# Bi-directional & Evershed flows in penumbral filaments of sunspot simulations

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There are many observations of sunspots, but few attempts at sunspot simulations. Rempel (2012) presented realistic magneto-hydrodynamic (MHD) sunspot simulations, where the horizontal magnetic field at the top boundary is artificially increased, and which show Evershed flows in all filaments. Jurčák et al. (2020) showed that the magnetic field of such simulations differs from observations; in particular, the $B_{ver}$ at the umbral boundary is too low, and the horizontal field in the penumbra is too strong.

Using the MURaM MHD code and a potential field top boundary condition, we simulated a sunspot using potential field initial conditions. Our simulations give $B_{ver}$ at the umbral boundary consistent with observations and show ongoing flux emergence in the penumbra. When running the simulation with these initial and boundary conditions and a 96 (32) km horizontal (vertical) resolution, the penumbral filaments show bi-directional flows: in- & down-flows in the inner penumbra and outflows in the outer penumbra. However, when using a 32 (16) km resolution, some filaments show the same behavior, whereas others show the typical Evershed (radially outward) flow.

The bi-directional flows are observed in high-resolution observations of penumbra formation by García-Rivas et al. (2024), whereas the Evershed flow is observed in the stable phase of sunspots. We investigate penumbral filaments with these different flow regimes within our high-resolution simulation, and with those in a lower resolution simulation and a simulation with a different top boundary condition. We compare the different 3D flow structures in these penumbral filaments.