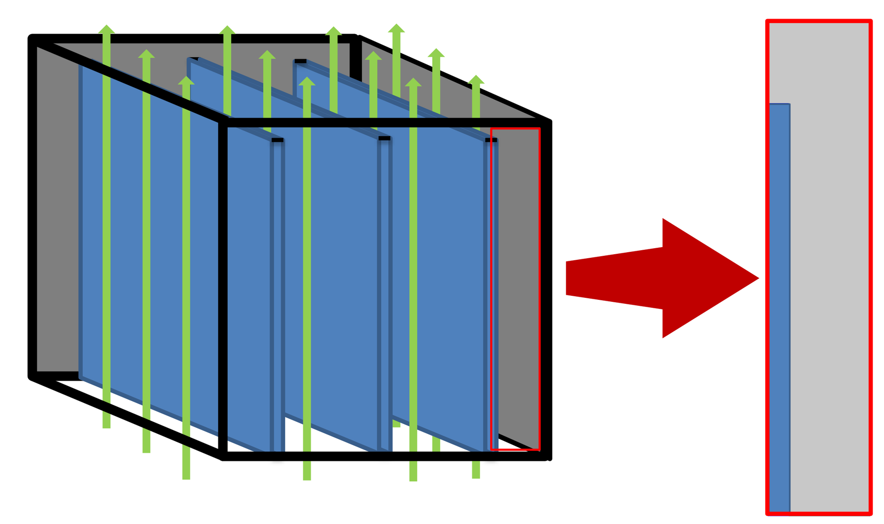
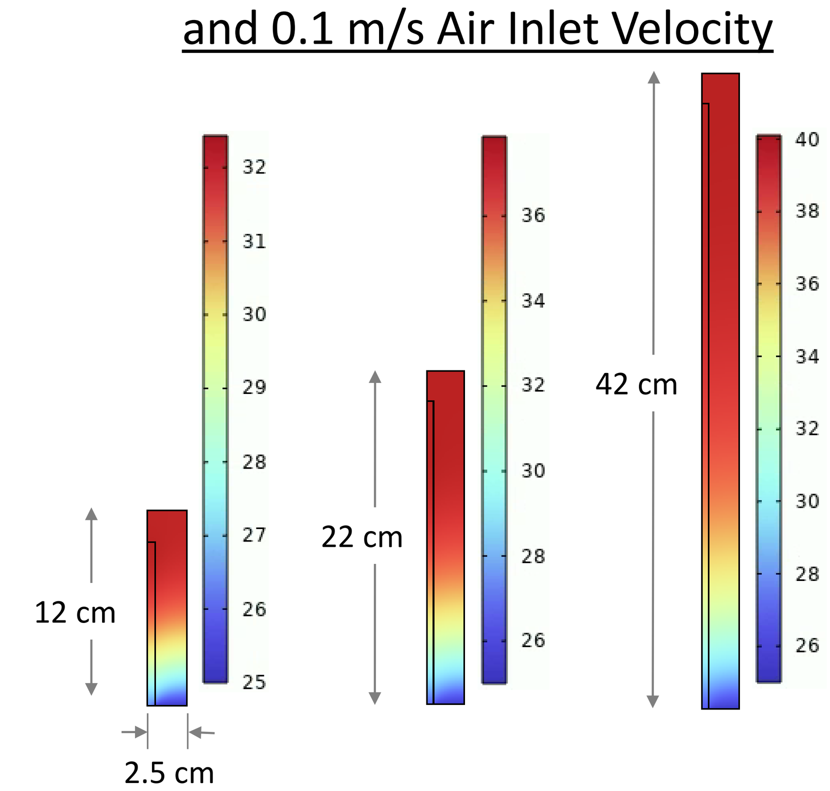
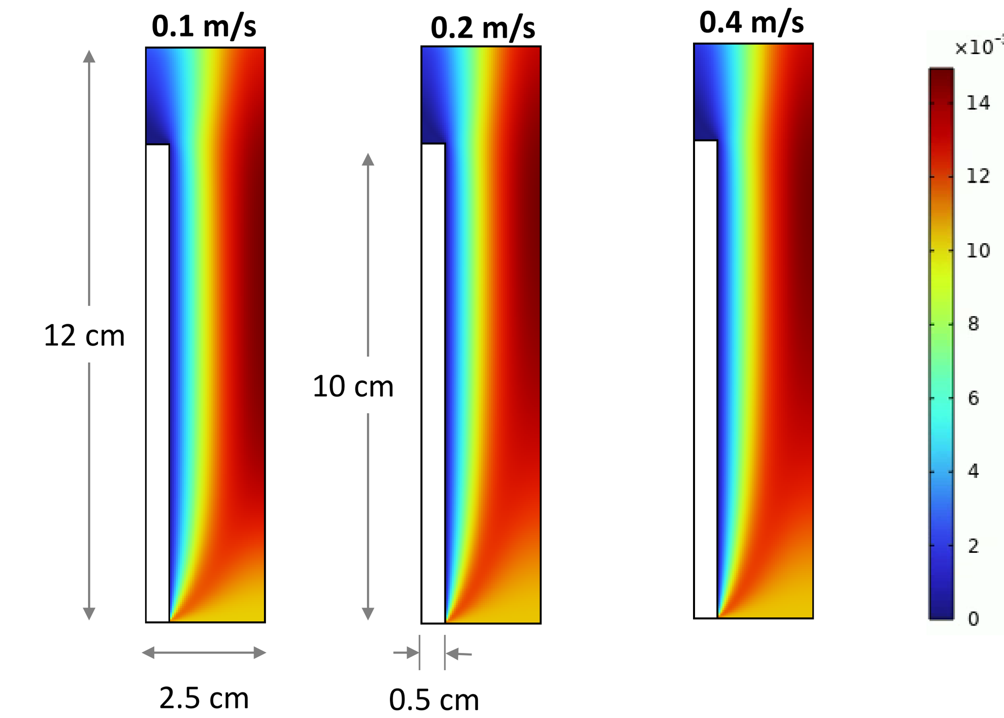


Figure 2. Sample design showing air flow (indicated by green arrows) through tray bioreactor with 10x10x1 cm trays (blue). Forced air to come in from bottom boundary and flow out through the top boundary, thus aerating the tray that is generating heat. The magnified front view snippet shows half of one tray and tray space. Symmetry of the bioreactor allows for this one segment to be modeled for heat transfer/velocity fields and be representative of the other trays.

Heat Transfer (°C) With Varying Tray Lengths and 0.1 m/s Air Inlet Velocity



Velocity Field for Different Air Inlet Velocity (m/s)



Future Research

- Experimentally determining what porous media results in optimized penicillin production
- Expanding on SSF bioreactor system to include other air inlet configurations and possible cooling mechanisms
- Optimizing bioreactor for space habitat conditions

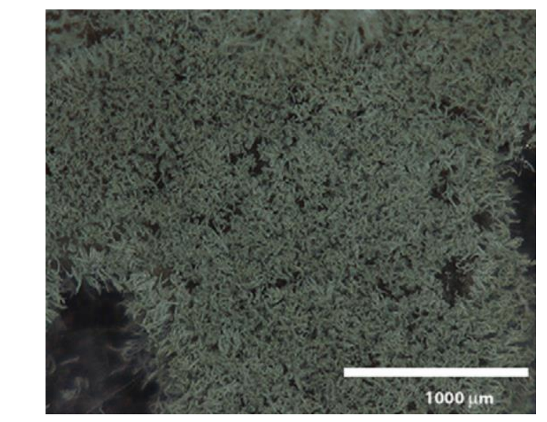


Figure 3. *P. chrysogenum* growth after 3 days. Presence of spores indicated by blue-green color. [5]

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