Asymptotic analysis of the thermal interaction of geothermal boreholes with aquifers valid for all groundwater flow regimes

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Abstract: Heating and cooling needs of buildings represent a significant share of the world's total energy consumption. To reach a more sustainable energy future, it is crucial to enhance the efficiency of heating, ventilation and air conditioning (HVAC) systems. Reducing energy demand in buildings contributes not only to the preservation of limited natural resources but also to the mitigation of greenhouse gas emissions and other environmental impacts. Among the available technologies, HVAC systems that harness low-temperature geothermal energy are among the most promising solutions to achieve such reductions.

Optimal sizing of geothermal heat exchangers is essential to guarantee that geothermal HVAC systems achieve both economic viability and their intended energy efficiency over the typical lifespan of a building, around one hundred years. Reaching this optimal design demands reliable forecasts of the long-term thermal response of the geothermal boreholes, which unfortunately cannot be obtained conducting detailed numerical simulations due to their excessive computational cost. Hence, simplified theoretical models are generally preferred as they are accurate, flexible and fast.

Modeling heat transfer in ground requires accounting for two fundamental phenomena, namely, heat conduction through the soil and heat convection driven by groundwater movement. Numerous theoretical models have been developed to represent these mechanisms, each relying on simplifying assumptions suited to specific groundwater flow conditions, namely, creeping groundwater flows and strong groundwater flows. However, the challenge arises in intermediate flow regimes, where neither of simplifying assumptions are valid. Hence, a unified theoretical model capable of describing heat transfer process consistently across the entire range of groundwater flow conditions is highly desirable.

The model developed in the present work is derived by exploiting the disparity of time scales in the problem, which allows significant simplification of the governing equations. By convenient manipulation of these simplified equations, analytical expressions are obtained that constitute the proposed model. Comparisons of the proposed model with detailed numerical simulations of the complete heat transfer problem, obtained with the commercial software package COMSOL, reveal the capabilities and limitations of the performed work.

Keywords**:** HVAC Systems, Geothermal Heat Exchangers, Geothermal Boreholes, Groundwater Flows, Asymptotic Solution