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Enhanced steam generation based on a bilayer water and light absorber

Modelling and optimization of capillary imbibition and water evaporation

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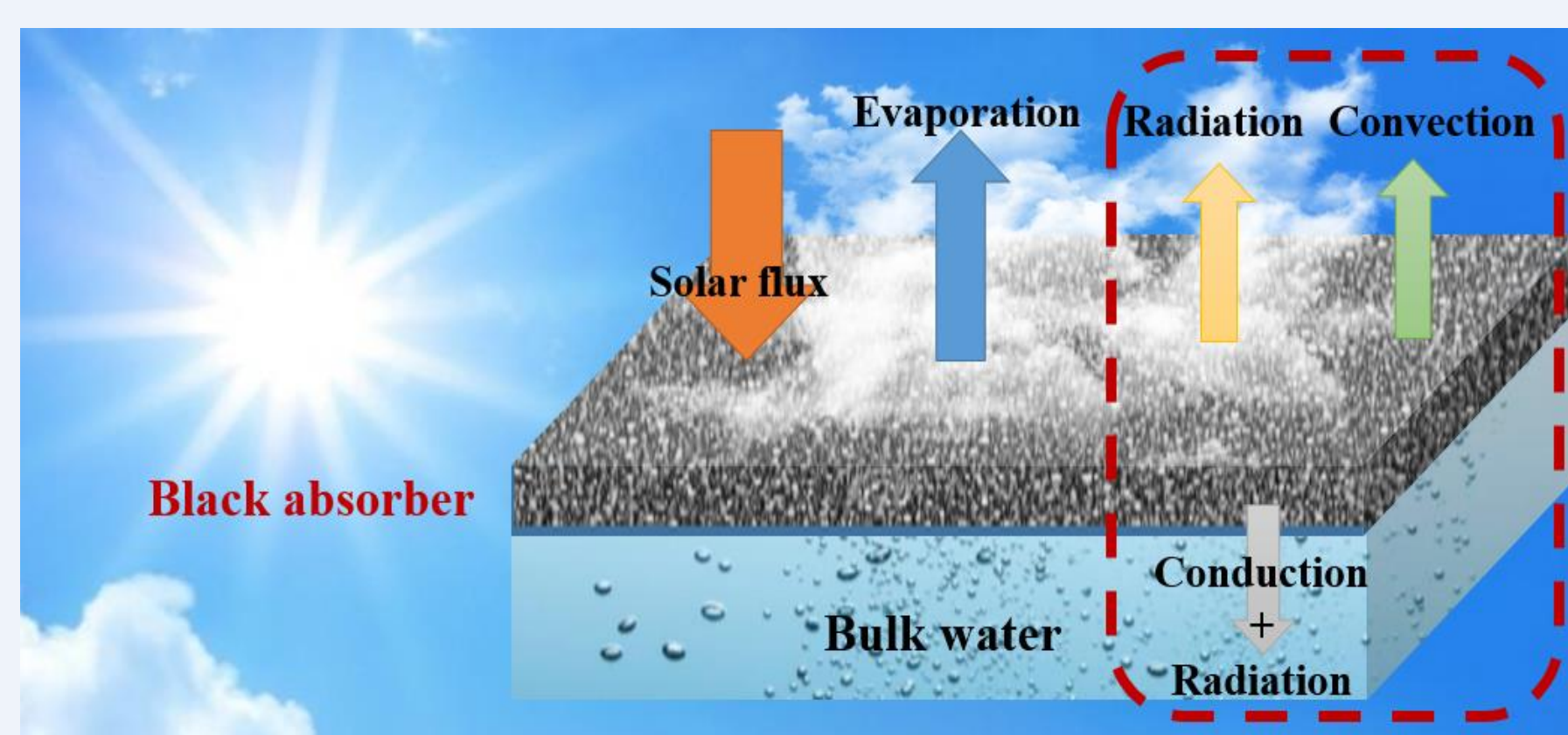
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Introduction

Enhanced steam generation is a robust and promising process for water purification. This is a method of increasing the evaporation efficiency by localizing the heat at the water-air interface using a black absorber. It is worth mentioning at this stage that the two functions of localized heating and water imbibition are different functions that can be separated in their implementation. However, one can note that a vast majority of state-of-the-art implementations show that both functions are integrated together, which is typically a black and porous medium, hence providing simultaneous light absorption and water absorption capabilities. In addition, there is a concern about thermal conductivity so as to minimize loss of the surface-localized generated heat into the surrounding water bulk. As of late, bilayer structure black absorbers have been developed in different combinations of photothermal materials and porous media aiming to achieve efficient steam generation.

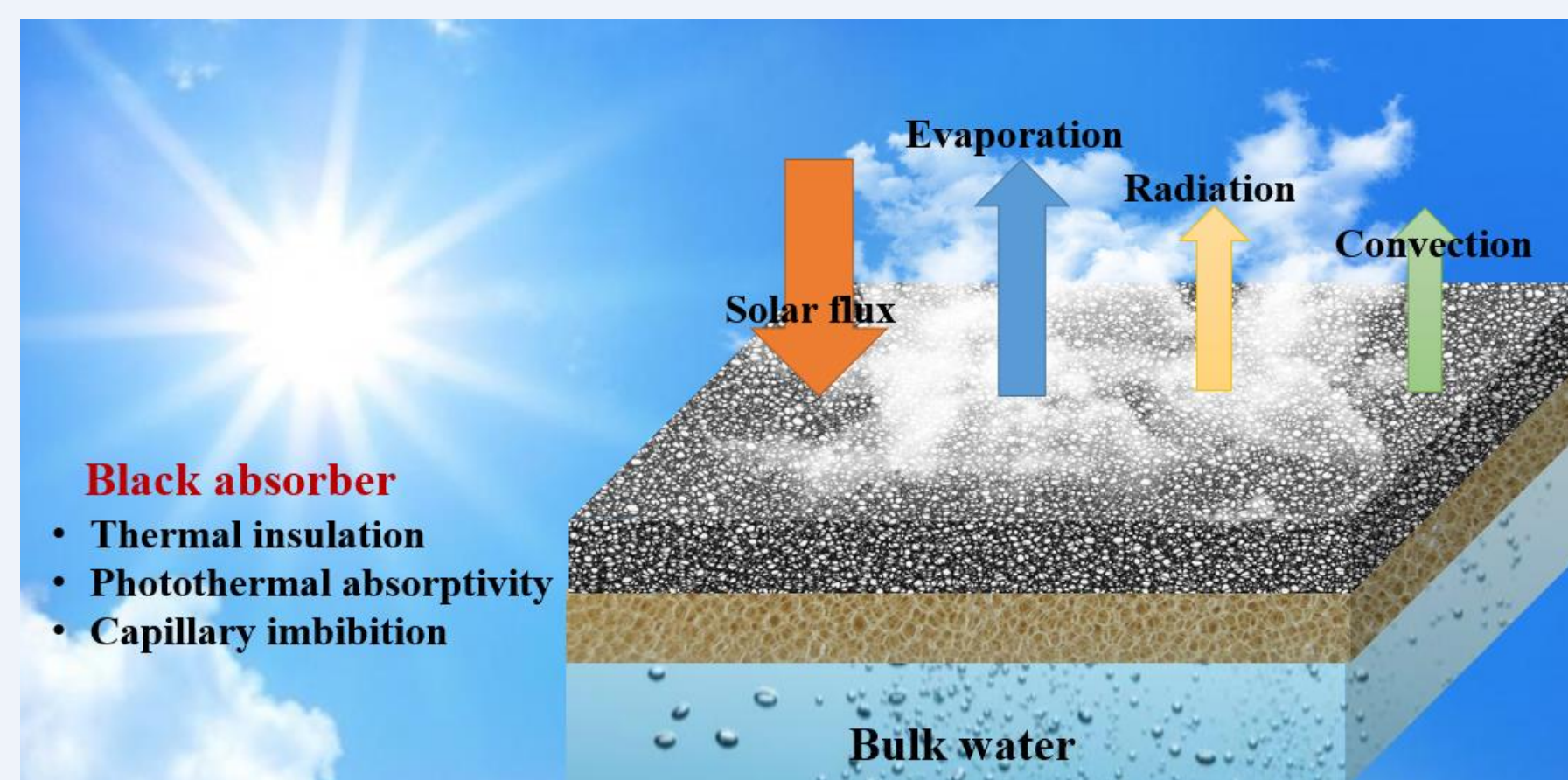
Bilayer modelling

Ideal model



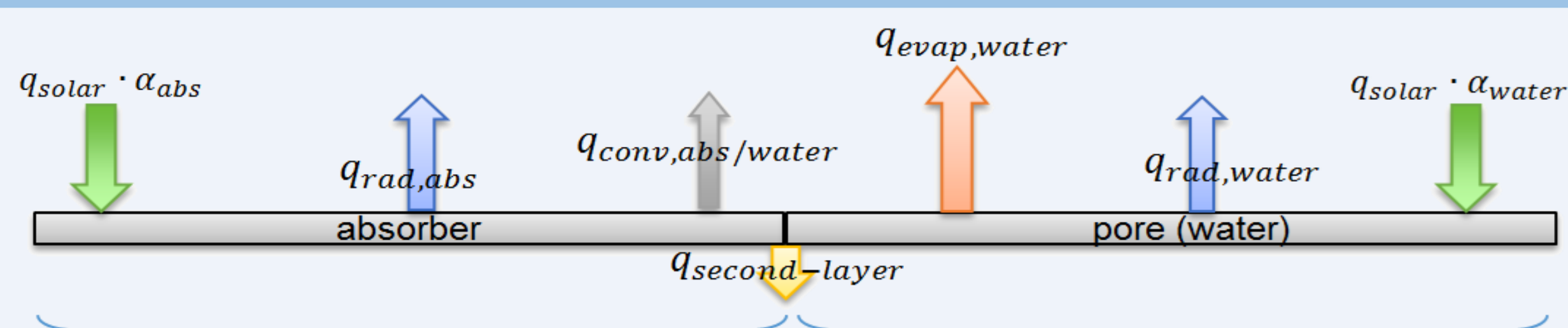
Energy balance in the enhanced steam generation process.

Bilayer model



Heat and mass transfer in the bilayer structure during the steam generation process.

First layer modelling : heat transfer



surface fraction (1-F)

surface fraction F

$$q_{conv} = h_{conv}(T_{layer1} - T_{ambient})$$

$$q_{rad,abs} = \epsilon_{abs}\sigma(T_{layer1}^4 - T_{ambient}^4)$$

$$q_{rad,water} = \epsilon_{water}\sigma(T_{layer1}^4 - T_{ambient}^4)$$

$$q_{second-layer} = k_{cond}(T_{layer1} - T_{water})$$

$$q_{evap,water} = q_{solar} \cdot \alpha_{evap} + q_{rad,abs} - q_{solar} \cdot \alpha_{abs} - q_{conv,water} - q_{rad,water} + \frac{q_{solar} \cdot \alpha_{abs} - q_{rad,abs} - q_{second-layer}}{F}$$

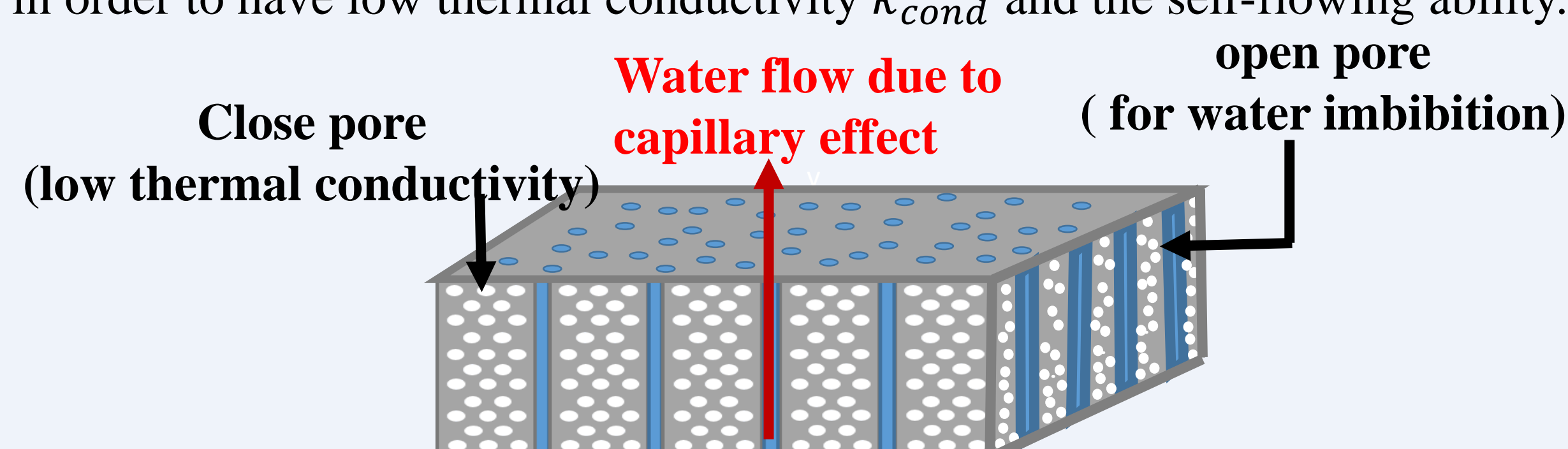
- q is the heat flux.
- ϵ is absorptivity.

- k is thermal conductivity.
- σ is Stefan-Boltzmann constant.

In the first layer modelling: the smaller the F, which means the smaller the total surface area of the pores, the larger the heat flux for evaporation, and the more evident the evaporation.

Second layer structure

In the second layer, we propose two kinds of pore for different functional uses. One is with the "open pores" to obtain water sustainable water imbibition. The other one is the "closed pores" in order to have low thermal conductivity k_{cond} and the self-flowing ability.



Different pore function integrated in one porous media.

Second layer modelling : perforated open pore

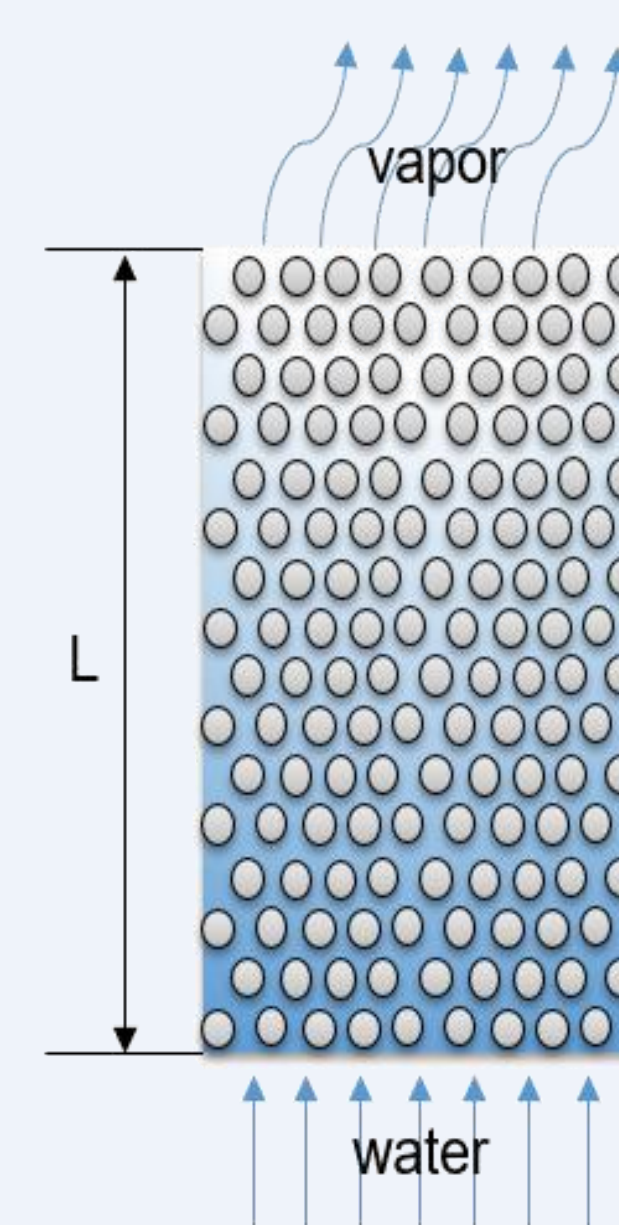
Capillary imbibition in transit state

In a perforated pore, the capillary phenomenon can be obtained from the following differential equation:

$$\frac{2\sigma \cos \theta}{r_{pore}} \pi r_{pore}^2 - \rho g H_c \pi r_{pore}^2 - \frac{8\mu}{r_{pore}^2} H_c \frac{dH_c}{dt} \pi r_{pore}^2 = \frac{d}{dt} (\rho \pi r^2 H_c \frac{dH_c}{dt})$$

- σ is the surface tension of water.
- θ is the contact angle.
- r_{pore} is the radius of the perforated pore.
- g is the gravity constant.
- ρ is the density of water.
- μ is the water viscosity.
- H_c is the capillary height.

Capillary imbibition in steady state



We assumed that the water only gets vaporized at the surface, which means there is no evaporation happened during the capillary imbibition.

While in the steady state, we can get :

$$p_c = \Delta p_1 + \rho g L$$

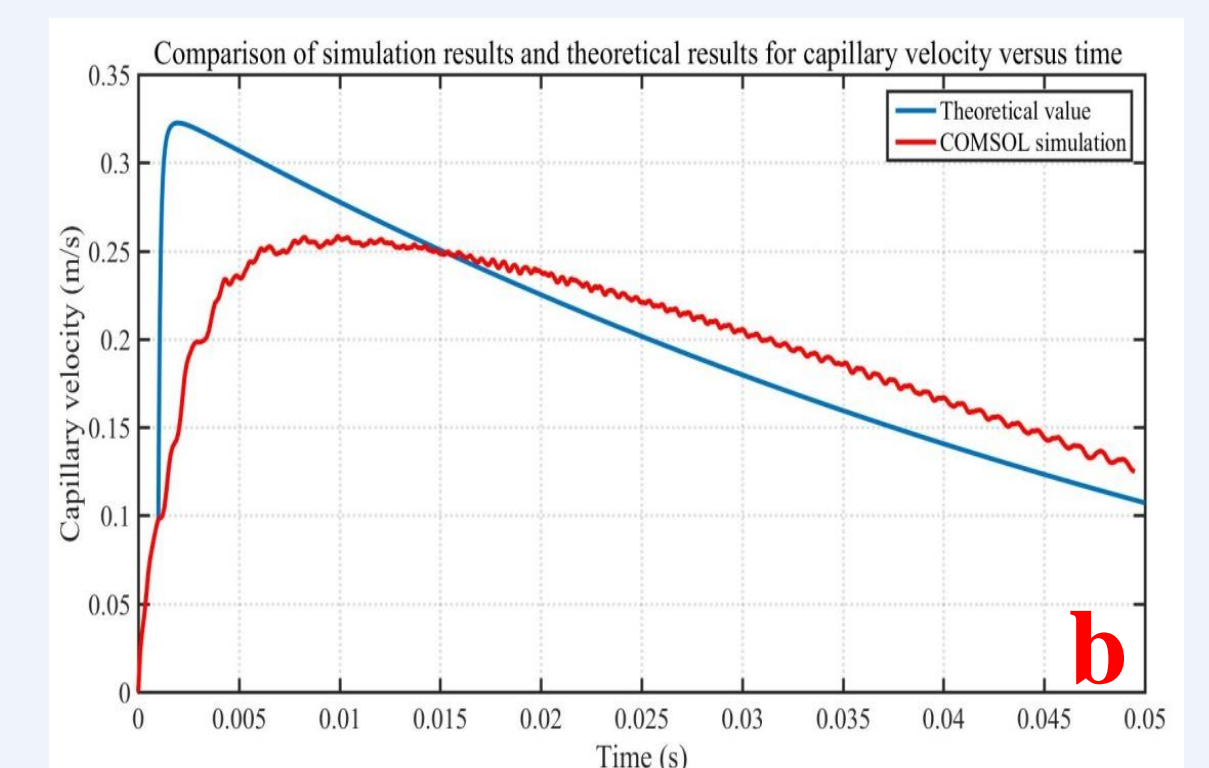
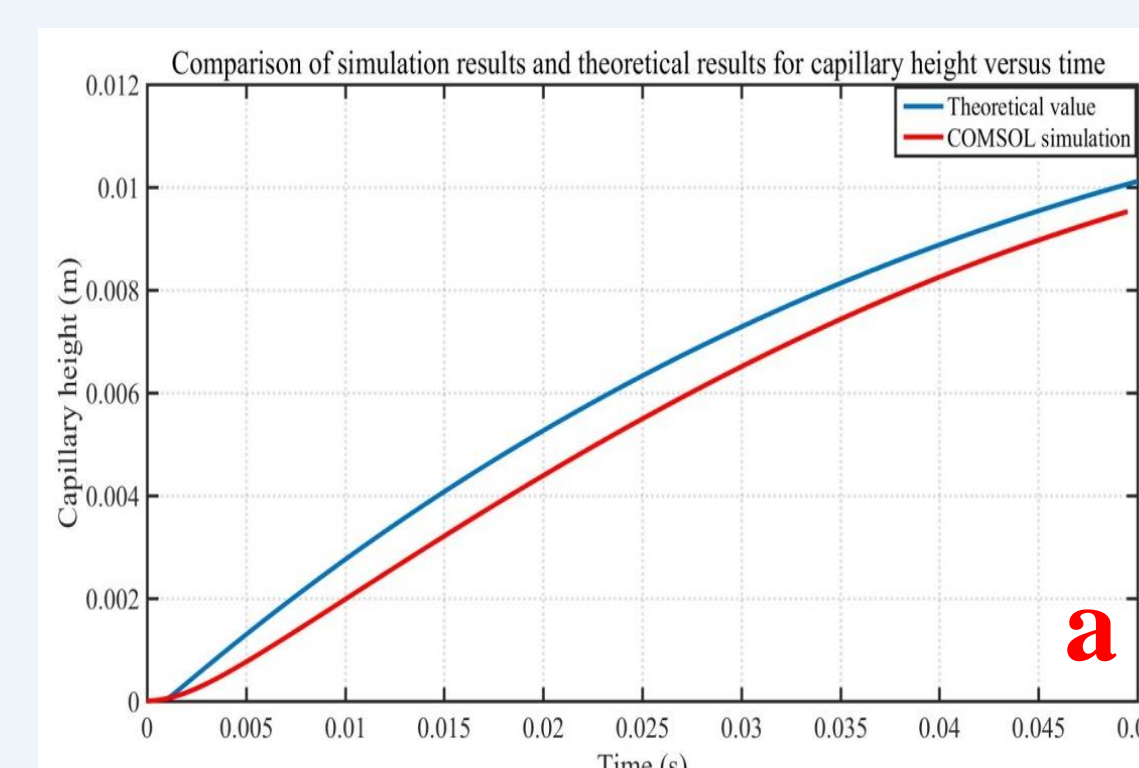
where p_c is the capillary pressure (or Laplace pressure) while Δp_1 is the pressure due to the water motion in the porous media. By combining the hydraulic conductivity with Darcy's law, the flow rate through the perforated pores is:

$$Q(r_{pore}, N, L) = \frac{2\sigma \cos \theta \pi r_{pore}^3 N^2 - \pi N^2 \times \rho g L \times r_{pore}^4}{8\mu L}$$

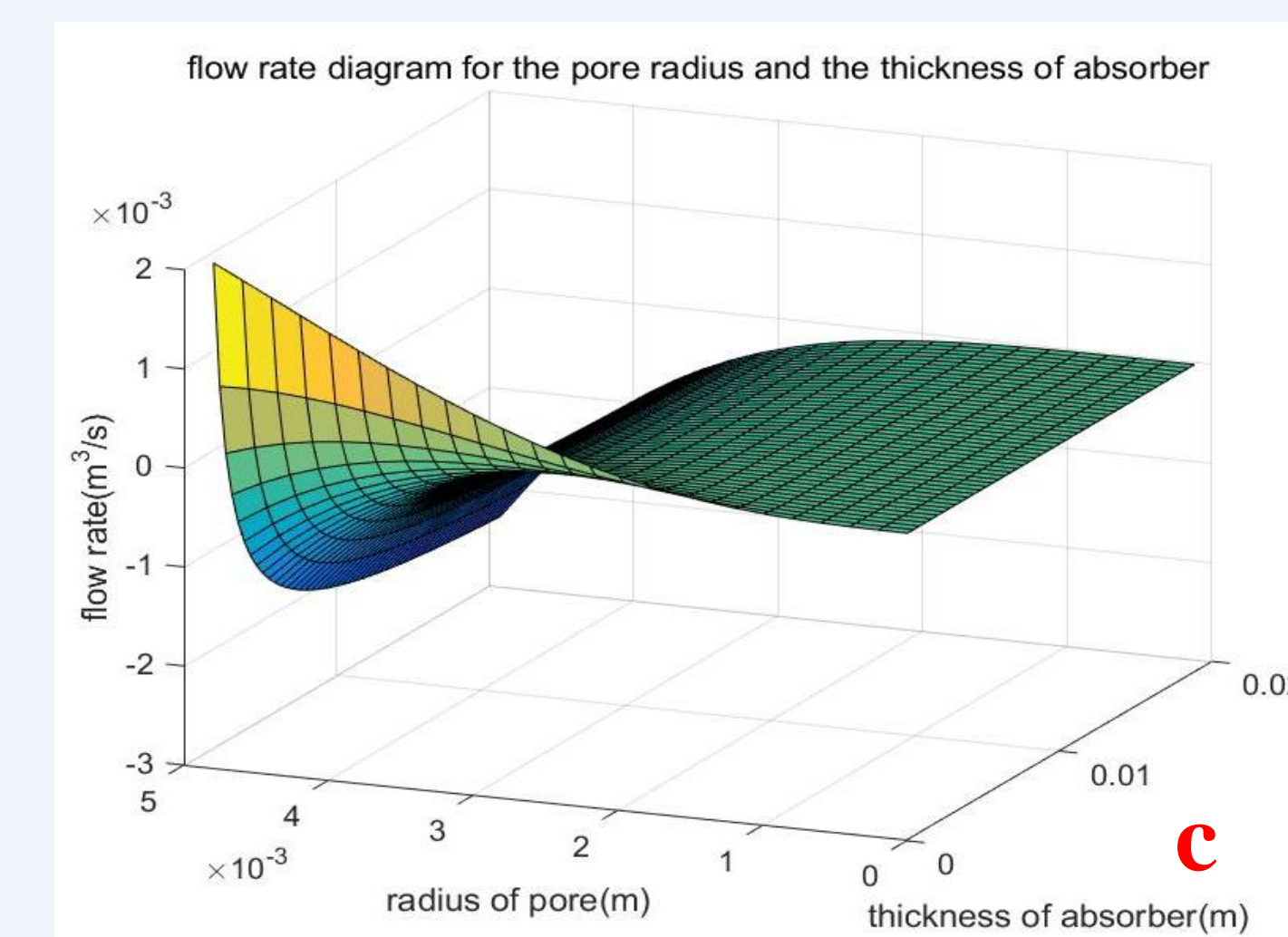
- N is the number of perforated pores.
- Q is the Darcy's flow rate in steady state.
- L is the thickness of porous media.

Theoretical results & Simulation results

For the reason that the flow rate increases monotonically with the number of pores N, so in the modelling of open pores, the radius of the hole and the thickness of the hole are more noticeable.



(a) Capillary height versus time (with a given value pore radius). (b) Capillary velocity versus height (with a given value pore radius).



(C) Flow rate versus the radius of pore and the thickness of absorber.

Conclusion

- The theoretical results have a good agreement with simulation results in water imbibition phenomenon.
- When giving a certain water imbibition flow rate, with the help of this modelling, we can determine the geometry from the perforate pore size, the number of pores and the thickness of absorber.
- The modelling of thermal conductivity and density in close pores need to be added to the current model in the following study.