Development and application of a new calculation method for double spiral ground heat exchangers

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- Validation
- Problem & Discussion
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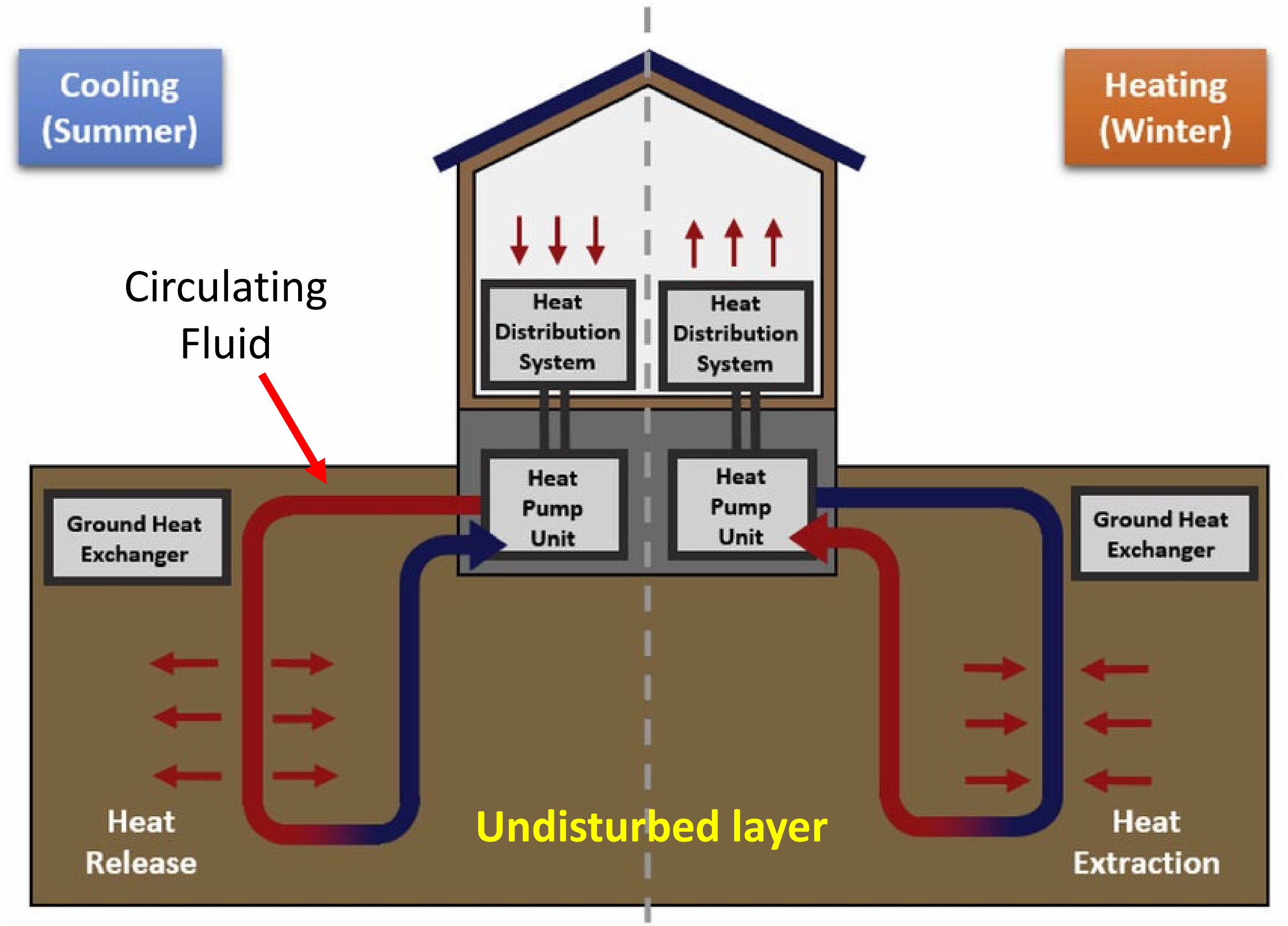
Ground Source Heat pump (GSHP) System

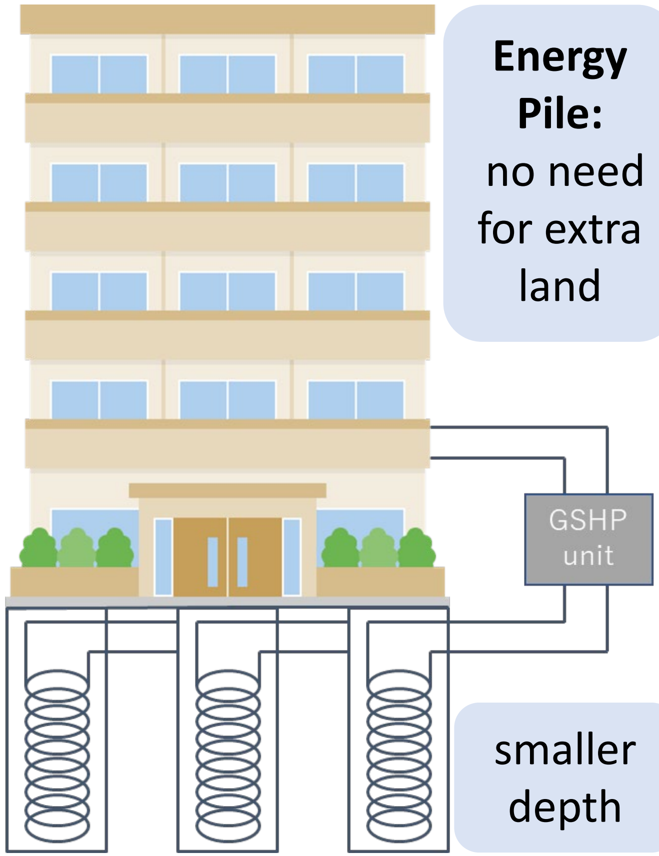


Undisturbed layer :
- constant temperature throughout a year
- 1-3℃ higher than annual mean temperature

Advantages :
1. Reliable heat source
2. Higher efficiency
3. Not intermittent
4. Less maintenance

Disadvantages :
1. Large site area required to install GHEs
2. high installation cost for drilling

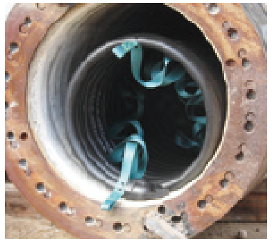
Energy Pile & Spiral GHE



Energy Pile: no need for extra land

smaller depth

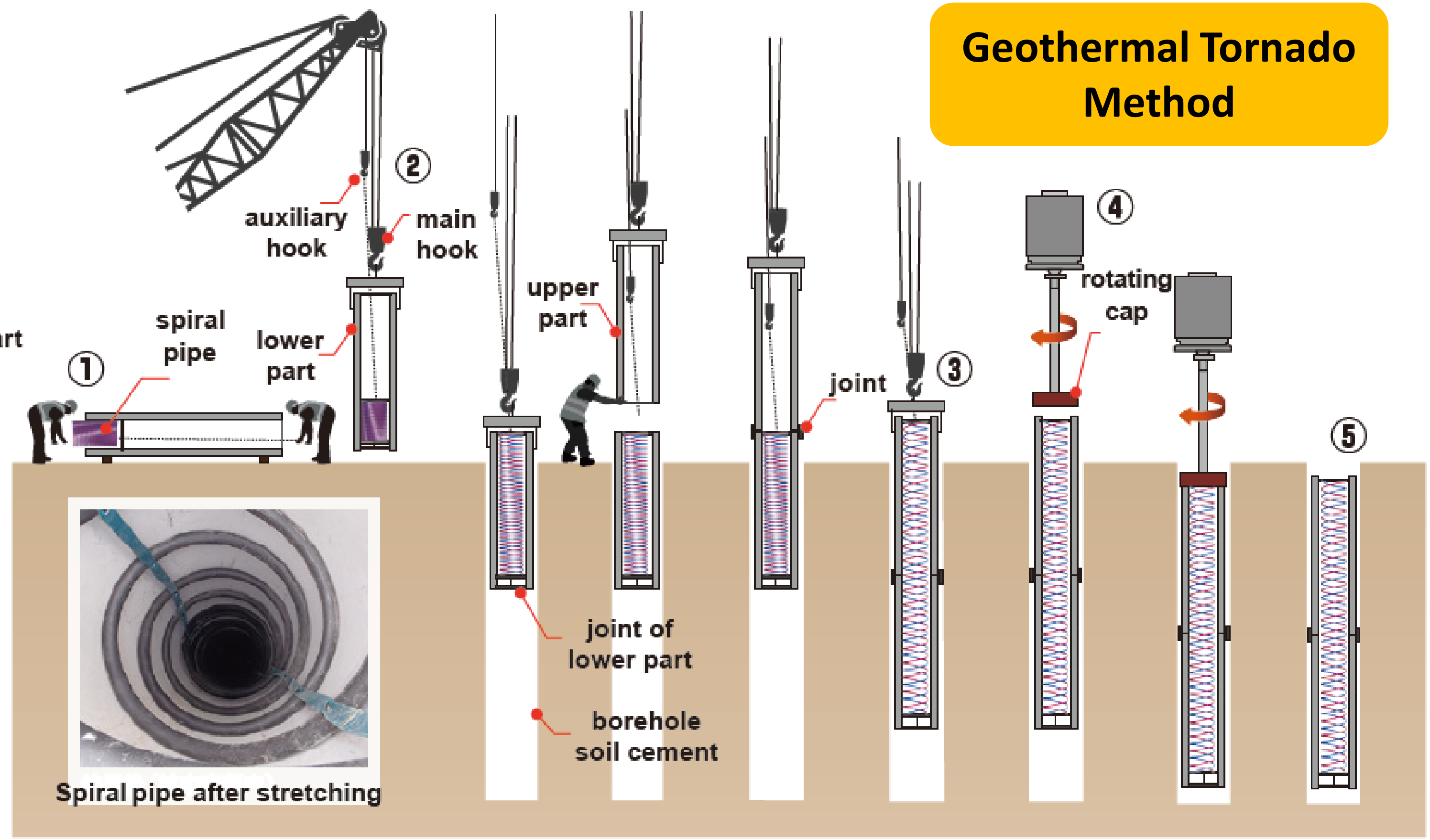
Installation in the hollow part



After installation

Joint of lower part

Geothermal Tornado Method



Spiral pipe after stretching

http://www.japanpile.co.jp/method/pdf/tornado.pdf

Installation of spiral GHE

①

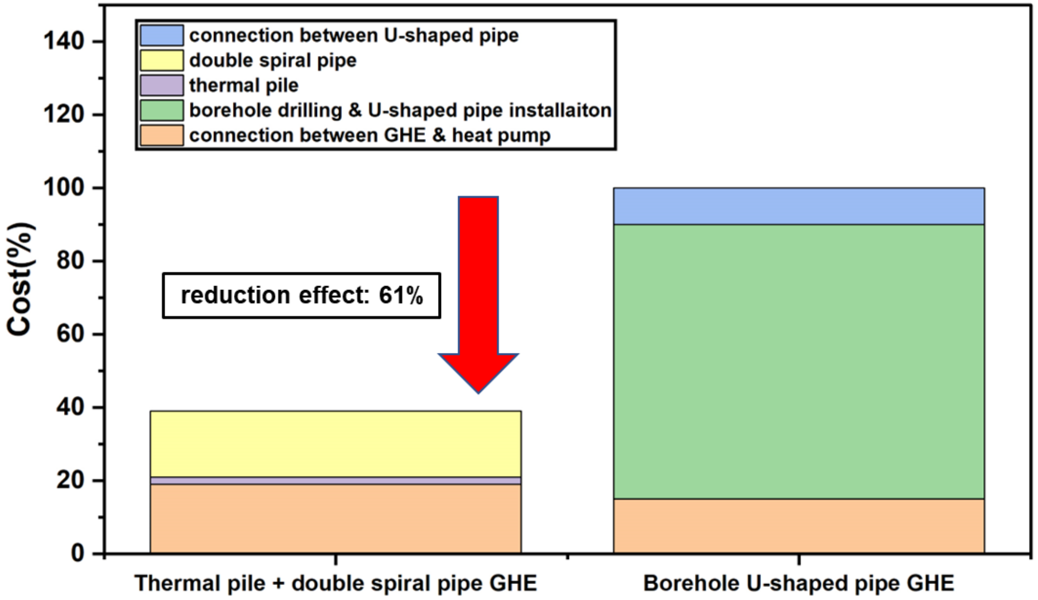

②


③


④


⑤

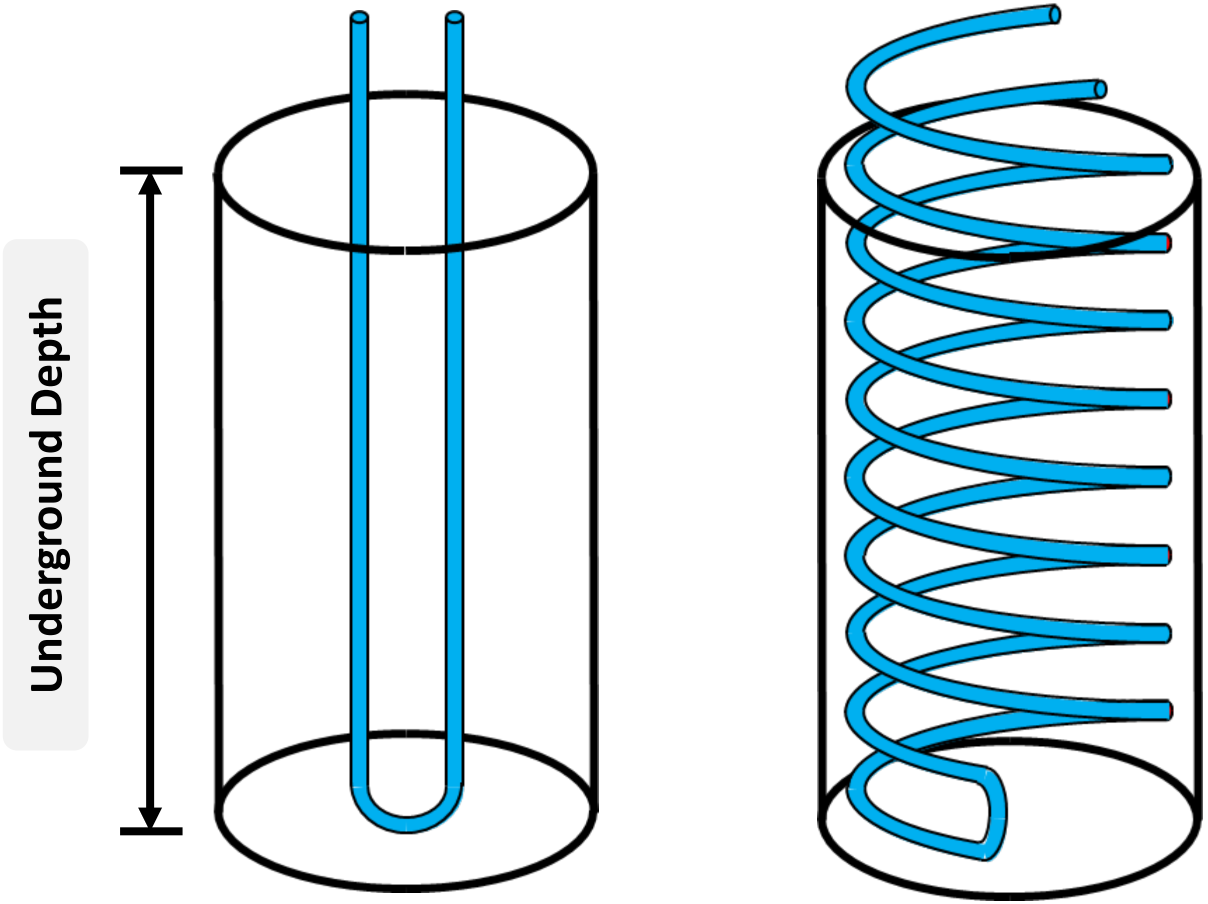

Drilling Work:
100 m (U-tube)
↓
20 m (spiral tube)



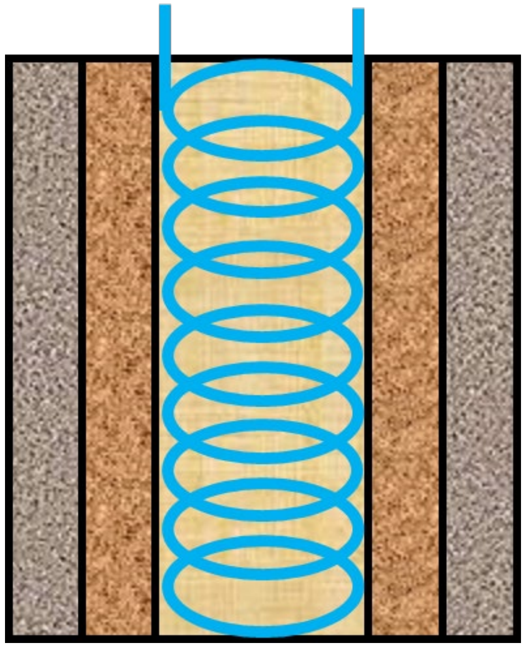
Heat Transfer of Spiral GHE

Spiral tube has **longer length** than conventional U-tube

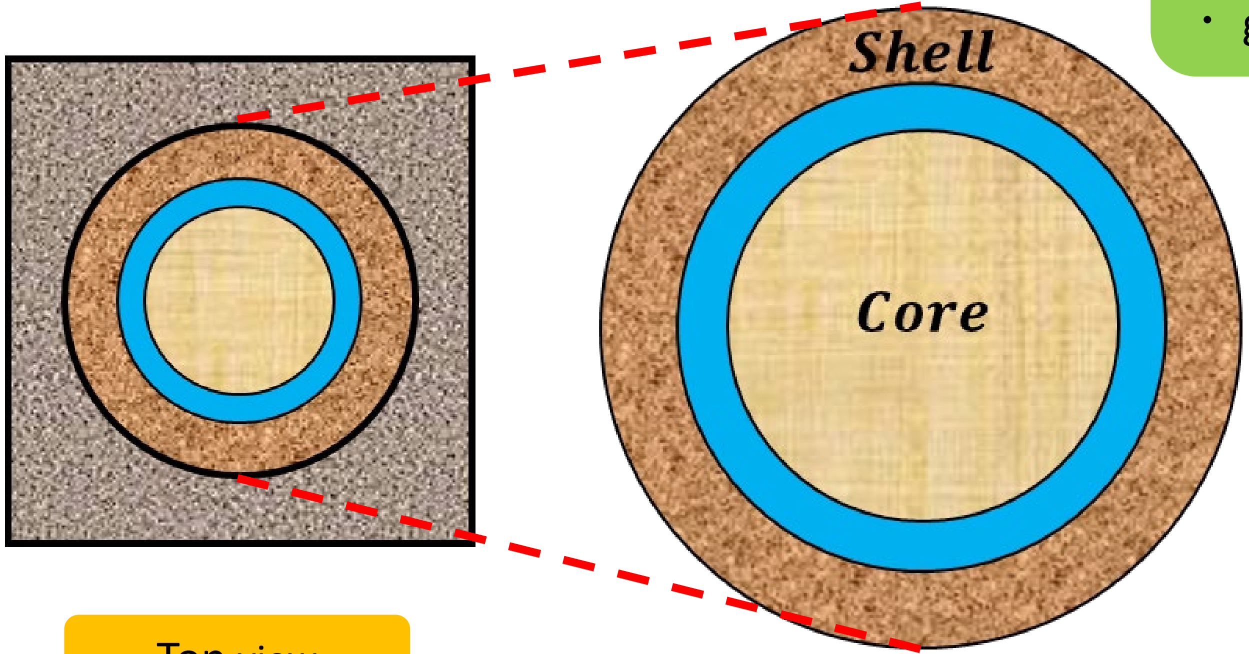
Larger heat transfer area between ground and circulating fluid



Heat Transfer of Spiral GHE



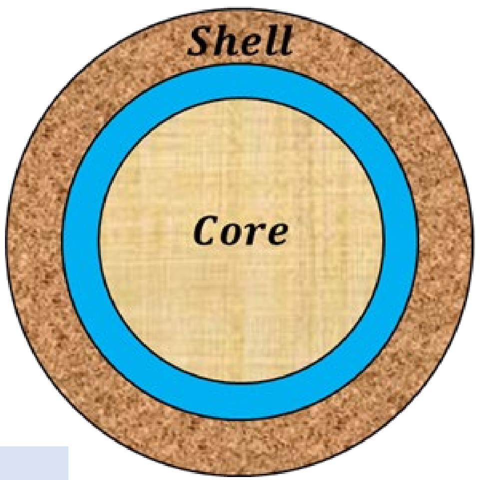
Sectional view

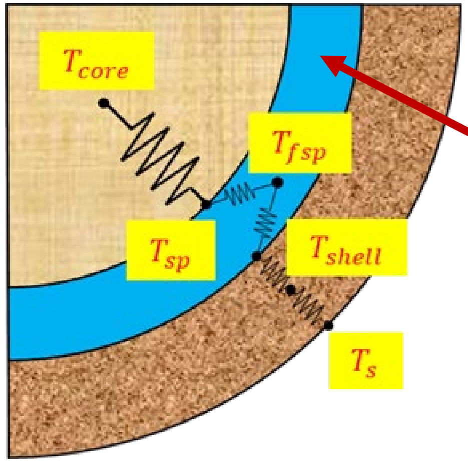


Top view

3 parts:
- pile material (shell)
- spiral tube
- grout material (core)

Capacity Resistance Model (CaRM)





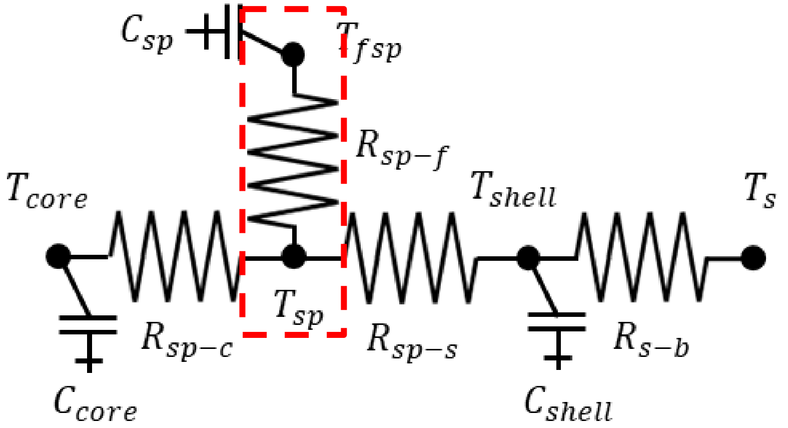
Spiral pipe (small diameter) can be neglected and simplified to a **line heat source/ heat sink**

Summer: inject heat to ground
Winter: extract heat from ground

Heat transfer inside energy pile

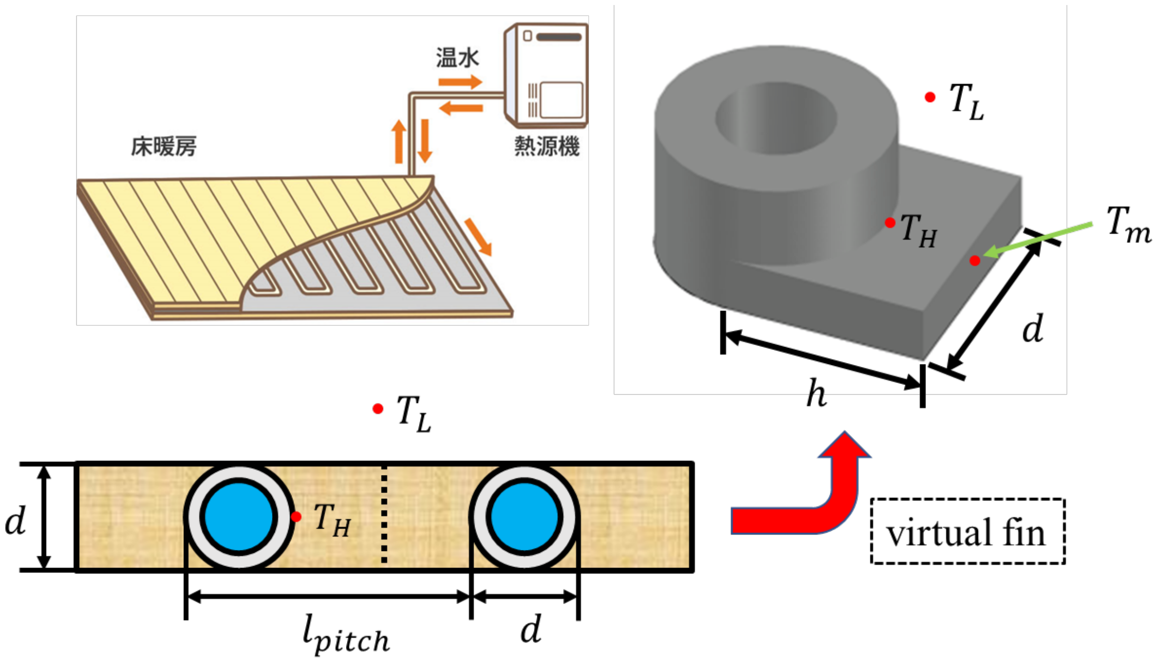
One-dimension heat conduction in multilayer cylindrical wall

Capacity Resistance Model
lumped thermal capacity model
- transient heat conduction approach



Zarrella, A. & de Carli, M. Heat transfer analysis of short helical borehole heat exchangers. Applied Energy 102, (2013).

Fin Efficiency



The heat transfer coefficient (**fin efficient**):

$$m = \sqrt{\frac{2\alpha}{\lambda d}}; h = \frac{1}{2} \times (l_{pitch} - d); \eta = \frac{\tanh(mh)}{mh}$$

Kollmar-Liese model

For **hot water floor heating system**, in the floor, a virtual fin is assumed

The mean temperature of the virtual fin:

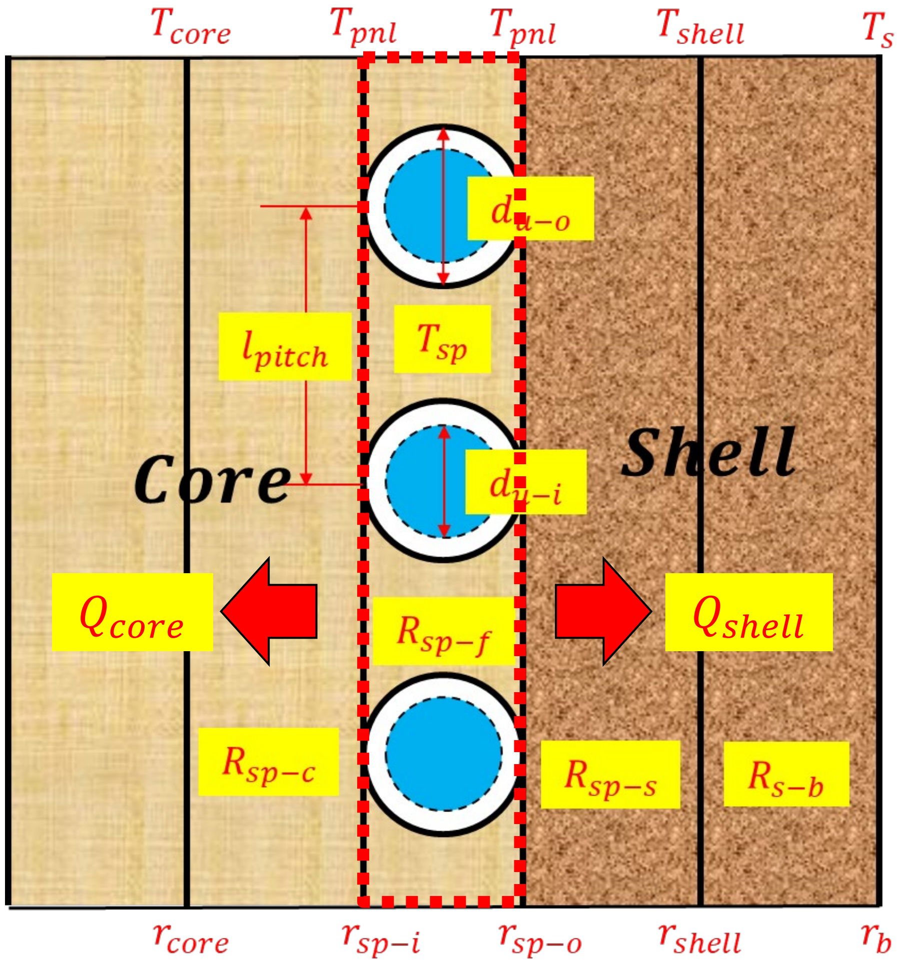
$$T_m = T_L + \eta \times (T_H - T_L)$$

Heat transfer rate from floor to air:

$$Q = \alpha \times \eta \times (T_H - T_L)$$
$$= \alpha \times (T_m - T_L)$$

Ishino, H. "Research on Calculation Method of Thermal Design Load in Radiant Heating and Cooling Systems." Sixth International IBPSA Conference (BS' 99). 885-892 (1999).

New Calculation Method



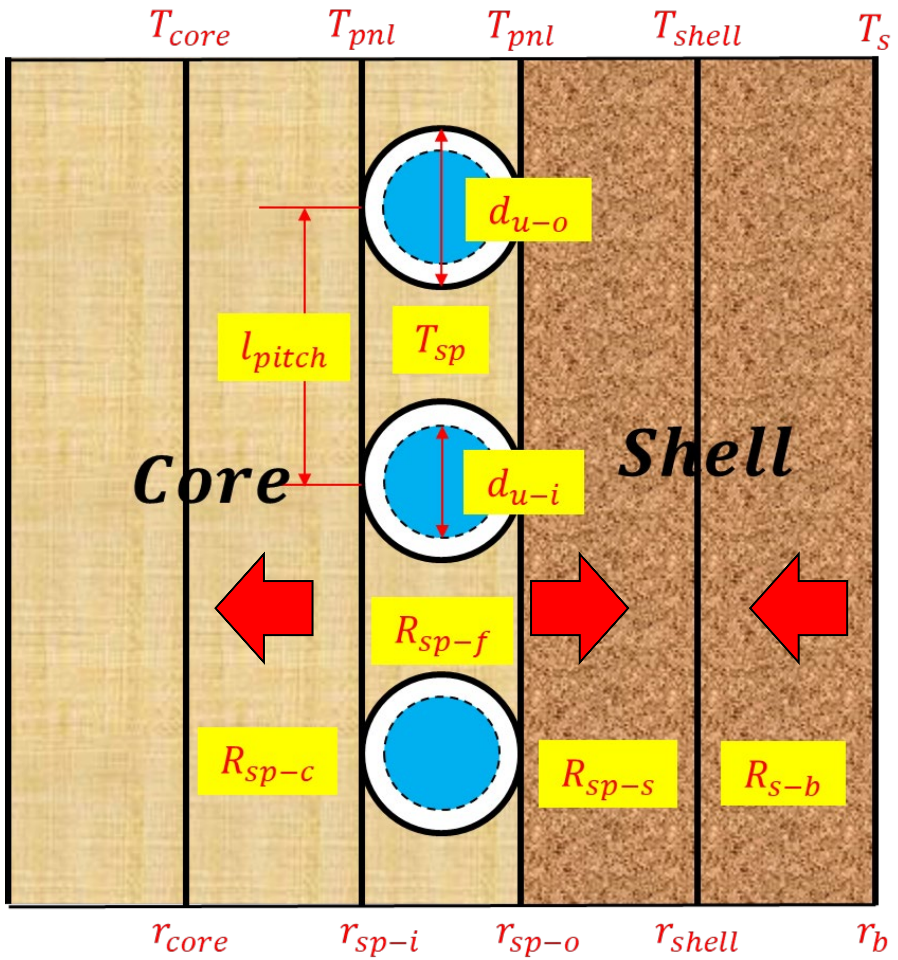
Layer between "core" and "shell" is considered as a "vertical" floor panel.

By analogy, temperature of the "panel" T_{pnl} :

$$T_{pnl} = T_{core} + \eta_{core} \times (T_{sp} - T_{core})$$
$$T_{pnl} = T_{shell} + \eta_{shell} \times (T_{sp} - T_{shell})$$

$$T_{pnl} = \frac{1}{2} \times [(T_{sp} - T_{core})\eta_{core} + T_{core}] + \frac{1}{2} \times [(T_{sp} - T_{shell})\eta_{shell} + T_{shell}]$$

New Calculation Method



Thermal resistance between spiral tube surface and circulating fluid:

$$R_{sp-f} = \frac{1}{2\pi \times r_{u-i} \times l_{sp} \times \alpha_f} + \frac{1}{2\pi \times \lambda_p \times l_{sp}} \times \ln(\frac{r_{u-o}}{r_{u-i}})$$

Heat balance in

- spiral tube:

$$c_f \rho_f V_{sp} \frac{dT_{fu}}{dt} = c_f \rho_f L V_f \left(T_{p-in} - T_{p-out}\right) + \frac{T_{sp} - T_{fsp}}{R_{sp-f}}$$

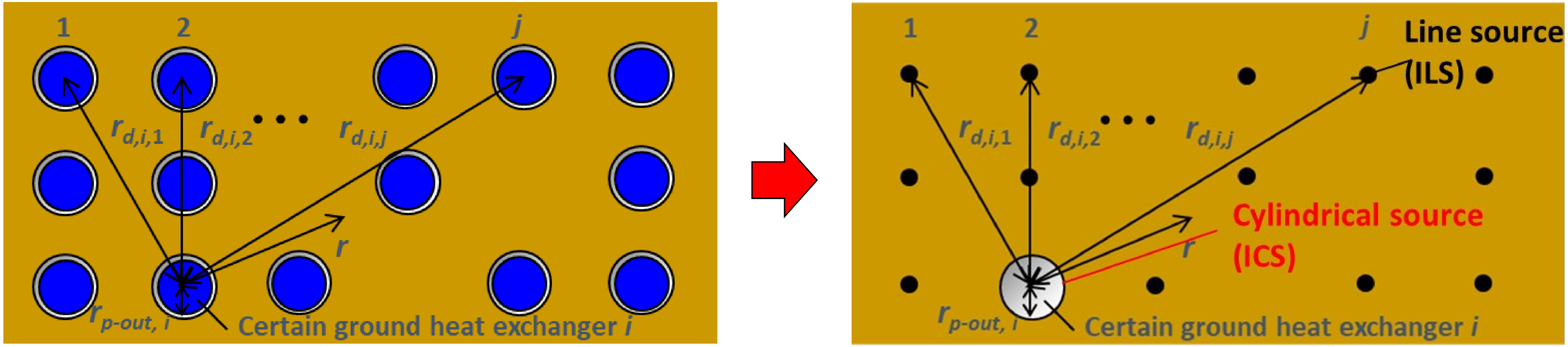
- core:

$$c_g \rho_g V_{core} \frac{dT_{core}}{dt} = \frac{1}{R_{sp-c}} \left(T_{pnl} - T_{core}\right)$$

- shell:

$$c_g \rho_g V_{shell} \frac{dT_{shell}}{dt} = \frac{1}{R_{sp-s}} \left(T_{pnl} - T_{shell}\right) + \frac{T_s - T_{shell}}{R_{s-b}}$$

GroundClub （GSHP system simulation program）



Infinite cylindrical source

Infinite line source

$$\Delta T_{s,i}(r_{p-out,i},t) = \Delta T_{s,i,i}(r_{p-out,i},t) + \sum_{j=1}^{m} \Delta T_{s,i,j}(r_{d,i,j},t)$$

Temperature change of the considered GHE

Temperature change of the neighboring GHE

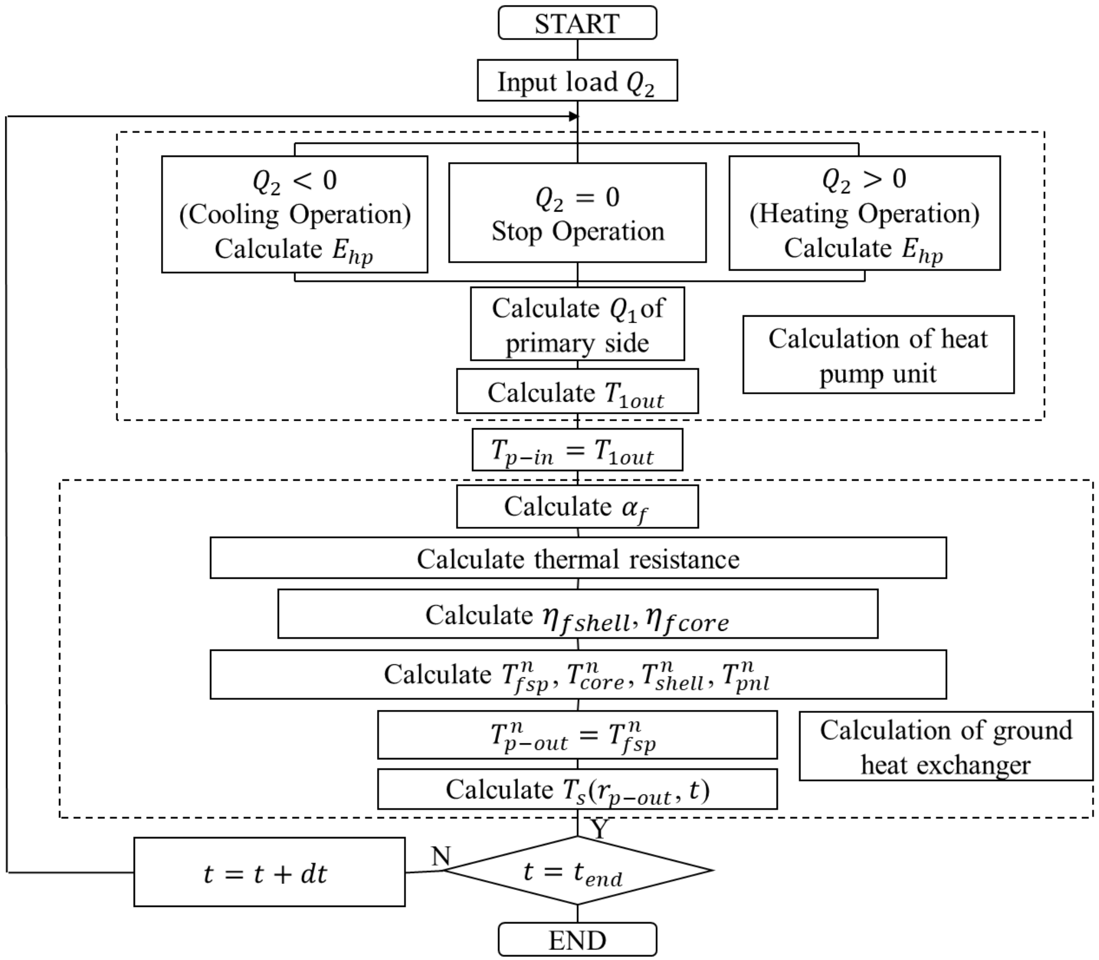
Calculation of ground temperature change

- simplified & fast speed
- accurate

Calculation Flow

Input: building data, specifications of heat pump and ground heat exchanger, soil data, etc.

Output: pipe inlet/outlet temperature; ground temperature



Platform: MATLAB

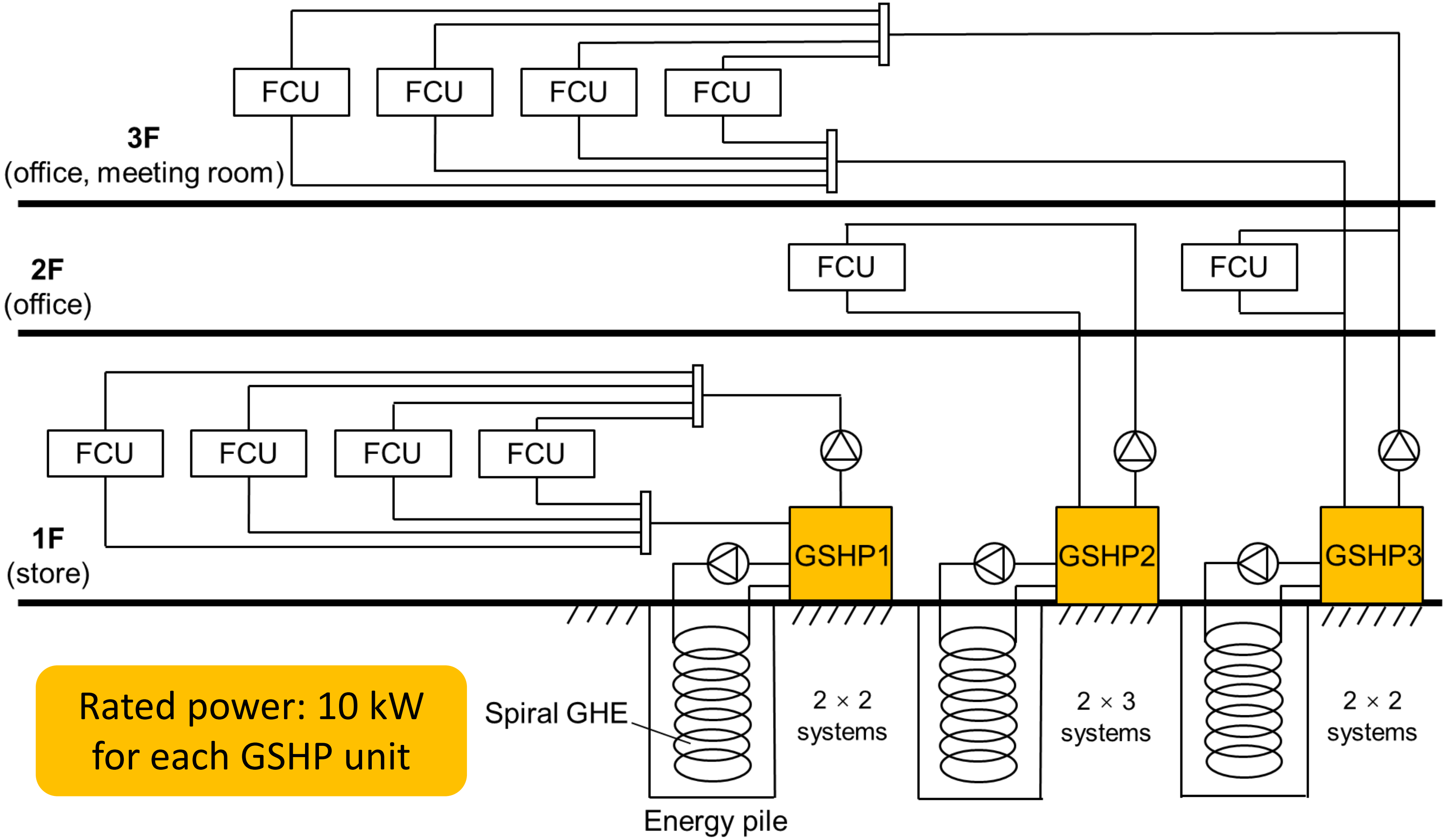
Inside borehole (energy pile): New calculation method

Outside borehole (ground): GroundClub

Building Overview

M's Industry Group	
Building	・Location: Sapporo, Japan ・Floor area: 650.85 m^2 ・Number of floors: 3 ・Nearly ZEB verified ・Operation time: 2021/7 ~
ZEB technology	・GSHP system ・Total heat exchange ventilation system ・PV system ・Radiant air conditioning system
PHC energy pile	・Outer diameter: 600 mm ・Depth: 20 m ・Pile material: concrete
Spiral GHE	・Diameter: 400 mm ・Pipe outer diameter: 32 mm ・Pipe inner diameter: 26 mm ・Pitch: 250 mm

Building Overview

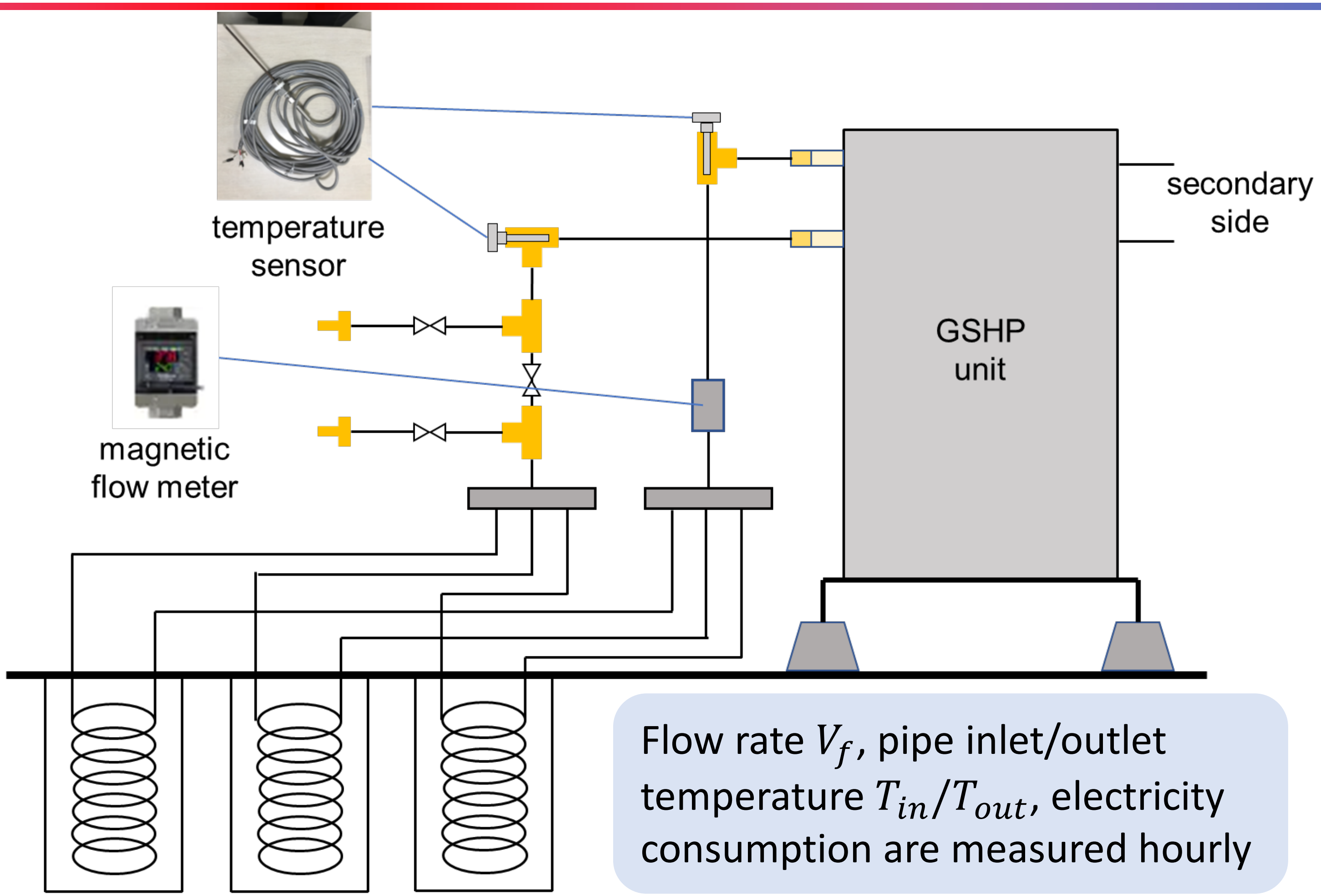


Longest operating time

Rated power: 10 kW for each GSHP unit

Measure Points

GSHP units in 1st floor



Flow rate V_f, pipe inlet/outlet temperature T_{in}/T_{out}, electricity consumption are measured hourly

Energy Pile Layout

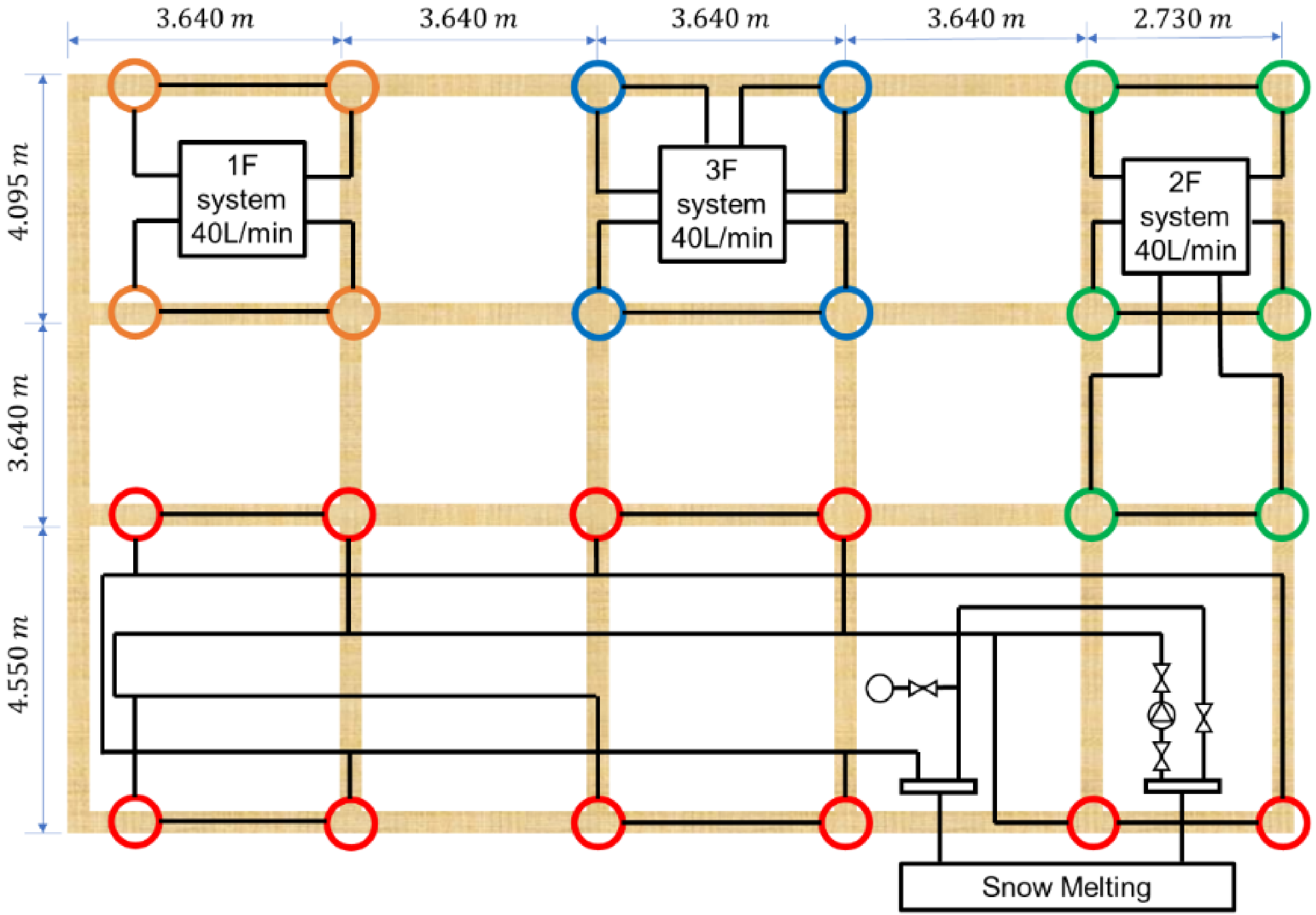
24 thermal piles installed on each floor of the house

1st Floor:
- 4 (2 series × 2 parallel)

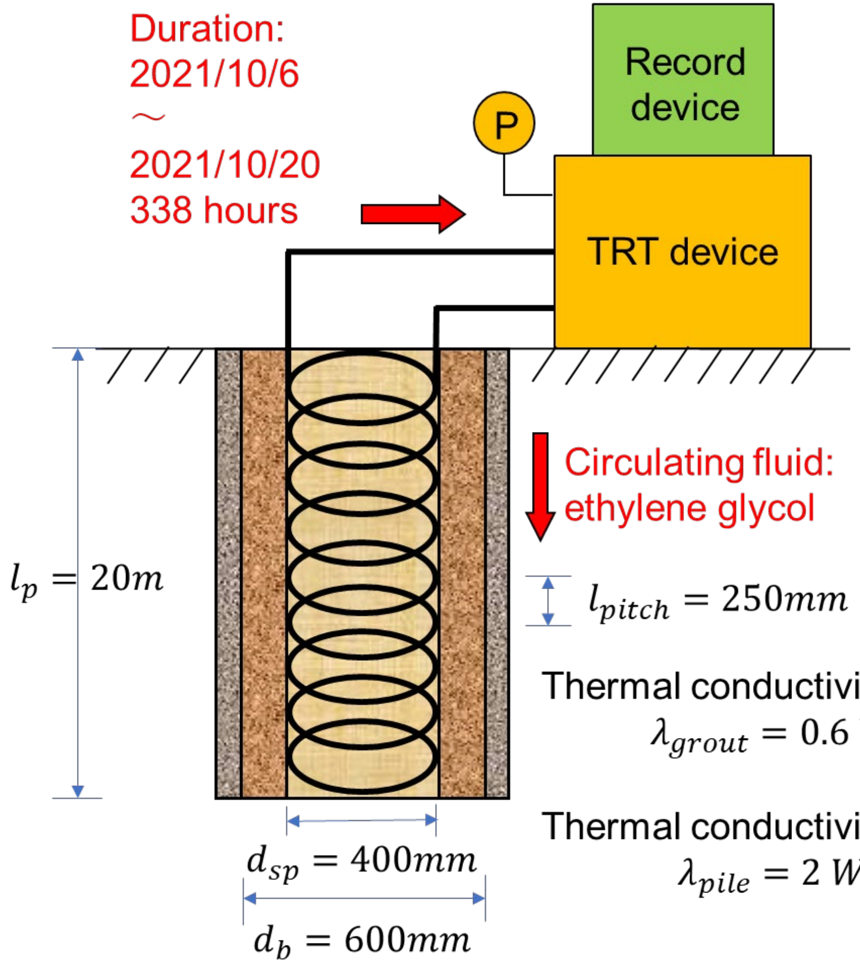
2nd Floor:
- 6 (2 series × 3 parallel)

3rd Floor:
- 4 (1 + 1 + 2)

Snow melting: 10



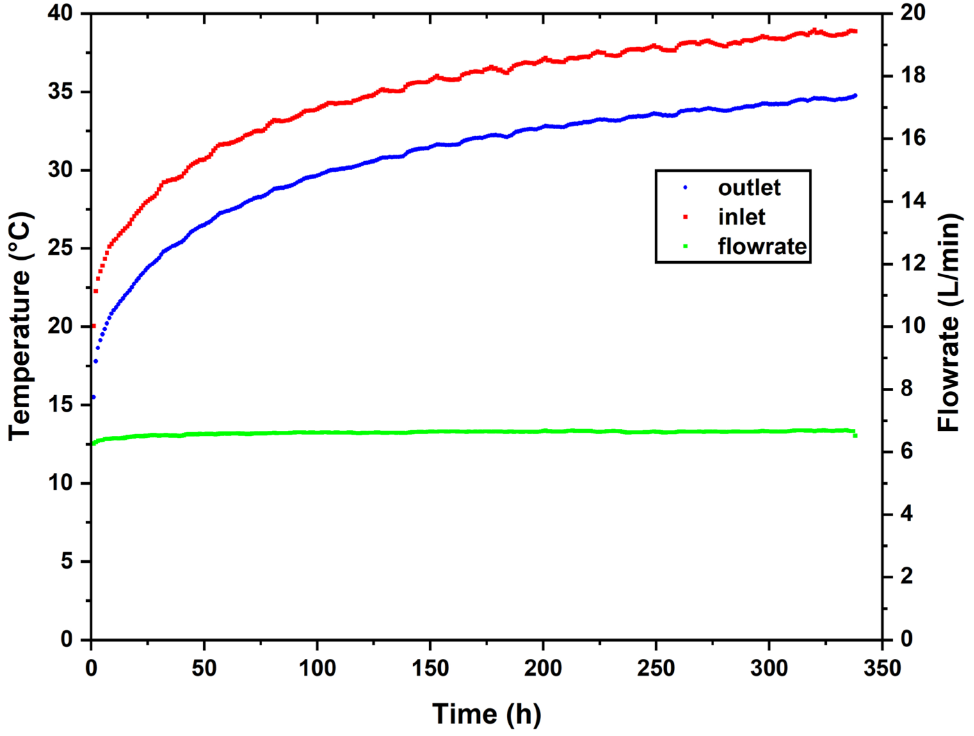
Thermal Response Test



Thermal conductivity of grout:
$\lambda_{grout} = 0.6\,W/(m \cdot K)$

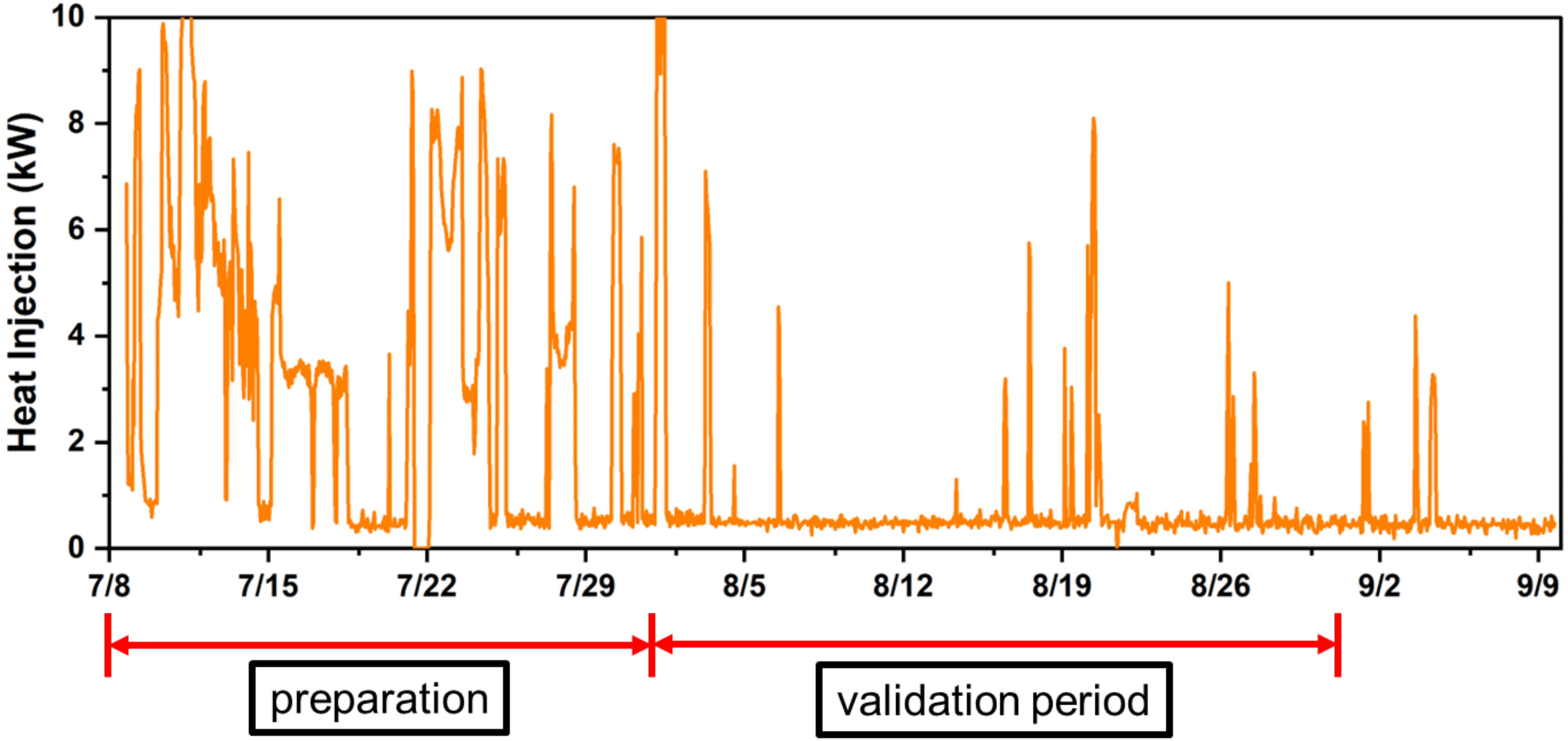
Thermal conductivity of energy pile:
$\lambda_{pile} = 2\,W/(m \cdot K)$

Kelvin's line source model



Effective thermal conductivity of ground soil:
$\lambda_a = 1.846[W/m \cdot K]$ (used for simulation)

Space cooling operation (summer)



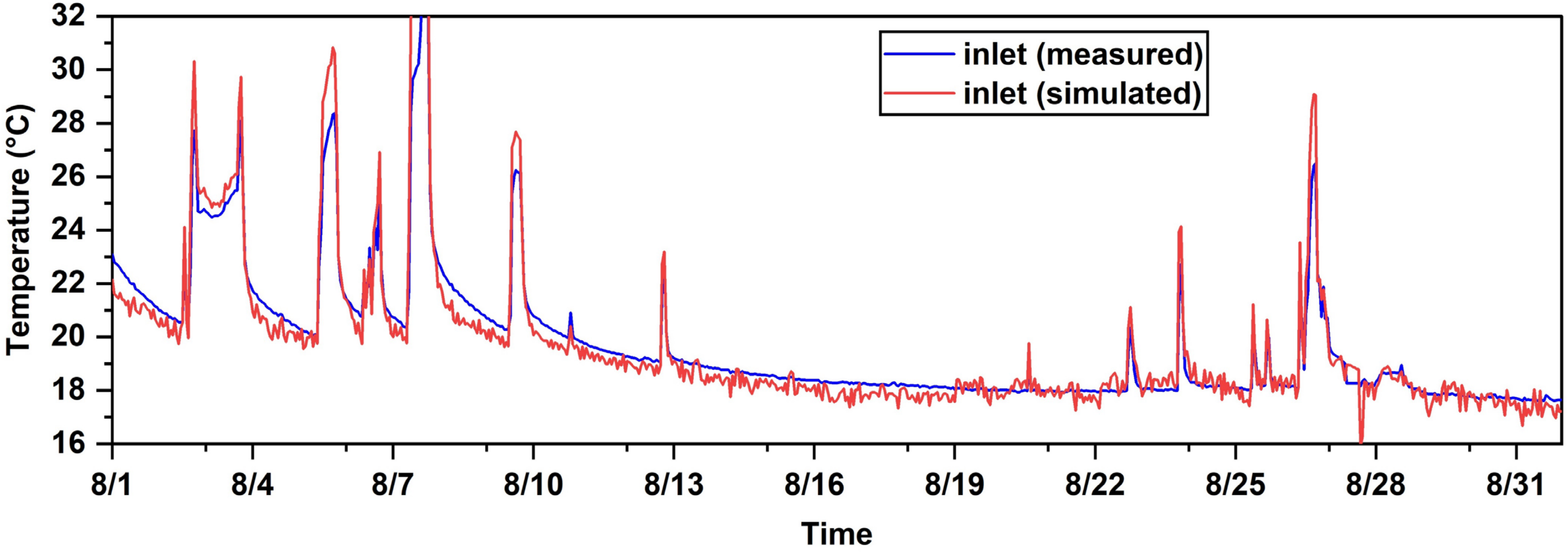
Time period:
2021/8/1 ～ 2021/8/31

Heat injection to the ground (primary load):

$$Q = \rho_f c_f V_f (T_{in} - T_{out})$$

long-term operation at low load

Space cooling operation (summer)



Initial ground temperature: 12 ℃

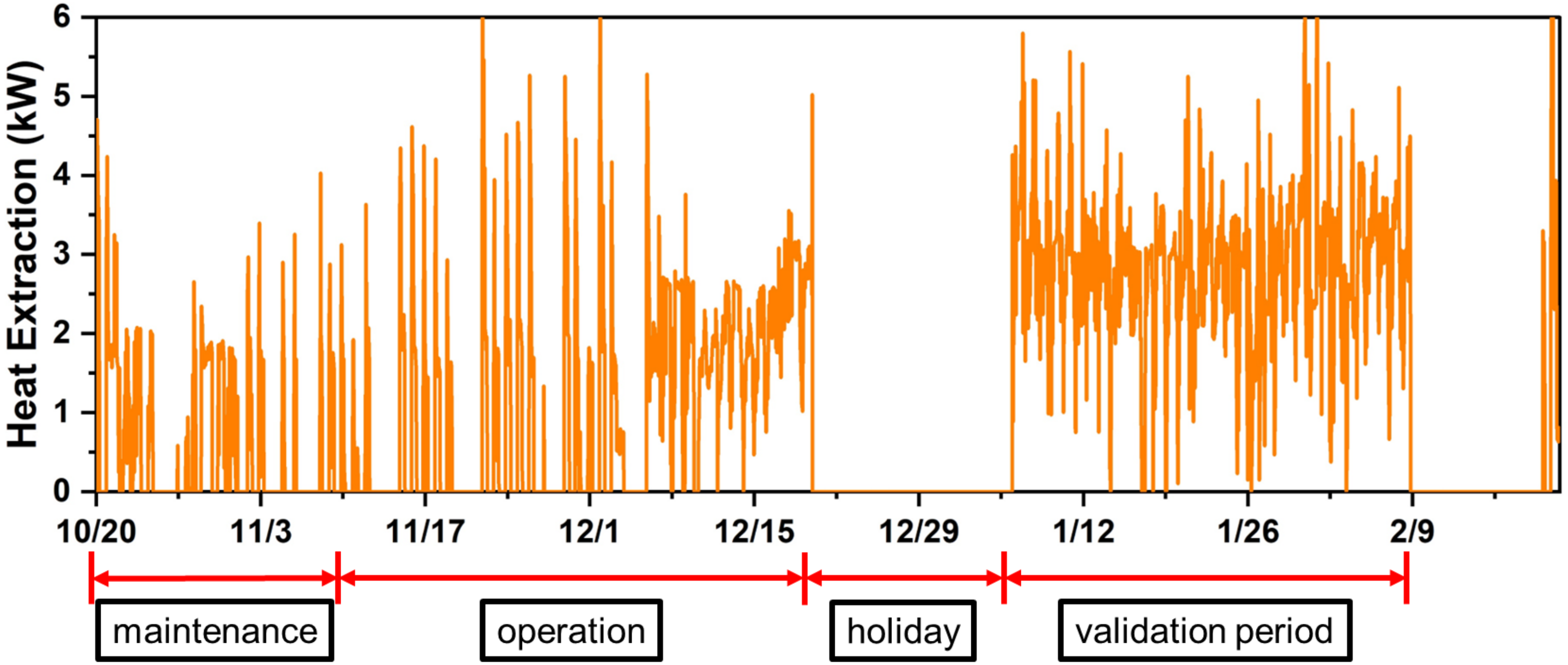
For pipe inlet temperature:

・ Root Mean Squared Error (**RMSE**): **0.73**

・ Average temperature:
simulation: 19.71 ℃
measurement: 19.77 ℃

・ Small differences when quick temperature changes occur

Space heating operation (winter)



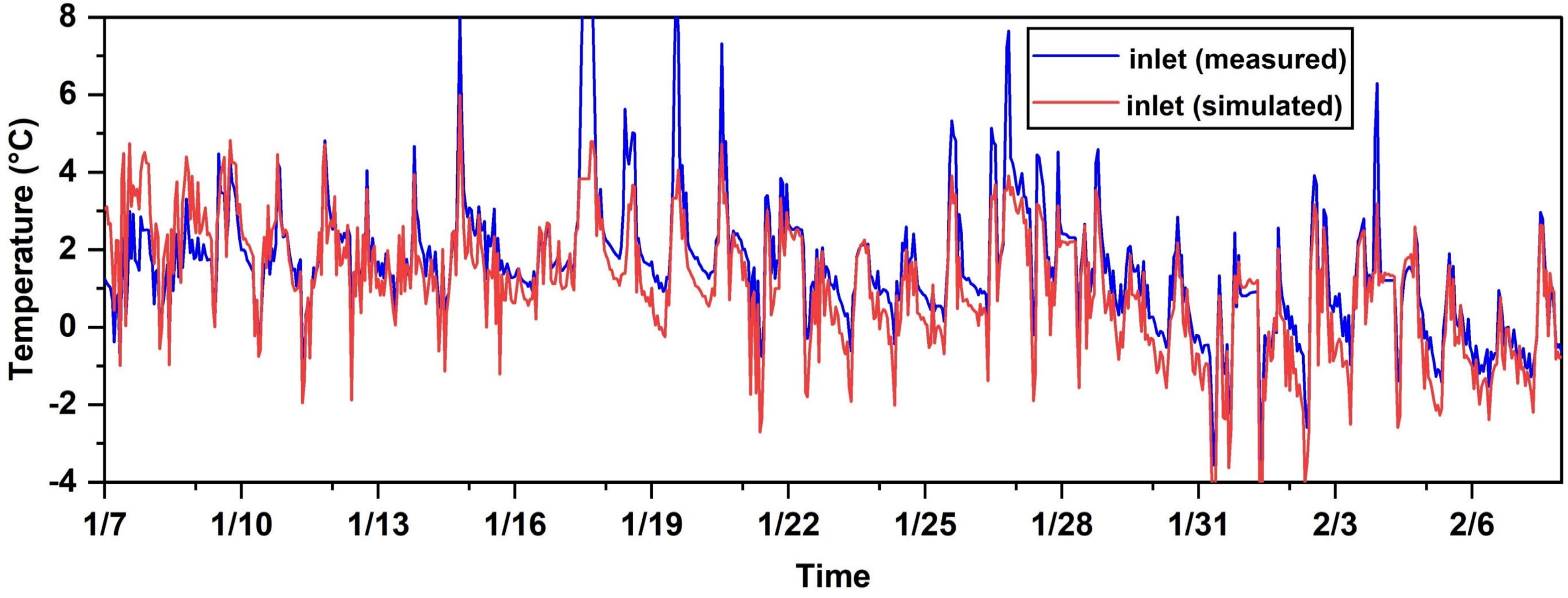
Time period:
2022/1/7 ~ 2022/2/7

Heat extraction from the ground (primary load):

$$Q = \rho_f c_f V_f (T_{out} - T_{in})$$

Continuous operation under high load

Space heating operation (winter)



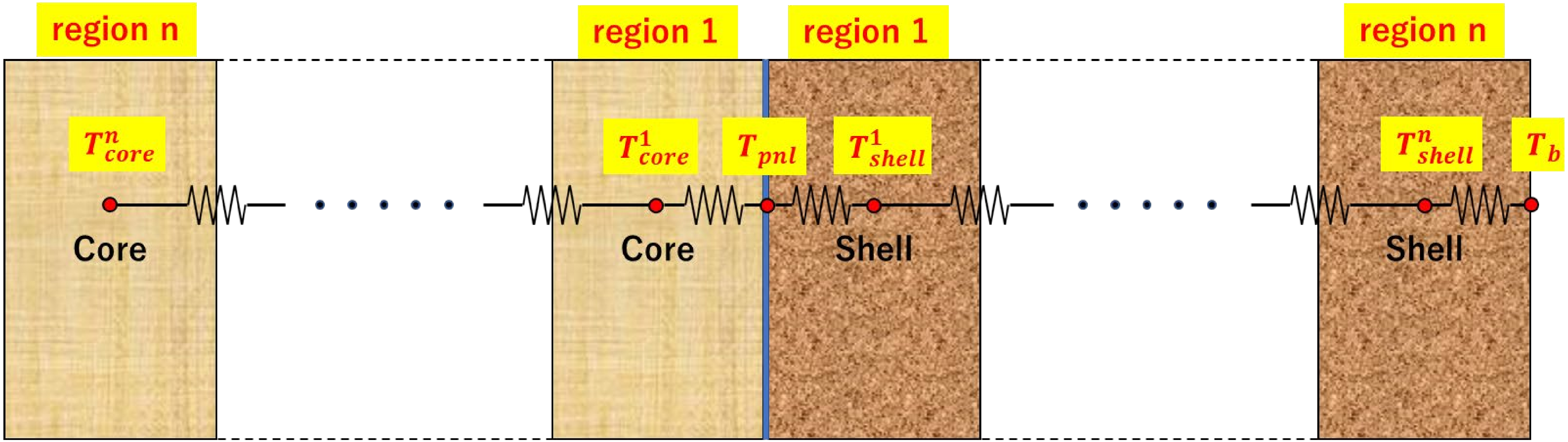
Initial ground temperature: 12 ℃

For pipe inlet temperature

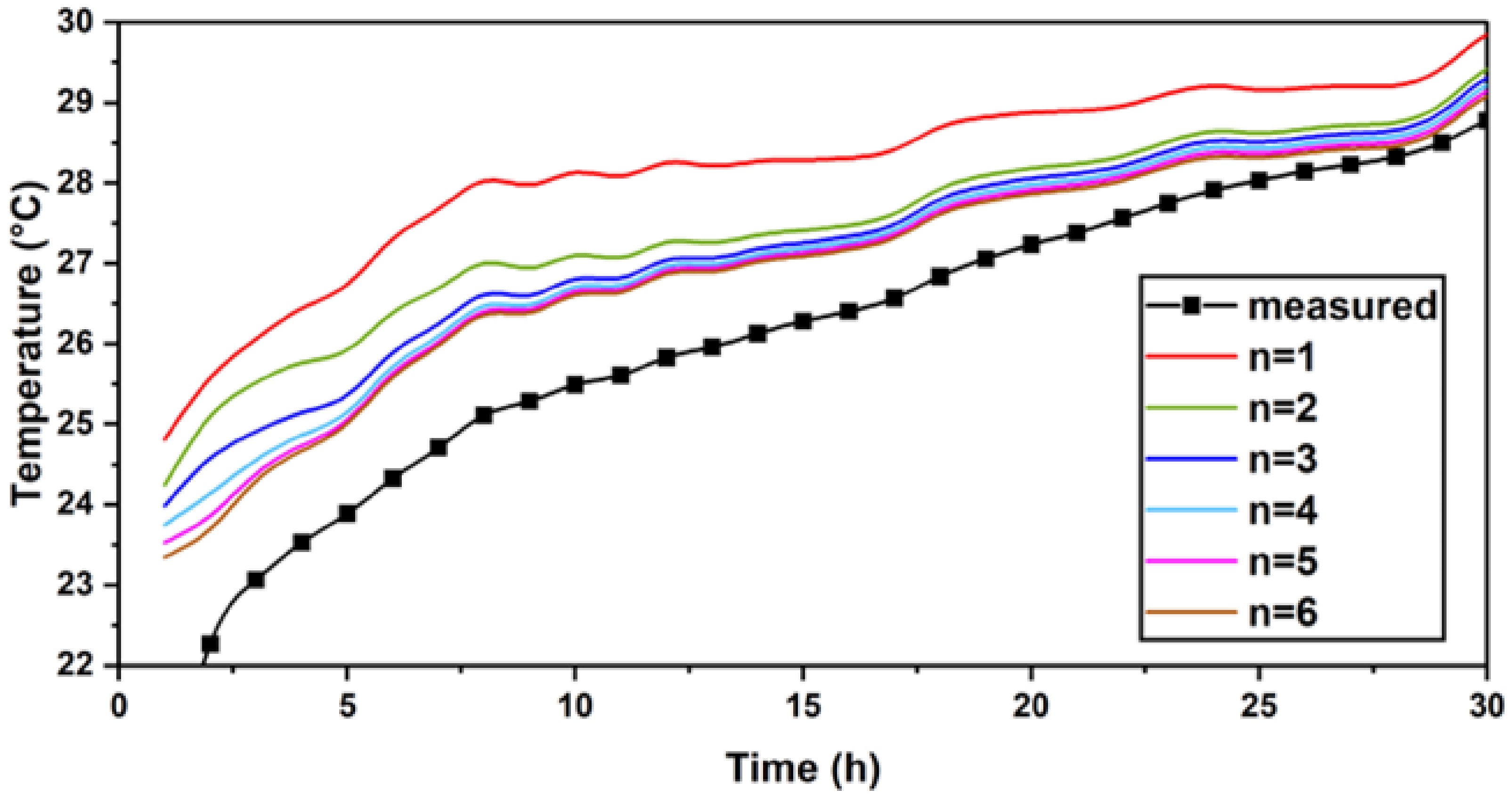
- **RMSE: 1.06**
- Average temperature :
  simulation: 1.55 ℃
  measurement: 1.05 ℃
- This simulation tool is suitable for GSHP systems using energy pile and spiral GHE.

Problem & Discussion

Instantaneous large heat injection → Temperature difference between simulation and measurement → Set up more temperature nodes and divided the core part and shell part into n regions



Short-term simulation



First 30 hours of TRT

More temperature nodes can make CaRM model be more applicable

The simulation over a short period of time get closer to the actual measurement

Conclusion

1. Using energy pile and spiral GHE can largely reduce the required land for installation and drilling cost

2. New simulation tool adopting the concept of fin efficiency can make the calculation to be simple, fast and accurate

3. This simulation tool is suitable to predict the long-term operation of GSHP systems using energy pile and spiral GHE

4. For short-term operation, setting more temperature nodes can get better simulation results

Thank you for listening