## Title
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# Improvement on the calculation of heat transfer rate for a new type of geothermal energy pile

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**ABSTRACT**: This study focuses on refining the solution used to calculate the heat transfer in a novel, self-operating geothermal energy pile based on the principle of a thermo-syphon. This new type of energy pile, formed by pressurizing a hollow helical pile with carbon dioxide ($CO_2$) to form a heat pipe, is highly efficient, which could be an important alternative of existing energy pile. Specifically, this new type of energy pile utilizes spontaneous liquid-vapor phase change and natural convection inside the pile to transfer heat from the pile tip and the head. By isolating the pile from the soil and analyzing it as an independent heat transfer unit, the pile seems to have equivalent thermal conductivity that is thousand times of common metals. A simplified closed-form solution has been developed to estimate the heat transfer rate as well as equivalent thermal conductivity, which links the geometry of the energy pile with its thermal efficiency. This simplified solution could be used as a preliminary approach to assess such an energy pile system, but it has great room for improvement since the derivation used a number of assumptions. This study refines the simplified solution by replacing some of the assumptions with mathematical quantifying components, and leads to more accurate heat transfer estimates.

## INTRODUCTION

Due to strong thrust to promote usage of clean energy, thermal energy together with wind, solar, hydropower and biomass will become our major energy resource in the future. The most commonly used approach to harvest shallow geothermal energy are closed-loop geothermal heat exchange pipes that are embedded in vertical boreholes, buried in shallow excavations, or embedded in building foundations (DOE 1998). In recent years, energy piles, which is drilled shaft foundation with embedded geothermal circulation loops, have been increasingly used for various commercial and residential buildings (Brandl 2006; Bourne-Webb et al. 2009; McCartney et al. 2010). These energy piles are often used in conjunction with a heat pump to realize heat exchange between buildings and subsurface soil, in which soil acts as a heat source or sink depending on the direction of heat transfer (Bourne-Webb et al. 2013; Rybach et al. 2000; Spitler and Ramamoorthy 2000; Xiao et al. 2013). In the past decade, research has greatly improved our understanding on the heat transfer mechanism and possible mechanic-thermal interaction of the system, which has extensively promoted the adoption the energy foundation systems (Amatachaya and Srimuang 2010; Brandl 2006; Laloui et al. 2006; McCartney and Murphy 2017; Murphy and McCartney 2015; Murphy et al. 2015; Ozudogru et al. 2014). In recent years, besides supplementing building energy consumption, energy piles have been used to de-ice bridges, roadways, and railroads in North America, Europe and Japan (Xiao et al. 2013). Although energy piles represent an appealing technology to harvest shallow geothermal energy, they in general consume about 30 – 70% of the energy they harvest to maintain the circulation of working fluid, which may make them uneconomical for some circumstances (DOE 1998).

Alternatively, a two-phase thermo-syphon can be used to achieve a self-running circulation (Huang et al. 2019). In the thermo-syphon, the circulation of a pressurized working fluid is achieved by natural convection (i.e., a combination of gravity and buoyancy) without external energy for operation (Amatachaya and Srimuang 2010). Huang et al. (2019) proposed an energy pile based on the thermo-syphon principle, in which carbon dioxide ($CO_2$) was used as the working fluid. Basically, $CO_2$ was pressurized and sealed inside a steel pile (i.e., helical pile), in which $CO_2$ underwent vapor-liquid phase change to achieve heat exchange between surface and subsurface. Specifically, during heating the $CO_2$ at the tip of the pile absorbs heat, evaporates and travels to the pile head, where it encounters cold pile head and then condenses and releases heat. This process repeats until the temperature difference between the pile tip and head becomes too small. For cooling operation, the process reverses with the assistance of a build-in wick structure (Huang et al. 2019). For such a system, no electrical and mechanical parts are needed to run the system, so it may be more reliable with lower maintenance costs when compared with existing energy piles (Loeffler 2012; Sabharwall et al. 2008; Tsai et al. 2010). Thermo-syphon in reality is a very matured technology, which has wide applications in mechanical engineering and electrical engineering, such as computer central processing units (CPUs), soil freezing, solar water heating, neutron cooling for nuclear research, spacecraft and satellite cooling, and cooling/heating of foods (Esen and Esen 2005; Habte, 2008; Haider et al. 2002; Hossain 2013; Sabharwall 2009). More commonly, ammonia, Freon, and propane are used in these applications, but $CO_2$ may be more suitable for energy pile applications as it is non-toxic and non-flammable (Huang et al. 2019; Wu et al. 2010; Zurcher et al. 1999).

## REIVEW AND DISCUSSIONS OF HUANG EL AL. (2019) SOLUTION

Based on the thermodynamics and fluid dynamics of a thermo-syphon, Huang et al. (2019) proposed a simplified solution to estimate the heat transfer capacity of an energy pile using two-phase thermo-syphon. The prototype energy pile is shown in FIG. 1. In the derivation, they ignored the complicated interaction between vapor and fluid as well as the possible turbulence of the flow and treated the tip of the energy pile as a point heat source. In addition, they assumed:

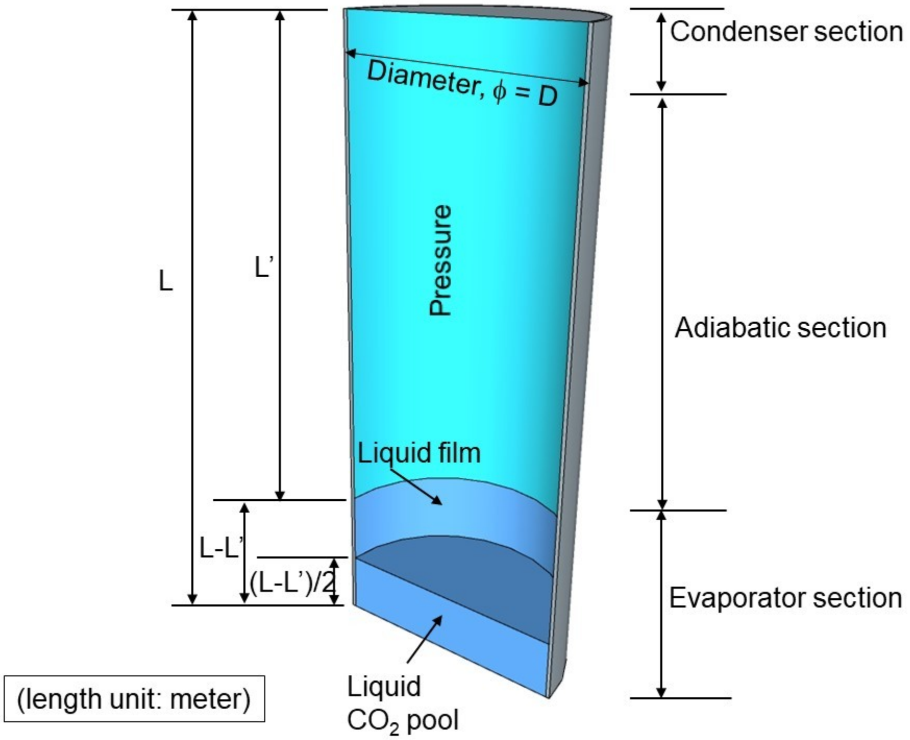


FIG. 1. Prototype model of a thermo-syphon energy pile (modified from (Huang et al. 2019))

- The pressure is uniform inside the pipe that contains the $CO_2$.
- The flow of $CO_2$ vapor is unidirectional, i.e., directly from the tip to the head of the pile.
- The condenser section is the section of the pile that below L' as shown FIG. 1.
- The soil temperature is constant below a depth L'.
- Initial fluid flux momentum is assumed to be negligible.
- Evaporation is assumed to primarily occur at the liquid film, which account for half of the evaporation section if the filling ratio is 0.5.

By adjusting the pressure inside the pile, the tip of the pile is above the saturation temperature of $CO_2$ and the head of the pile is below the saturation temperature of $CO_2$, which can be illustrated in the phase diagram shown in FIG. 2. For example, for a heating scenario, at a certain operational pressure, $P_1$, the $CO_2$ will be in the vapor and liquid phase zones in the evaporator and condenser at their initial temperatures (i.e., $T_1$ and $T_o$), respectively. When phase change starts, the liquid $CO_2$ at the tip of the pile vaporizes and travels to the head by buoyance. Then it gets condensed when encounters the cooler pile head and flows back to the tip by gravity. As a result, the pile tip temperature increases and the pile head temperature increases. The whole process will stop whenever $T_1$ reaches $T_2$ or $T_o$ reaches $T_2$. However, Huang et al. (2019) did not consider the temperature change at both ends of the pile; instead, they assumed the temperature was constant, which may not be a problem if they were evaluating the heat transfer at a short period.

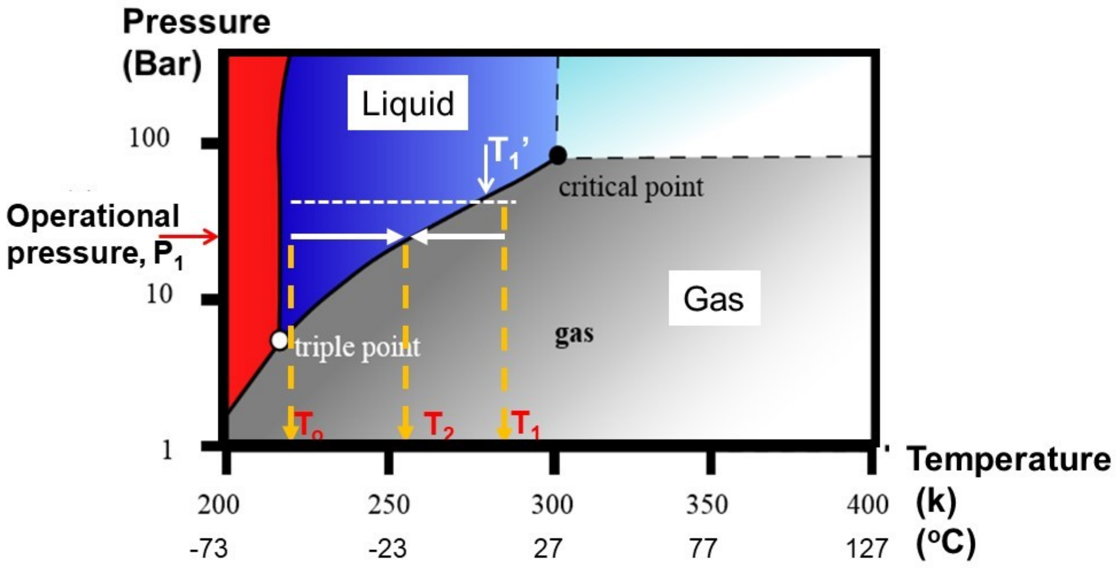


**FIG. 2. $CO_2$ phase diagram for thermo-syphon energy pile (modified from Huang et al. (2019))**

Based on the above-mentioned scenario, Huang et al. (2019) claimed that the heat transfer rate ($h_e$) due to the phase change of $CO_2$ can be estimated by Eqn. 1 below:

$$h_e = m_v h_v + m_v C_p \Delta T = 10.2 \left( h_v + C_p \Delta T \right) \left( \pi D (L - L')/2 \right)^{\frac{3}{2}} \sqrt{(4 g \rho \Delta \rho_o)/(L + 3L')} \tag{1}$$

where $m_v$ is $CO_2$ mass flow rate, $m_v = Q\rho = w_m A \rho$; $h_v$ and $C_p$ are the latent heat (unit: kJ/kg) and specific heat capacity of $CO_2$ (unit: kJ/(°C·kg)), respectively; g is the acceleration due to gravity; ρ is the density of $CO_2$ vapor (unit: kg/m$^3$); and $\Delta\rho_o$ is the spatial variation of the density of $CO_2$ vapor; L is the total length of the pile; L' is the length of the evaporator section; D is the diameter of the pile.

The formula in general provides an acceptable preliminary estimate of the heat transfer rate of the proposed of energy pile using thermo-syphon phenomenon to transfer heat. The results indicate the estimated the heat transfer rate is in the same magnitude of other published experimental data of thermo-syphons (Huang et al. 2019).

## IMPROVEMENT OF HUANG ET AL. (2019) SOLUTION

Even though Huang et al. (2019) solution is simple to use and provides reasonable estimation of the heat transfer, the solutions can be further improved or refined by replacing two assumptions with mathematical quantifications that can be incorporated into the existing solutions. First, Huang et al. (2019) assumed that the travel of vapor is unidirectional, i.e., vapor flows directly from pile tip to pile head as shown in FIG. 3(a). This assumption makes the flow distance equals to the distance between pile tip and head. However, the travel velocity was estimated by the formula used for a plume with cylindrical boundaries, as indicated below (Fischer et al. 1979):

$$w_m (z/B)^{1/3} = f\left( B^{1/3} z^{2/3} / \nu \right) \tag{2}$$

where z is the vertical distance of flow, B is the specific fluid flux due to buoyancy (unit: m$^4$/s$^3$), and ν is the kinematic viscosity of the fluid (i.e., $CO_2$ vapor in this study) (unit: m$^2$/s).

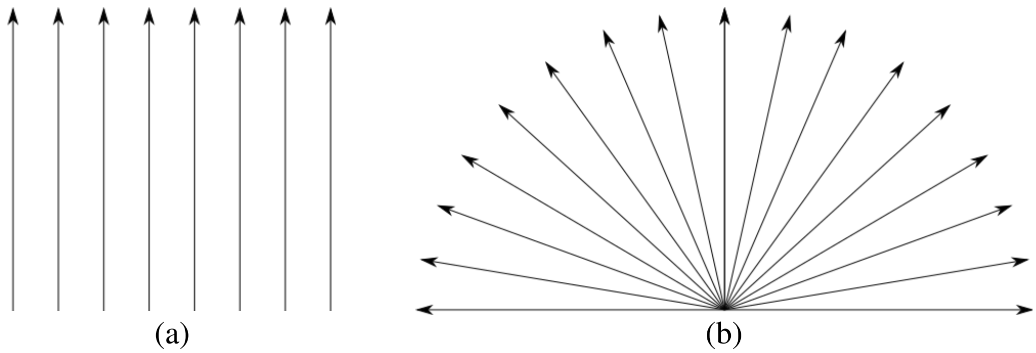

(a) (b)

FIG. 3. Unidirectional vs. radial flow

Eqn. 2 is applicable to radial diffusion from a point source as shown in FIG. 3(b), which implies a repetitive, reflective flow inside a confined cylinder as shown in the comparison in FIG. 4. Initially, the flow starts radially so the flow forms a different angle with respect to the vertical wall, which will bounce back. The process continues until the pile head is reached, which will form a zigzag flow pass as illustrated in FIG. 4. Huang et al. (2019) solution underestimated the flow distance or, in another word, overestimated the flow velocity. As a result, the heat transfer rate of the energy pile could be overestimated. Second, Huang et al. (2019) assumed that the evaporation primarily occurs at the liquid $CO_2$ but not at surface of liquid $CO_2$ pool. This assumption may exclude a reasonable portion of evaporation if the pile diameter is reasonably large. Therefore, the heat transfer rate of the energy pile may be underestimated. In summary, Huang et al. (2019) can be improved to provide a better estimate, especially for piles with large dimeter.

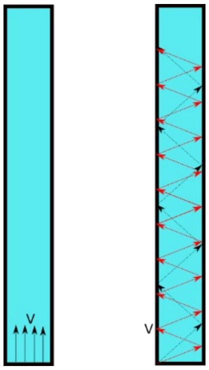


**FIG. 4.** Uniform vs. reflective flow

## MODIFICATION OF HUANG ET AL. (2019) SOLUTION

The modification encompasses two parts, which considers the radial flow on the interior pile wall and on liquid pool surface, respectively as shown FIG. 5. The velocity of the flow proposed by Huang et al. (2019) is still valid, which is a function of gravity (g), density gradient (Δρ) and flow distance (z) as shown in Eqn. 3:

$$w_m = 10.2\sqrt{(g\,\Delta\rho_o A)/(\rho z)} \qquad (3)$$

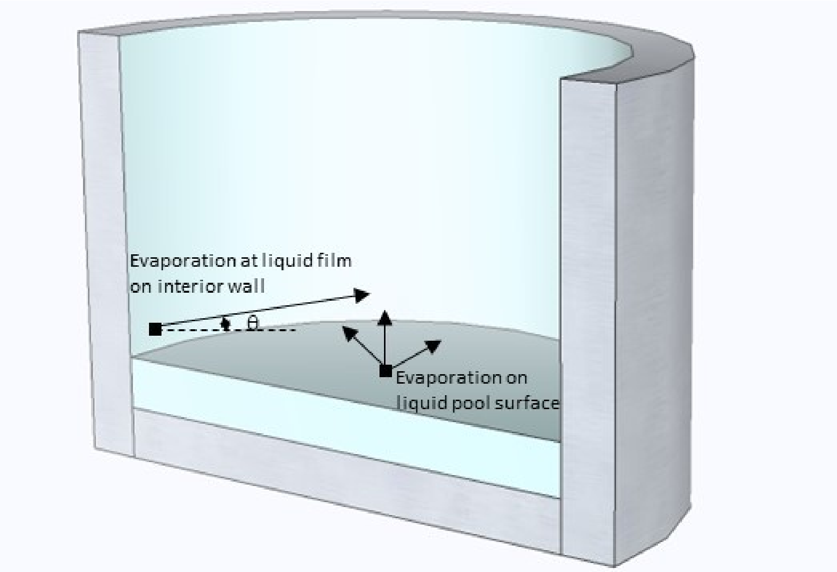


**FIG. 5.** Analysis for the refined model

As to the flow from the liquid film located at the interior of the pile wall, the velocity forms an angle (θ) with the horizontal direction. Thus, the vertical flow velocity is:

$$w_{m,v} = w_m \sin\theta \tag{4}$$

Considering the average velocity in a ¼ quadrant space, it can be calculated as a weighted average over radian of 2/π, which is a quarter of a circle :

$$w'_{m,v} = \frac{\int_0^{\frac{\pi}{2}} w_m \sin\theta d\theta}{\frac{\pi}{2}} \tag{5}$$

Since $w_m$ is not relevant to the angle (θ), Eqn. 5 simplifies to:

$$w'_{m,v} = \frac{w_m \int_0^{\frac{\pi}{2}} \sin\theta d\theta}{\frac{\pi}{2}} \tag{6}$$

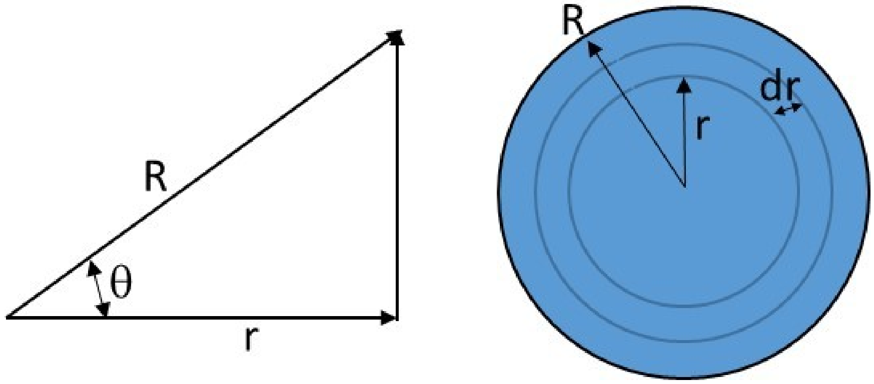
Thus, it can be determined that $w'_{m,v} = \frac{2}{\pi} w_m = \frac{20.4}{\pi} \sqrt{(g\,\Delta\rho_o\,A)/(\rho z)}$.

The flow initiated from the liquid pool surface is much more complicated, since it involves the weighted average in an area. By assuming the radius of the pile is R, at a random distance, r, from the center, the vertical velocity can be calculated as:

$$w_{m,v} = w_m \frac{\sqrt{R^2 - r^2}}{R} \tag{7}$$

As to the weighted average of the flow velocity, it requires integrating over a circular area. Taking an infinitely small ring, the product of velocity and area can be calculated as, which is illustrated in FIG. 6:

$$w_{m,v} \times \Delta A = w_m \frac{\sqrt{R^2 - r^2}}{R} 2\pi r dr \tag{8}$$



(a) (b)

**FIG. 6.** Analysis of the liquid pool surface flow

The weighted average shall be:

$$w'_{m,v} = \frac{\int_o^R w_m \frac{\sqrt{R^2 - r^2}}{R} 2\pi r dr}{\pi R^2} \tag{9}$$

Substituting $w_m$ with Eqn. 3 and replacing $A = \pi r^2$, the following integral form is obtained:

$$w'_{m,v} = \frac{\int_o^R 10.2 \sqrt{\frac{\pi r^2 g \Delta \rho_o}{\rho z}} \frac{\sqrt{R^2 - r^2}}{R} 2\pi r dr}{\pi R^2} \tag{9}$$

Eqn. 9 can be simplified into:

$$w'_{m,v} = \frac{20.4 \sqrt{\frac{\pi g \Delta \rho_o}{\rho z}}}{R^3} \int_o^R \sqrt{R^2 - r^2}\, r^2 dr \tag{10}$$

Letting r=R · sinθ, Eqn. 10 is transformed into:

$$w'_{m,v}=20.4R\sqrt{\frac{\pi g\,\Delta\rho_o}{\rho z}}\int_{o}^{\frac{\pi}{2}}(\sin\text{¿¿}2\,\theta-\sin^4\theta)\,d\theta\,\text{¿} \tag{11}$$

By replacing $\int_{o}^{\frac{\pi}{2}}(\sin\text{¿¿}2\,\theta-\sin^4\theta)\,d\theta=\text{¿}\frac{\pi}{16}\text{¿¿}$, the weighted average velocity of the vapor from the liquid surface is:

$$w'_{m,v}=\frac{20.4\,R\pi}{16}\sqrt{\frac{\pi g\,\Delta\rho_o}{\rho z}} \tag{12}$$

As suggested by Huang et al. (2019), the total heat transfer rate includes two components, which are specific and latent heat:

$$h_e=m_v\left(h_v+C_p\Delta T\right)=w'_{m,v}A_{surface}\left(h_v+C_p\Delta T\right)$$
$$\text{¿}\frac{20.4\,R\pi\,A_0}{16}\sqrt{\frac{\pi g\,\Delta\rho_o}{\rho\,z_o}}\left(h_v+C_p\Delta T\right)+\frac{20.4\,A_1^{3/2}}{\pi}\sqrt{\frac{g\,\Delta\rho_o}{\rho\,z_1}}(h\text{¿¿}v+C_p\Delta T)\text{¿} \tag{13}$$

where A is the area for evaporation, i.e., $A_0=\pi\,R^2$for liquid pool surface, $A_1=\pi D\left(L-L'\right)/2$for liquid film at the interior wall of the pile, $z_o$ is the flow distance for vapor starting from the liquid pool surface, i.e., $z_o$= (L+L')/2; and $z_1$ is the flow distance for vapor starting from the liquid film, i.e., $z_1$=L'/4+3L/4.

## CONCLUSIONS

This study focuses on improving the simplified equation proposed by Huang et al. (2019) to calculate the heat transfer rate based on a thermo-syphon principle. Two refinements have been made that have resulted in a more accurate analysis: considering the zigzag flow pass for vapor transfer and including the evaporation at the liquid pool surface.

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