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Micrometeorological modeling of an idealized cave and application to Carlsbad Cavern, NM, USA

S. Shindo(1), P. J. Boston(1,2), J. L. Wilson(1) and P. Burger(3)

1. Department of Earth and Environmental Sciences, New Mexico Institute of Mining and Technology, New Mexico, USA, (sshindo@nmt.edu, jwilson@nmt.edu / Fax: 505 835 6436 / Phone: 505 835 5466).
2. National Cave and Karst Research Institute, Carlsbad, New Mexico, USA, (pboston@nmt.edu / Fax: 505 835 6436 / Phone: 505 835 5657).
3. Carlsbad Caverns National Park, New Mexico, USA, (Paul_Burger@nps.gov).

Air–filled caves are subsurface, semi-closed systems with their own poorly understood internal micrometeorology. Cave micrometeorological processes may contribute to the formation and subsequent enlargement of caves and control some of the details of secondary mineral deposition. For example, airflow has been suggested as a factor orienting the growth of cave popcorn (Hill, 1987) and hypothesized as the cause of so-called “corrosion residue” breakdown products in caves like Lechuguilla Cave, NM (Davis, 2000).

In this work, we consider some aspects of the internal fluid-thermal dynamics of caves, especially buoyancy and natural convection due to geothermal heating. Two dimensional computer models of idealized caves were created using FEMLAB multiphysics computer software (COSOL, 2004) . The thermal properties of limestone and air, and geothermal flux were incorporated into the models. The models coupled the incompressible Navier-Stokes equations (air phase only) with thermal energy convection and conduction equation using the finite element method.

Although, the constructed models are limited in scale and have highly simplified geometries compared to real caves, they have identified some important factors that influence internal cave dynamics. In the deeper parts of caves, where there is less influence from the surface, natural convection cells occur due to the geothermal forcing and the relative properties of air and rock. Unlike conventional models of natural convection

in enclosures heated from below (Bejan, 1995), the air components of cave models are inherently unstable because the geothermal forcing is located far below the cave structure and, thus, the conductive heat flux on cave walls is not constant. This instability creates air movements at ultra-low velocities producing well-organized small scale convective patterns.

Humidity is an important factor frequently cited as influencing cave features. However, Rayleigh number and instability analysis indicate that humidity has less impact on flow dynamics; on the contrary, humidity may be affected by fluid flows. Flow patterns are strongly controlled by cave geometries. Surface influence tends to be limited to the vicinity of cave entrances due to air flow resistance (and viscosity), provided there are not multiple entrances with different air (atmospheric) pressures. Cave air mass is largely conserved. Temporarily, however, an excess pressure of air may be created locally, triggering a movement of air to move to areas of lower pressure. As a result, if a cave entrance is large enough, inflow and outflow components can be observed at a single entrance. The models were applied to help explain several observed phenomena within Carlsbad Cavern, NM. This cave is an extremely large and geometrically complex cave; however the simple models constructed in this study shed light on the interpretation of observations.

To our knowledge, this modeling effort is the first attempt to capture the behavior of such cave micrometeorological systems in a quantitatively rigorous manner. We believe that computer modeling can be very useful to assist understanding of the dynamics of cave interiors and possible effects on the enlargement and subsequent mineralogical decoration of caves. Modeling combined with detailed and continuous site monitoring in real caves, and attempts to include salient aspects of cave geometries, will be especially fruitful.

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