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INTERACTION OF TEMPERATURE- AND SALINITY-DRIVEN NATURAL CONVECTION IN HOMOGENEOUS POROUS MEDIA

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INTRODUCTION

Onset of thermal and haline convection was studied **separately** by Lapwood (1948) and Wooding (1956) in theoretical models using analytical methods. They established that the buoyancy force caused by temperature (ΔT) and concentration difference (Δc) can induce natural convection. In this study, the combined effect of temperature- and salinity-driven natural convection was examined in 2D homogeneous porous media in the cases of three scenarios (Model A, B, C).

THE MAIN QUESTIONS

- **How does the interaction of the thermal and haline term affect the onset of the natural convection?**
- **Under what conditions does a time-dependent flow system evolve in the theoretical models?**
- **How can the thermohaline convection be characterized by the non-dimensional numbers?**

PHYSICAL BACKGROUND

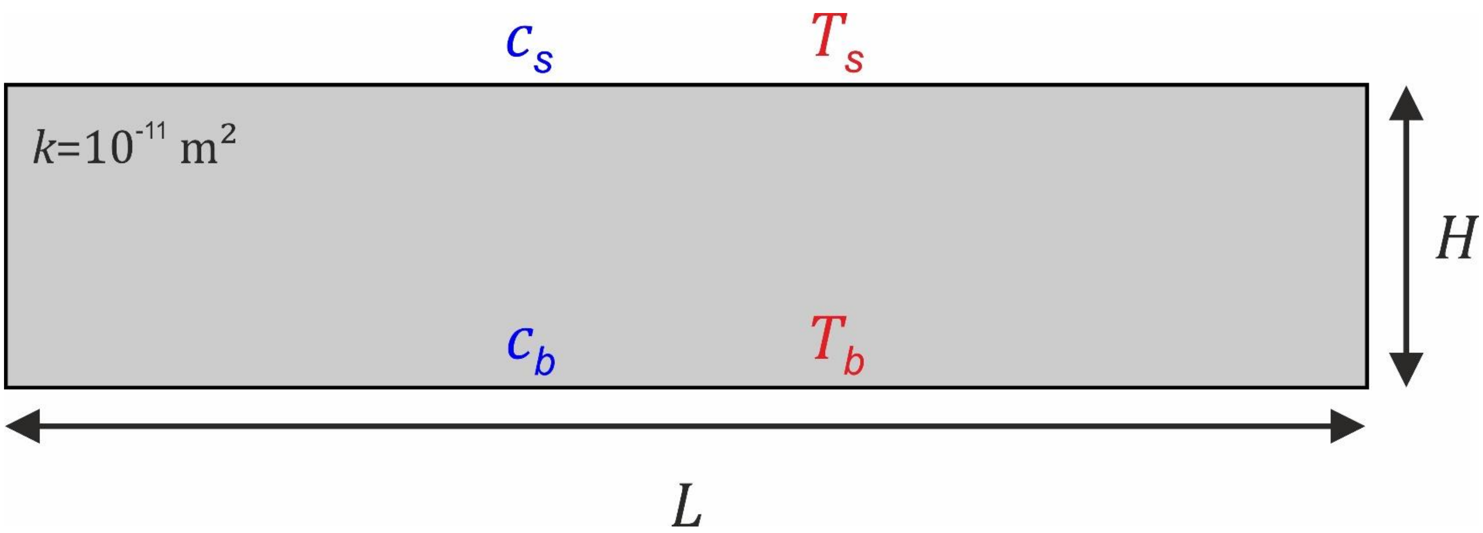
Partial differential equation system

- Mass conservation
- Darcy's Law
- Mass transport
- Heat transport

The equations were coupled by the Darcy flux (q) and the temperature- and concentration-dependent water density ($\rho_w(c,T)$) .

Definition	Symbol	Value	Unit
Non-dimensional thermal expansion	$\alpha\Delta T$	0.01–1	-
Non-dimensional haline concentration	$\beta\Delta c$	10^{-5}–10^{-3}	-
Permeability	k	10^{-11}	m^2
Reference water density	ρ_0	1000	kg/m^3
Model thickness	H	10	m
Dynamic viscosity of water	η	0.001	Pa·s
Thermal diffusivity	κ	$7.16 \cdot 10^{-7}$	m^2/s
Diffusion coefficient	D_0	10^{-9}	m^2/s

Numerical model



Non-dimensional thermal expansion and haline concentration were increased from $\alpha\Delta T$=0.01 to 1 and from $\beta\Delta c$=10^{-5} to 10^{-3} respectively, while the average Darcy flux (q_{av}) the Nusselt number (Nu) and the Sherwood number (Sh) were computed. Other physical properties (e.g. thickness (H=10 m), length (L=200 m), permeability (k=10^{-11} m^2) of the model domain were kept constant values.

Variable density of the pore water: $\rho_w(c,T) = \rho_0[1 + \beta c - \alpha T]$

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Non-dimensional numbers

Thermal Rayleigh number

$$\mathrm{Ra}_T = \frac{gk\rho_0 H}{\eta}\frac{\alpha\Delta T}{\kappa}$$

Lewis number

$$\mathrm{Le} = \frac{\kappa}{D_0}$$

Buoyancy ratio

$$\mathrm{BR} = \frac{\beta\Delta c}{\alpha\Delta T}$$

Haline Rayleigh number

$$\mathrm{Ra}_H = \mathrm{BR}\cdot\mathrm{Le}\cdot\mathrm{Ra}_T = \frac{gk\rho_0 H}{\eta}\frac{\beta\Delta c}{D_0}$$

Thermohaline Rayleigh number

$$\mathrm{Ra}_{TH} = \frac{gk\rho_0 H}{\eta}\left[\frac{\alpha\Delta T}{\kappa} + \frac{\beta\Delta c}{D_0}\right]$$

Region of the stability

$$\mathrm{Ra}_T + \mathrm{Ra}_H = 4\pi^2$$

(Nield and Bejan, 2006)

One of the most important questions is whether the previous formulas are universal. If this is not the case, how could the flow be easily characterized by the non-dimensional numbers?

Three model scenarios

Model A

$c_s=1$ $T_s=0$

$c_b=0$ $T_b=1$

ΔT – facilitate

Δc – facilitate

$$\mathrm{Ra}_{TH} = \frac{gk\rho_0 H}{\eta}\left[\frac{\alpha\Delta T}{\kappa} \overset{?}{+} \frac{\beta\Delta c}{D_0}\right]$$

Model B

$c_s=0$ $T_s=0$

$c_b=1$ $T_b=1$

ΔT – facilitate

Δc – reduce

$$\mathrm{Ra}_{TH} = \frac{gk\rho_0 H}{\eta}\left[\frac{\alpha\Delta T}{\kappa} \overset{?}{-} \frac{\beta\Delta c}{D_0}\right]$$

Model C

$c_s=1$ $T_s=1$

$c_b=0$ $T_b=0$

ΔT – reduce

Δc – facilitate

$$\mathrm{Ra}_{TH} = \frac{gk\rho_0 H}{\eta}\left[\frac{\beta\Delta c}{D_0} \overset{?}{-} \frac{\alpha\Delta T}{\kappa}\right]$$

Results – Model A

Temperature | **Initial conditions** | **Concentration**

$\log_{10}\alpha=-2$ | $\mathbf{Ra_{TH}=23.51}$ | $\log_{10}\beta=-5$

$\log_{10}\alpha=-2$ | $\mathbf{Ra_{TH}=111.9}$ | $\log_{10}\beta=-4$

$\log_{10}\alpha=-1$ | $\mathbf{Ra_{TH}=148.8}$ | $\log_{10}\beta=-5$

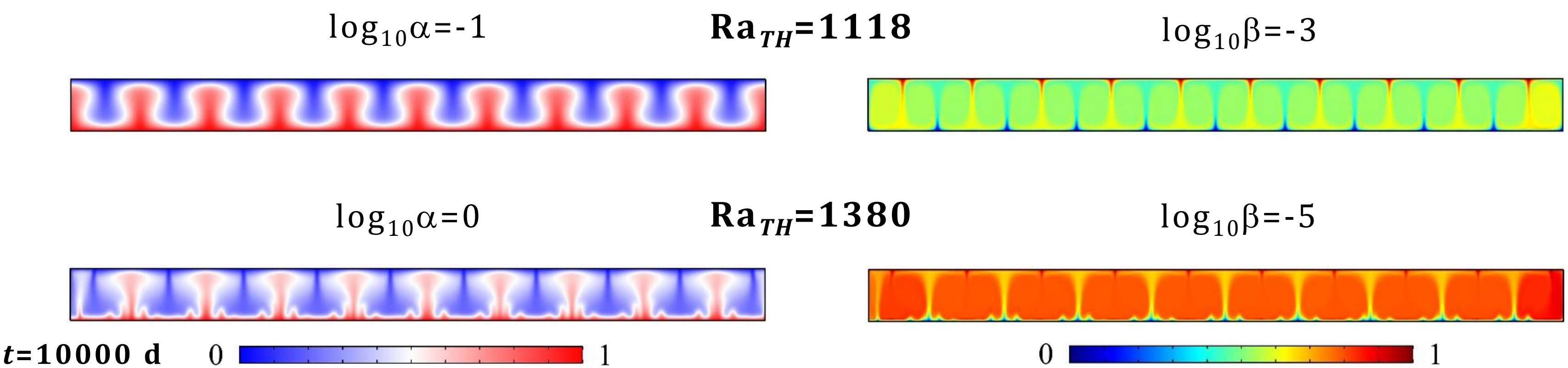
$\log_{10}\alpha=-1$ | $\mathbf{Ra_{TH}=238.1}$ | $\log_{10}\beta=-4$

$\log_{10}\alpha=-2$ | $\mathbf{Ra_{TH}=994.7}$ | $\log_{10}\beta=-3$

$\boldsymbol{t}$**=10000 d**

RESULTS – MODEL A

Temperature **Concentration**

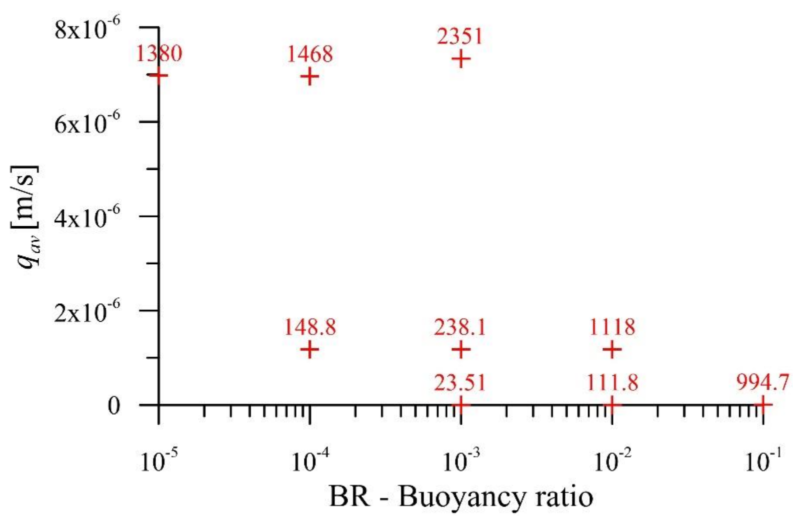


- $\alpha\Delta T$<=10^{-2} and $\beta\Delta c$<=10^{-5} → **no thermal and haline convection** in the porous medium
- $\alpha\Delta T$<=10^{-2} and $\beta\Delta c$=10^{-4}–10^{-3} → steady-state and time-dependent **haline convection** without any thermal effects
- $\alpha\Delta T$=10^{-1} and $\beta\Delta c$=10^{-5}–10^{-3} → steady-state **thermohaline convection**
- $\alpha\Delta T$=1 and $\beta\Delta c$=10^{-5}–10^{-3} → time-dependent **thermohaline convection**

The effect of salinity-driven convection was strongly influenced by the heat transport mechanisms, because the Lewis number was Le=716. However, the natural convection might not be universally characterized by the thermohaline Rayleigh number!?

Results – Model A

Average Darcy flux



No convection

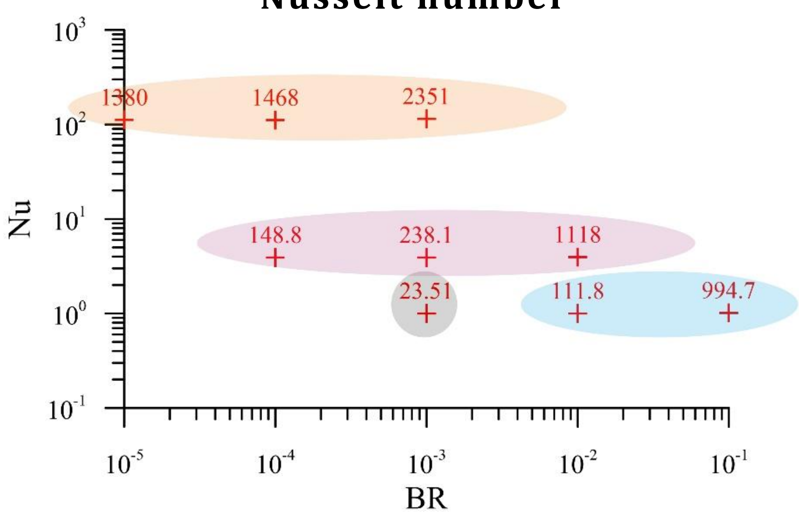
Haline convection

Steady-state thermohaline convection

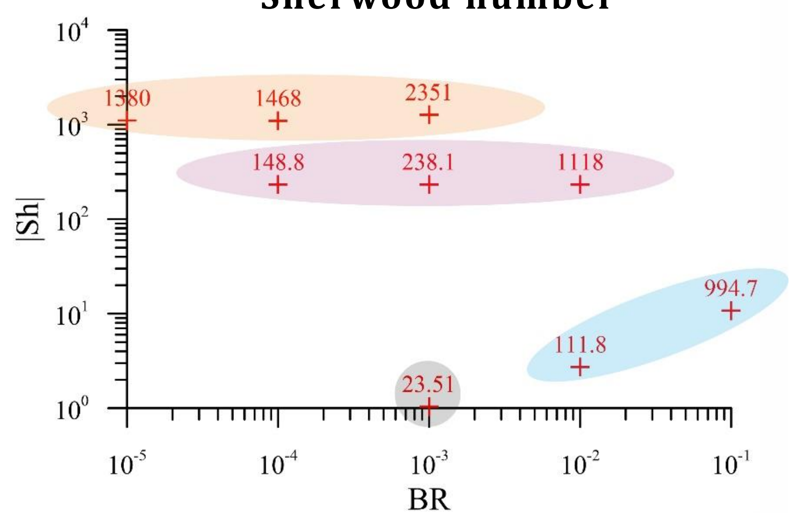
Time-dependent thermohaline convection

Ra_{TH} – Thermohaline Rayleigh number

Nusselt number

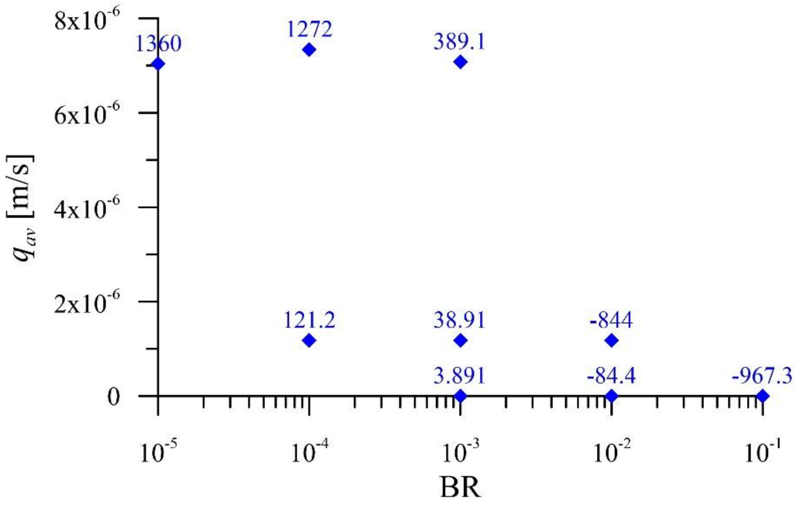


Sherwood number



RESULTS – MODEL B

Average Darcy flux



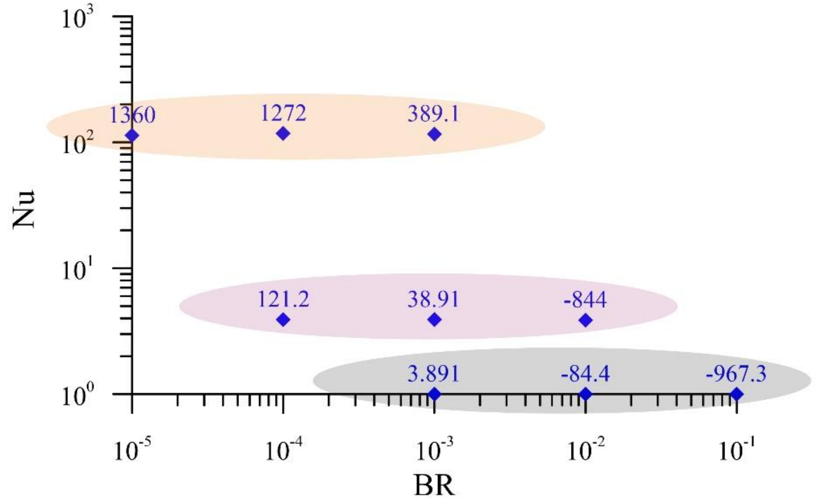
No convection

Steady-state thermohaline convection

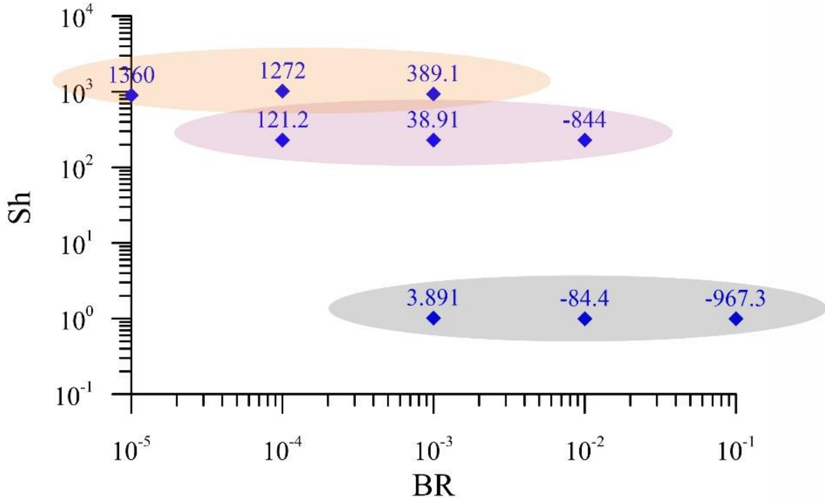
Time-dependent thermohaline convection

Ra_{TH} – Thermohaline Rayleigh number

Nusselt number

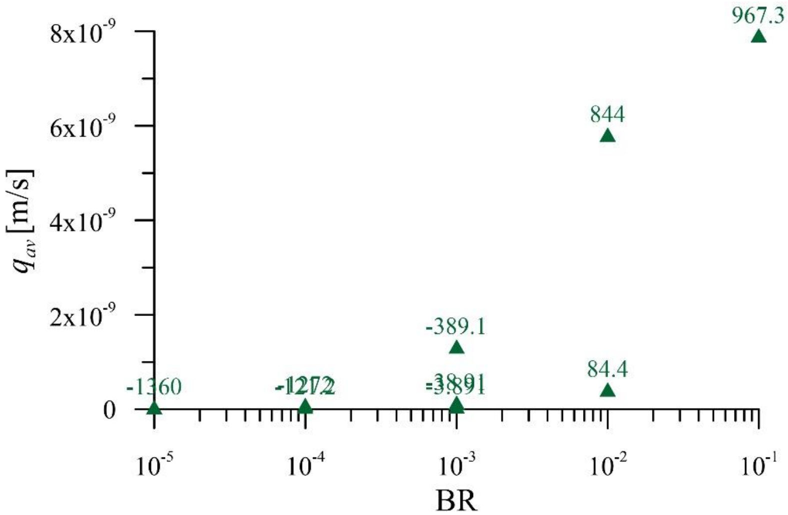


Sherwood number



Results – Model C

Average Darcy flux



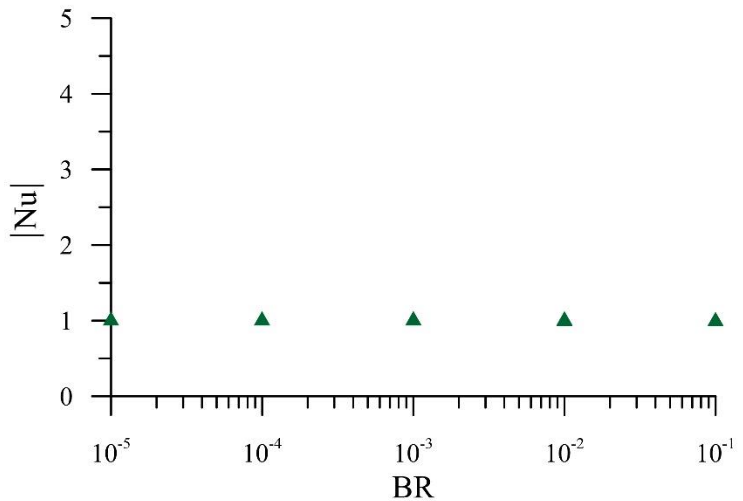
No convection

Steady-state haline convection

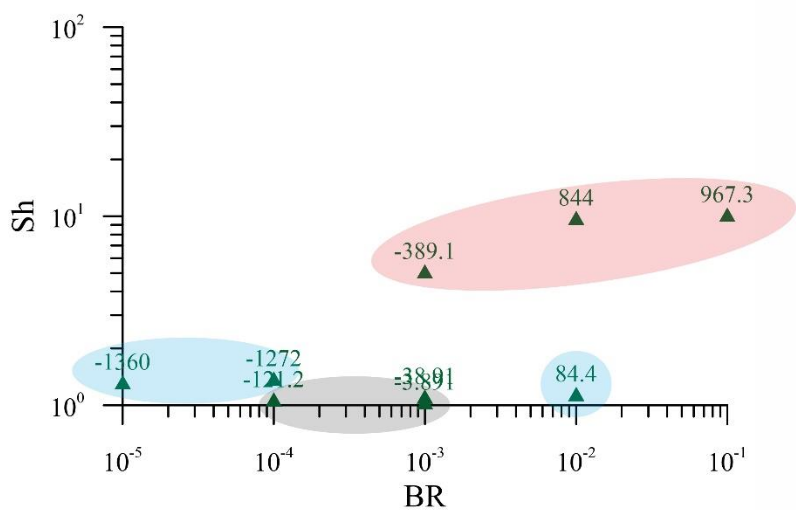
Time-dependent haline convection

Ra_{TH} – Thermohaline Rayleigh number

Nusselt number



Sherwood number



SUMMARY & OPEN-ENDED QUESTIONS

Model A

Both effects facilitated the onset of natural convection. However, the effect of salinity-driven natural convection was strongly influenced by the heat transport mechanisms (k>>D_0). Steady-state haline, thermohaline and time-dependent thermohaline convection were noticed (e.g. Nu vs BR , Sh vs BR).

Model B

The natural convection was facilitated by thermal effect, but it was reduced by saline effect. In this case, steady-state and time-dependent thermohaline convection were noticed in the numerical model. The onset of thermohaline convection might be defined by a critical Rayleigh number (Ra_{TH}) with a buoyancy ratio (BR).

Model C

The natural convection was facilitated by saline effect, but it was reduced by thermal effect. In this case, only haline convection evolved in the numerical model, which was shown by the Darcy flux ($q_{av}>10^{-10}$), the Sherwood (Sh>1) and the Nusselt number (Nu=1).

- **How to define the thermohaline Rayleigh number in the different model scenarios?**
- **What is the critical value of the thermohaline Rayleigh number?**
- **Maybe a new non-dimensional number should be defined in order to characterize the thermohaline convection?**

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