# 11 Modeling Approach for Gradient-Based Motion of Microorganisms in Porous Media and Applications in Biosystems

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## 11.1 INTRODUCTION

One of the adaptive behavioral responses of living organisms in their environment is *thermotaxis*, by which they migrate toward a preferred temperature or away from the uncomfortable heat sources. Thermotaxis or motion in the field of temperature gradient is a very common phenomenon and can be found in many events in nature, from biological ones such as the motion of *Dictyostelium* slugs (Maree et al. 1999), self-organized thermoregulation of honeybees (Watmough and Camazine 1995), *Caenorhabditis elegans* behaviors (Matsuoka et al. 2008), human and animal sperm (Bahat and Eisenbach 2006, Bahat et al. 2012) to the migration of colloidal particles (Golestanian 2012).

Various papers have revealed the characteristics of thermotaxis in the life sciences and in engineering. Different models were suggested to mathematically describe this phenomenon. Watmough and Camazine (1995) suggested a thermotaxis diffusion model for thermoregulating bees. These living organisms respond to decreases in their immediate or local temperature with a combination of increased metabolic activity and with movements toward their neighbors. This is modeled by coupling a thermotaxis diffusion equation for the cluster density to a heat equation with a temperature- and density-dependent source. The authors assumed that the heat transfer within the cluster is dominated by conduction. Maree et al. (1999) modeled the motion of the *Dictyostelium discoideum* slugs in the absence and in the presence of a thermal gradient. Their model is an extension of the hybrid cellular automata/partial differential equation model, as formulated by Savill and Hogeweg (1997). Experiments realized by Maree et al. (1999) showed that the modeled slugs maintain their shape and crawl, with a velocity depending on slug size. The authors also showed thermotactic behavior independent on initial orientation.

Many authors tried to suggest different models on nematodes, *C. elegans*, one of the well-known microorganisms with thermotactic behavior, and researchers expected that they could withdraw many interesting conclusions from this particular species for applications into neurobiology, developmental biology, and various other fields. Matsuoka et al. (2008) suggested a simple model with Monte Carlo simulation for *C. elegans* behavior. One important feature of this model is that the authors incorporated isothermal tracking, based on the investigation of Luo et al. (2006), the cryophilic tendencies and thermal adaptation (Ito et al. 2006, Matsuoka et al. 2008).

Their simple model could reproduce several properties of the population-level thermotaxis observed by Ito et al. (2006) related to the thermophilic and cryophilic tendencies of worms. They found that when thermal gradients are present, the distribution of worms, *C. elegans*, spreads faster toward the direction of falling temperature than toward the direction of rising temperature. However, they were unable to deal with states of the worms that depend on both the temperature and the direction of the worm movement. Their model actually could provide a viewpoint on the analyses of the population-level thermal response of real worms (Matsuoka et al. 2008).

Nakazato and Mochizuki (2009) built a simple biased random walk model of the *C. elegans* population behavior, which reflects the results of individual movement assays. Their results assert the importance of the steepness of the thermal gradient that may change the migration behavior drastically in experiments on thermotaxis.

Golestanian (2012) constructed a stochastic formulation to describe the collective behavior of a number of thermally active colloids. For extended time intervals and large length scale limits, as well as for dilute solutions, the formulation simplifies to a set of two nonlinear coupled differential equations for the density and temperature profiles. He found that when the Soret coefficient is positive, the system could be described in a stationary state by the nonlinear Poisson–Boltzmann equation and could adopt density profiles with significant depletion in the middle region when confined. For colloids with negative Soret coefficient, the system can be described as a dissipative equivalent of a gravitational system. The author also showed that in this case, the thermally active colloidal solution could undergo instability at critical laser intensity.

However, none of the models has mentioned the feedback convection that can be generated by the collective behavior of thermotactic microorganisms. In this chapter, we investigated this aspect in porous media. The mathematical model we suggested is a coupled system of partial differential equations wherein the thermotaxis is described under the form of temperature gradient–following term. The linear stability analysis will help us to define the onset of the thermotactic patterns that can get involved in many phenomena in nature.