Supplementary Information
of

Developing Kilometers-long Gravity Heat Pipe for Geothermal Energy Exploitation

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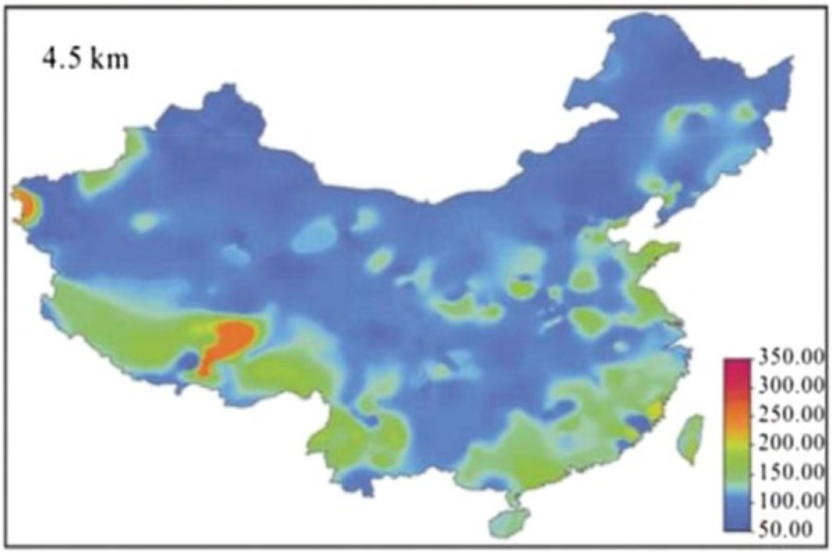
1. Geothermal resources distribution/reserves in China and USA

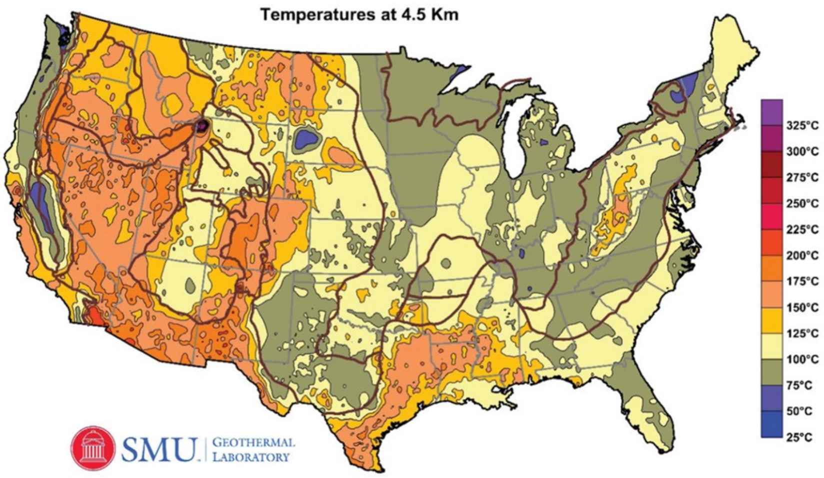
The Earth-deep geothermal resources are ubiquitous and their reserves are immense.

The temperature distribution mapping in China-mainland at depths of 3.5-8.5 km was calculated by Wang et al.[1] The results for a depth of 4.5 km are presented in Supplementary Fig. S1(a). The HDR resources in China-mainland were estimated based on the volumetric method by GIS (Geographic Information System) software. It can be noted that regions of high geothermal gradient are extensively available in the Qinghai-Tibet Plateau, southeast coastal provinces and inland basins. At depths 3.0 to 10.0 km, the total hot dry rock resources of China-mainland reaches a value of 7.00×10[18] kWh, which is equivalent to 856×10[6] million tons of standard coal[1,2].

Based on explored temperature data combined with rock thermophysical properties and surface temperatures, subsurface temperatures of USA were estimated by researchers at Southern Methodist University (SMU)[3,4]. Supplementary Fig. S1(b) displays the temperature distribution at a depth of 4.5 km, which indicates that regions of high geothermal gradient are located in the Western USA, parts of the Southern USA, and the Appalachian Basin. The total heat value of these geothermal resources in USA was estimated to be 12.4×10^{6} EJ (3.44×10^{18} kWh).



(a)

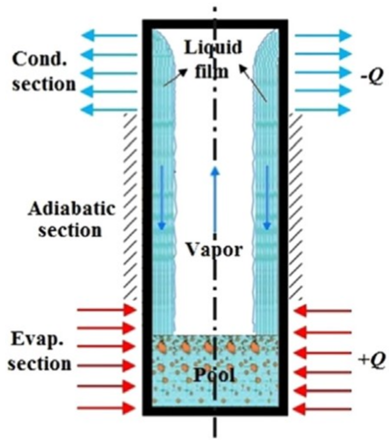


(b)

Supplementary Figure S1. Temperatures (°C) at 4.5 km of geothermal resources in China (a)[1,2] and USA (b)[3,4].

2. **Gravity Heat Pipe and its working principle**

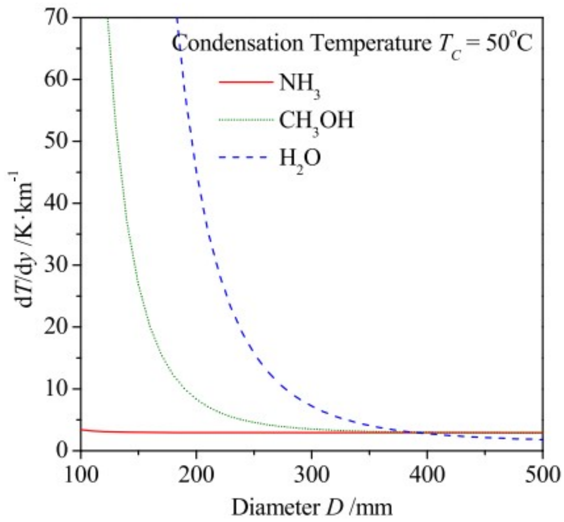
The Supplementary Figure S2 presents the gravity heat pipe and its working principle. The gravity heat pipe commonly encompasses three sections: evaporation, adiabatic, and condensation section. The evaporation section is positioned lower than the other two sections. The pipe is vacuumed and filled with the required amount of working liquid. In its operation, the liquid absorbs heat at the evaporation section, and while vaporizing it flows upward towards the condensation section, where it condenses and releases heat. The condensate flows downward towards the evaporation section by the action of gravity, completing a continuous cycle.



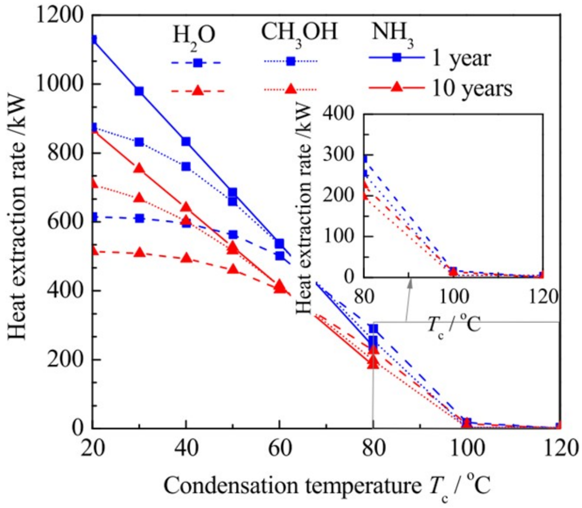
Supplementary Figure S2. Gravity heat pipe and its working principle[5].

3. SLGHP working fluid selection [6]

Supplementary Figure S3 reports the behavior of potential working fluids for SLGHPs. In Fig. S3 (a), the temperature gradient along the pipe axial direction, i.e. dT/dy, is reported as a function of the internal diameter of the SLGHP. The absolute value of this gradient was used as an index to assess the heat pipe performance, i.e., a small value of dT/dy relates to a good heat pipe performance. For the conditions taken in Fig.S3 and on the assumption of a low source temperature and/or small heat pipe diameter, ammonia is the preferred working fluid; by contrast, water is the preferred working fluid if the heat pipe diameter is large and/or the geothermal source temperature is relatively high. For most typical geothermal application scenarios, ammonia is the working fluid of choice.



(a)

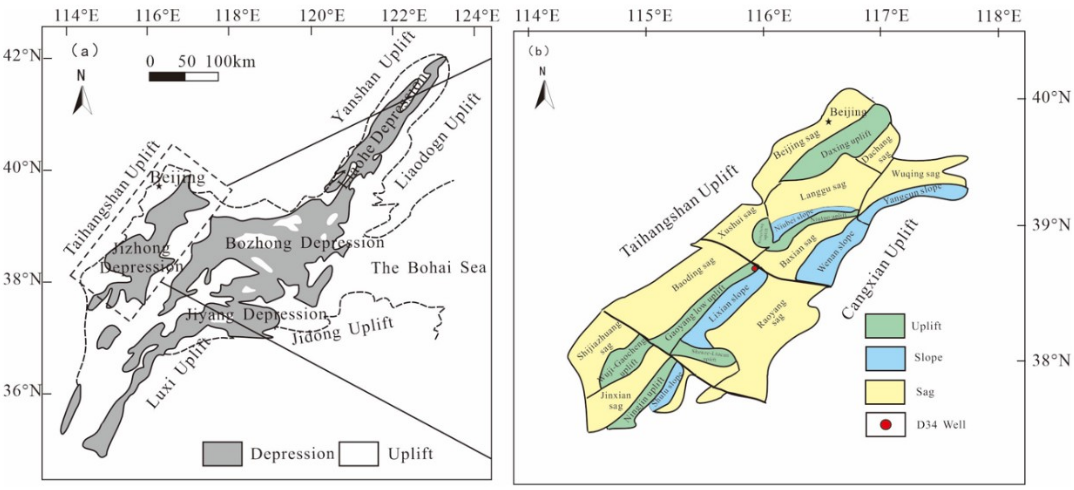


(b)

Supplementary Figure S3. (a) Value of d*T*/d*y* as function of the SLGHP diameter for three different working fluids, and (b) heat extraction rate for different condensing temperatures with the three working fluids - water, methanol and ammonia.[6]

4. Geological location of Xiong'an D34 well

The Supplementary Figure S4 shows the location of the Xiong'an D34 well, which is situated in the northeastern part of the Gaoyang Low Uplift within the Jizhong Depression.

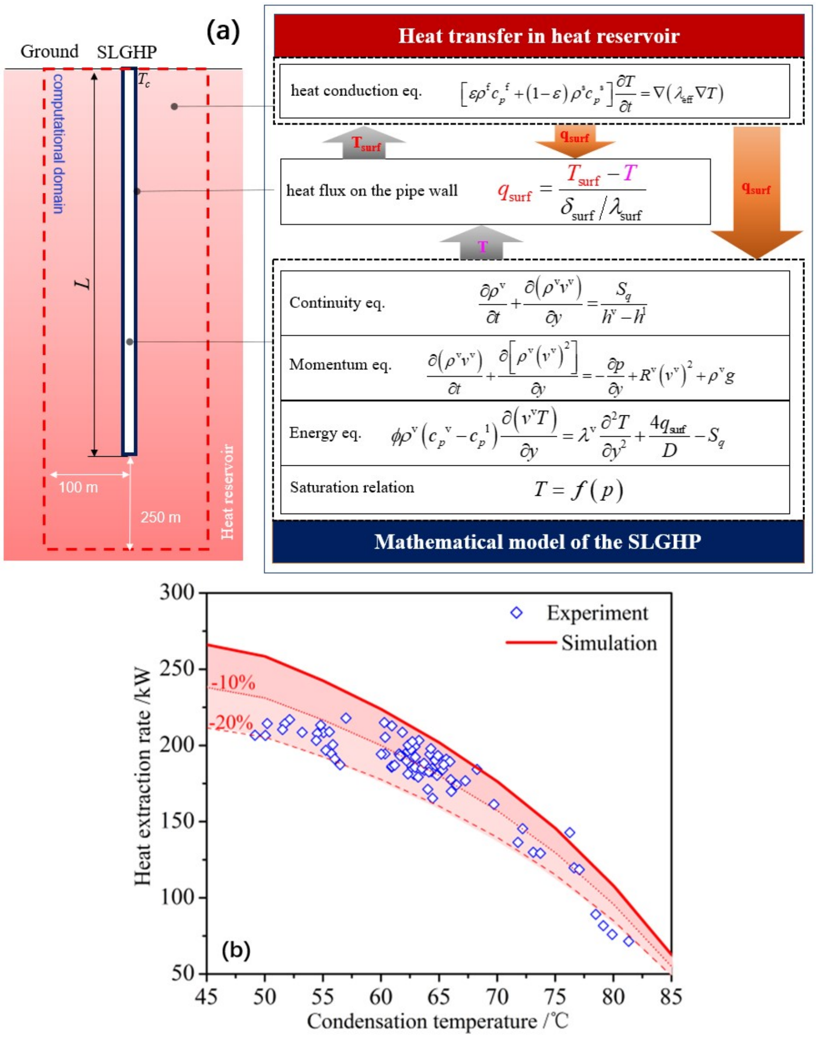


Supplementary Figure S4. Geological location of Xiong'an D34 well.

5. Simulation model of the SLGHP heat extraction process

Supplementary Figure S5 presents the framework and governing equations of the SLGHP heat extraction model. In the model, the interface between the heat pipe wall and the underground geothermal formation is a variable temperature boundary condition, which satisfies the heat transfer continuity conditions to allow the coupling of the heat transfer processes occurring inside and outside the heat pipe. Several assumptions are made, namely: i) No stagnant liquid pool or dry spot is present at the bottom of the heat pipe, i.e., no evaporation inhibition or local overheating is occurring at the bottom of the evaporation section of the heat pipe; ii) No liquid-vapor entrainment occurs along the heat pipe; therefore, the flow resistance in the SLGHP is mainly determined by the flow resistance of the vapor and it is formulated by an empirical in-pipe turbulent flow resistance correlation; iii) The fluid inside the heat pipe is in thermodynamic phase equilibrium; iv) The SLGHP working fluid outflow condenses at a constant temperature T_c; and v) The interphase momentum exchange of the gas-liquid phase is neglected. The simulation model was validated by the experimental data obtained at the SLGHP field test site in Tangshan, Hebei Province, China[7].

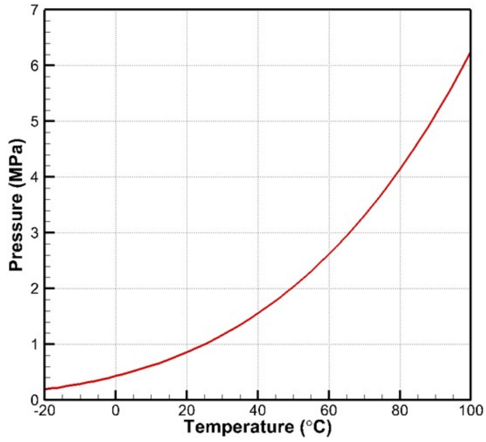
In the test, the SLGHP used water as the working fluid.



Supplementary Figure S5. Simulation model of SLGHP heat extraction process. (a) Framework of the numerical model; (b) model validation based on the experimental data from the SLGHP field test site in Tangshan[7].

6. Saturation pressure-temperature relationship of ammonia

In thermal equilibrium, the pressure and temperature of the working fluid (ammonia) are in a saturation state; consequently, they are a function of each other as reported in Supplementary Figure S6.



Supplementary Figure S6. Saturation pressure dependency on temperature for ammonia[8].

7. Heat extraction rate calculation

The heat extraction rate of the heat pipe is calculated by using Equation S1.

$$Q = CM(T_2 - T_1) \tag{S1}$$

where, C is the specific heat capacity of the cooling water, M is the mass flow rate of the circulating cooling water measured by an electromagnetic flowmeter, and T_1 and T_2 represent the condenser inlet and outlet water temperature, respectively, measured by the plug-in Pt resistance thermocouples.

8. Power generation calculations

The power generation calculations are based on the following assumptions: (i) Negligible pressure losses in the connection tubes; (ii) Minor heat loss to the environment; (iii) Negligible effects of kinetic energy and potential energy.

The power generation, P_e, is calculated by the following relation:

$$P_e = U \times I \tag{S2}$$

where, U and I are the measured voltage and current generated. The turbine efficiency is calculated as:

$$\eta_t = \frac{w}{w'} \tag{S3}$$

where, η_t is the turbine efficiency; w' is the ideal (isentropic) shaft work, and w is the actual shaft work.

The specific exergy for each thermodynamic state is defined by the following relation:

$$ex = (h - h_0) - T_0 \cdot (s - s_0) \tag{S4}$$

where, h is the specific enthalpy of the working fluid of the heat pipe; s is the specific entropy; and the subscript 0 refers to the state at ambient temperature. The exergy destruction/loss of each component is evaluated as:

$$Ex_L = Ex_{in} - Ex_{out} \tag{S5}$$

The exergy production rate from the SLGHP is calculated by:

$$Ex = Ex_{in} - Ex_0 \tag{S6}$$

Exergy efficiency of the power generation system is calculated by the following equation.

$$\eta_{ex} = \frac{P_e - W_e}{H_{out} - H_{in} - (S_{out} - S_{in})T_0} \tag{S7}$$

where, η_{ex} is the exergy efficiency; H is the enthalpy of the heat pipe working fluid; S is the entropy of the heat pipe working fluid; T_0 is the ambient temperature; W_e is the power consumption of the ammonia pump. The subscripts "in" and "out" represent the flow of working fluid into and out of the wellhead respectively. H and S are determined by using the physical property parameter database[8].

References

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