M42a On sunspot penumbra and Evershed flow: II. Analysis and interpretation

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We analyzed our high-resolution sunspot simulation in which the penumbra and the Evershed flow are reproduced and investigated the physical origin of these phenomena. As shown in our previous presentation in the ASJ meeting 2024 Spring (M38a), we reproduced the penumbra and Evershed flow in the high-resolution sunspot simulation with 6 km grid spacing. Earlier simulations that reproduced penumbra and Evershed flows required setups that imposed a strongly inclined (i.e. non-potential) magnetic field at the top boundary. Our work demonstrates that such inclined field is not necessary once the resolution is high enough. We analyzed the simulation result and understood the physical reason why we can reproduce these in the high-resolution simulation. The primary physical mechanism to accelerate the Evershed flow is almost identical to previous works (Rempel, 2011, 2012). The Lorentz force redirects upflows and leads to the Evershed flows. An essential difference in the different resolutions is the upflow structure in penumbral regions. In the high-resolution simulation small-scale elongated fast upflows exist that provide significant mass to the Evershed flow. These upflows can only be properly resolved in high-resolution simulations and consequently the Evershed flow is only present at higher resolution as well. The reproduced upflow structure is small (<100 km), and DKIST will help understand the sunspot fine-scale structure dynamics.