Core- and Pore-scale Investigation of Supercritical CO_2 Injected into Porous Media Containing Water

Prof. Peixue Jiang, Dr. Ruina Xu

Department of Thermal Engineering,
Tsinghua University, Beijing

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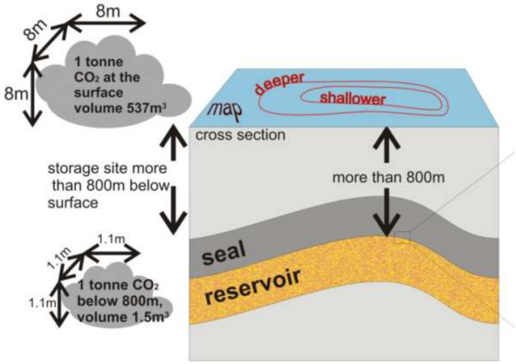
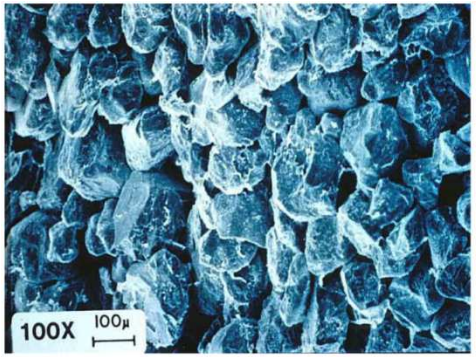
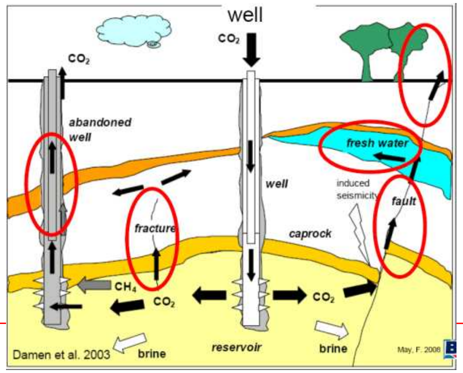
- ☐ **Research Background**
- ☐ **Research Contents**
  - ✓Visualization experimental investigations of supercritical CO_2 injected into porous media with the fissure defect
  - ✓Pore scale numerical simulation of supercritical CO_2 injecting into porous media containing water
  - ✓Fluid Flow and Heat Transfer of CO_2 at Super-critical Pressures in Mini/micro Channels and Porous Media
- ☐ **Conclusions**
- ☐ **Ongoing Researches**

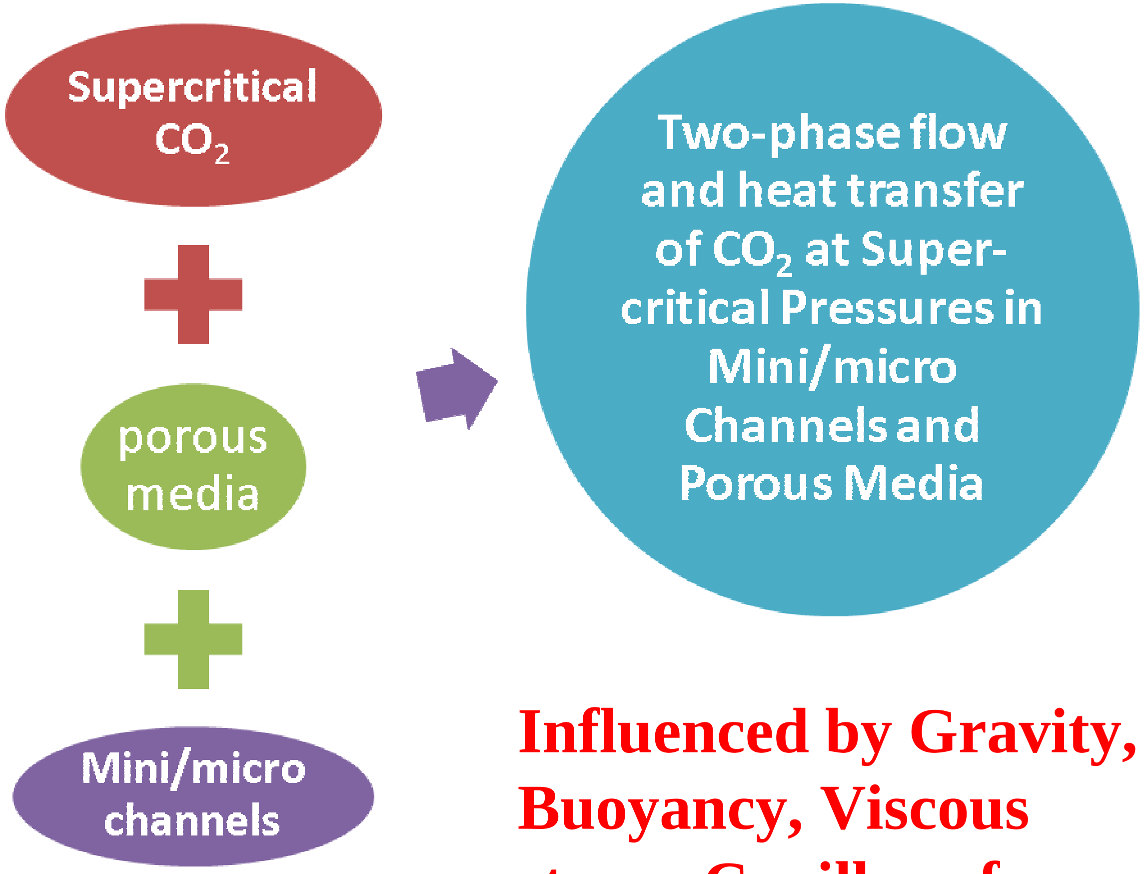
CO_2 storage





Scanning Electron Microscope (SEM) view of pore space in sandstone





Supercritical CO_2

+

porous media

+

Mini/micro channels

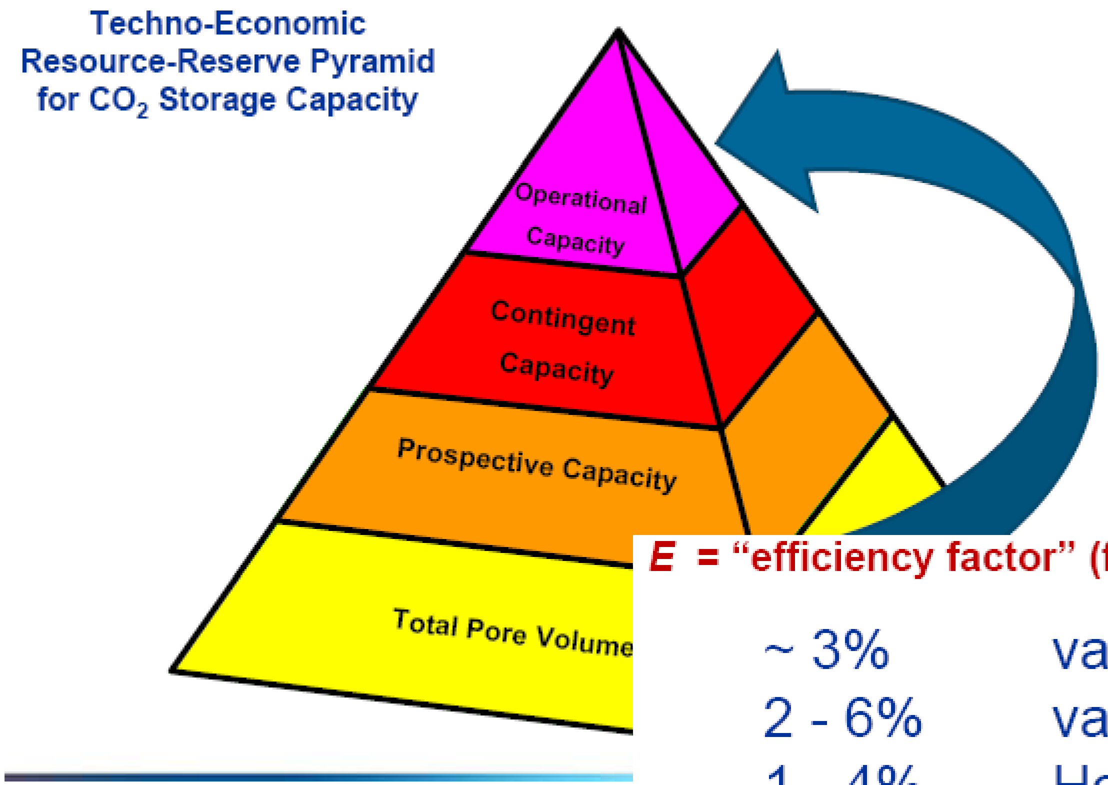
Two-phase flow and heat transfer of CO_2 at Super-critical Pressures in Mini/micro Channels and Porous Media

Influenced by Gravity, Buoyancy, Viscous stress, Capillary forces

Thermal Processes during CO_2 injection

- Heat transfers between the host reservoir and confining beds
  - Which can impact the reservoir T, in particular, near the reservoir/basement and reservoir/caprock interfaces
- Heat of CO_2 dissolution
- The Joule-Thomson effect
- Injection temperature
  - It depends on wellhead conditions, well completion and many other parameters, such as pressure losses and heat exchange along the wellbore.

Challenges



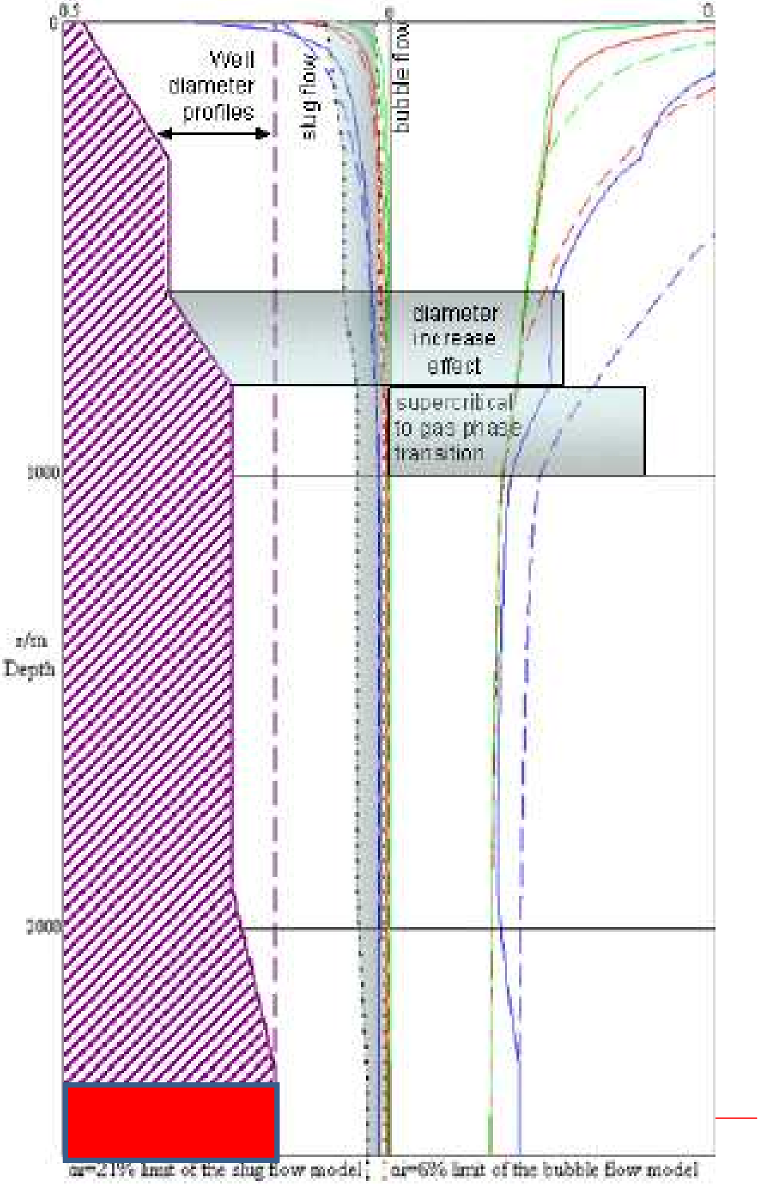
$$G_{CO2} = A\, h_g\, \phi\, \rho\, \enclose{circle}{E}$$

E = "efficiency factor" (fraction of total pore volume filled by CO_2)

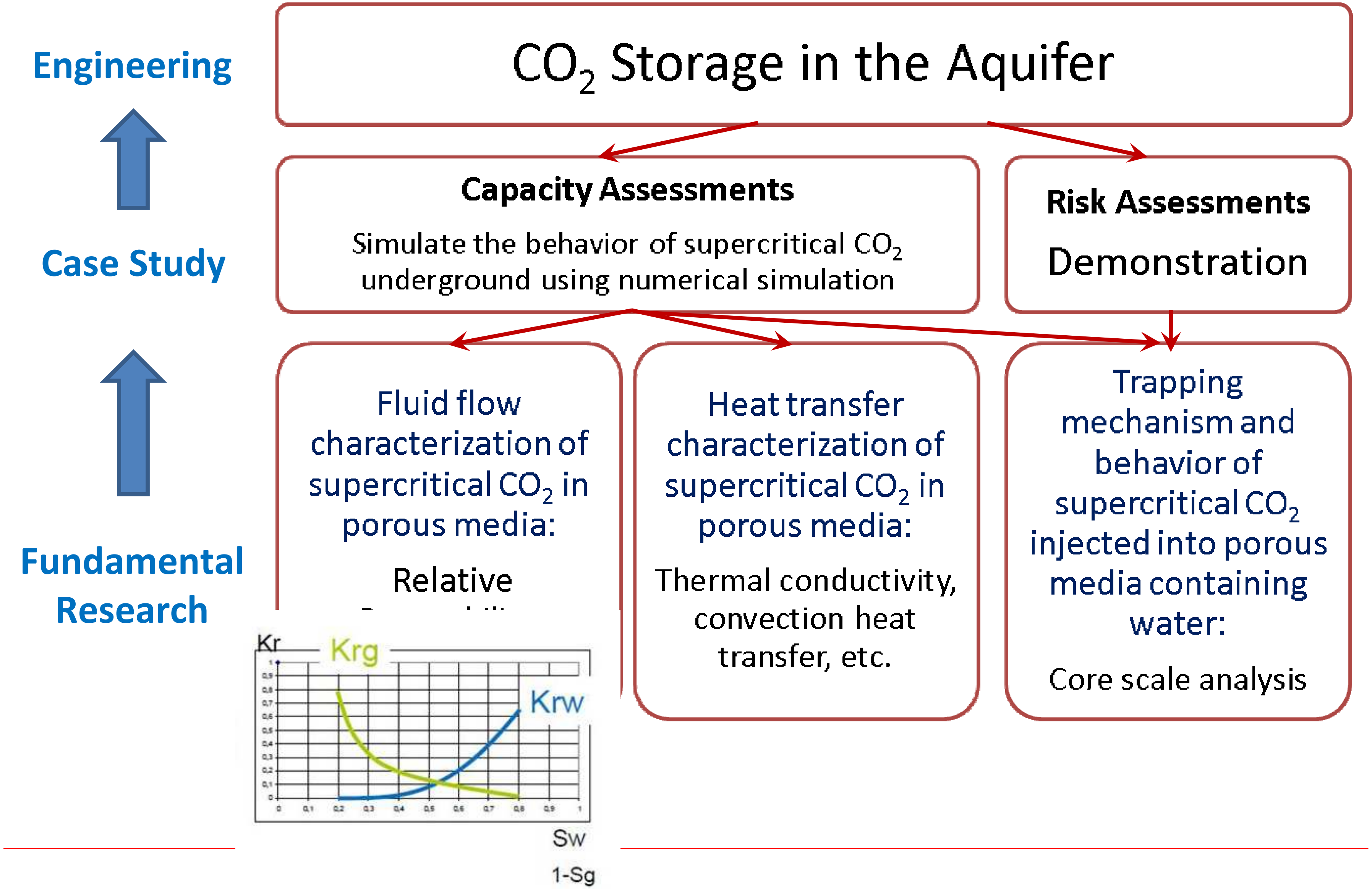
~ 3%	van der Meer, 1992
2 - 6%	van der Meer, 1995
1 - 4%	Holloway et al.,1996, 2006
1 - 4%	CSLF, 2007
1 - 4%	NETL DOE, 2007
1 - 4%	CO2CRC, 2008
1 - 4%	IEA GHG, 2008
4 – 20+%	EERC, 2009

Challenges

- The determination of downhole T has not yet received much attention.
- Joule-Thomson cooling effect
- Turbulent flow after wellbore
- No experimental results
- Heat non-equilibrium



CO_2 storage



Engineering

Case Study

Fundamental Research

CO_2 Storage in the Aquifer

Capacity Assessments

Simulate the behavior of supercritical CO_2 underground using numerical simulation

Risk Assessments

Demonstration

Fluid flow characterization of supercritical CO_2 in porous media:

Relative

Heat transfer characterization of supercritical CO_2 in porous media:

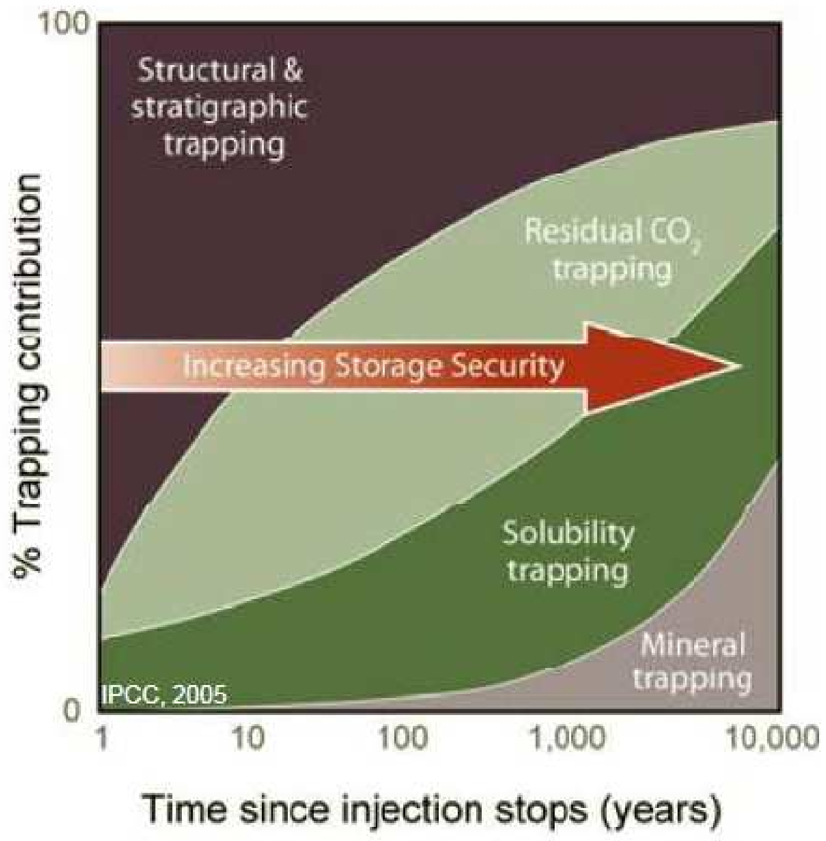
Thermal conductivity, convection heat transfer, etc.

Trapping mechanism and behavior of supercritical CO_2 injected into porous media containing water:

Core scale analysis

Four trapping mechanisms

- ☐ Structure Trapping
- ☐ Residual Trapping
- ☐ Dissolved Trapping
- ☐ Geochemical Trapping



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✓Visualization experimental investigations of supercritical CO_2 injected into porous media with the fissure defect

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☐ **Conclusions**

Experimental conditions and experiment methods

Tab.1 Experimental conditions

Pressure P	9.25 MPa
Particle diameter d_p	2.5-3.2 mm
Diameter of test section D	25.4 mm(1 inch)
Length of test section L	70 mm
Injection flow rate Q	1 ml/min
Notes	A vertical fissure was constructed near the outlet

Experiment methods

1. **Test section was saturated with water.**
2. **Supercritical CO_2 was injected into the test section, using MRI to measure the CO_2 saturation and T_2 curve and get the CO_2 distribution.**
3. **CO_2:H_2O=3:2 was injected, Via the MRI, relaxation time curve , water saturation distribution image andT_2 curve can be produced;**
4. **CO_2:H_2O=1:4 was injected, Via the MRI, relaxation time curve and water saturation distribution image andT_2 curve can be produced.**

Experiment results

Influence of buoyancy (MRI)

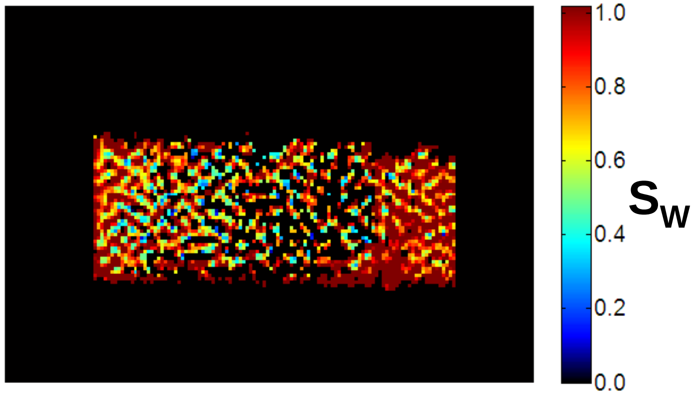


Fig.1 water saturation image with saturated water

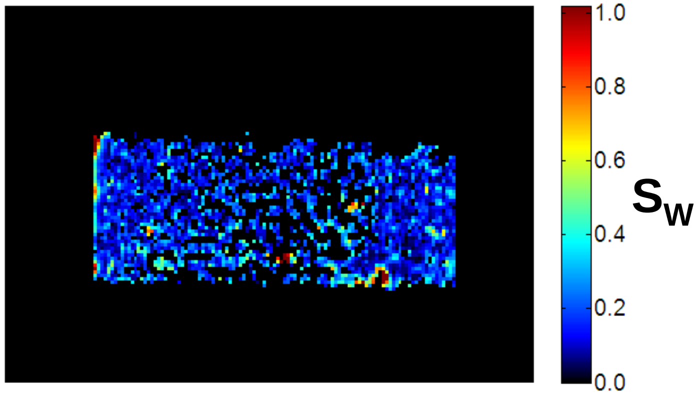


Fig.2 Bounded water image

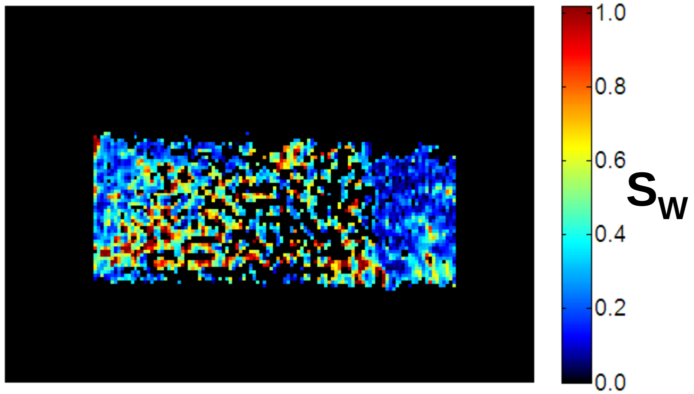


Fig.3 CO_2：H_2O=3：2

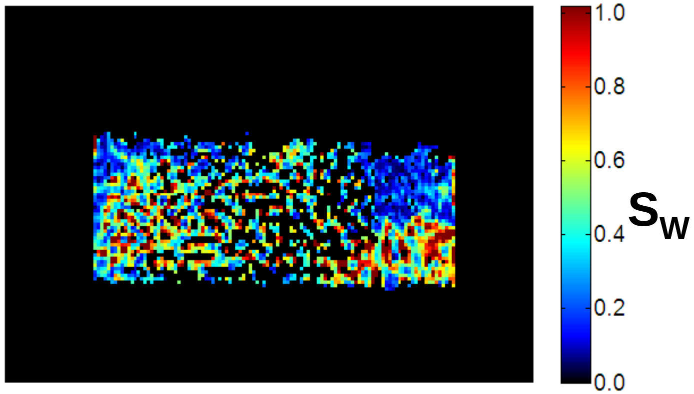
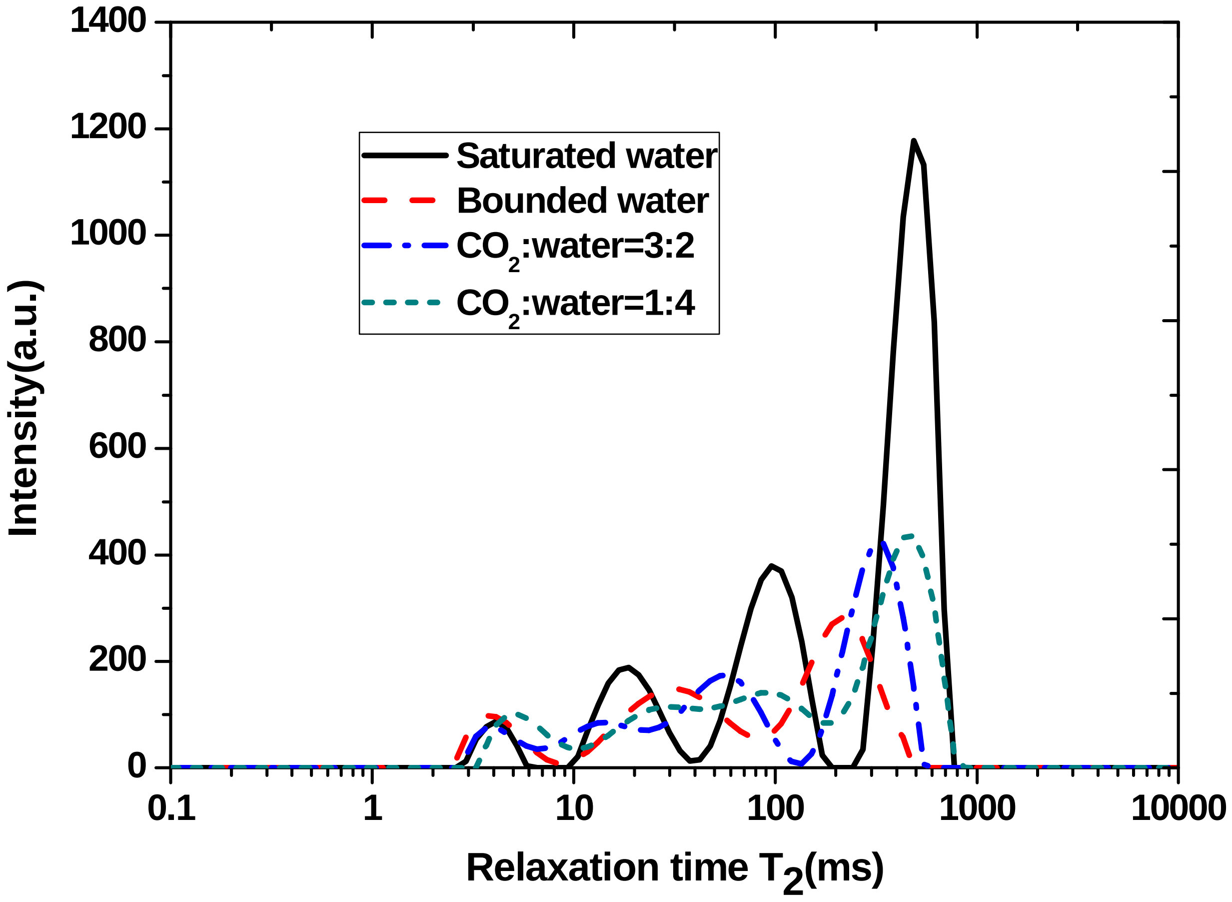


Fig.4 CO_2：H_2O=1：4

- ➢From the images, the water saturation increases by the reduction of the CO_2-water injection ratio
- ➢ CO_2 will migrate to the top of the test section under the effects of buoyancy and gravity forces.

Experiment results NMR



☐Relaxation time

✓Denotes pore size

✓H_2O tends to invade into the small pores, CO_2 tends to invade into the big pores, during the process of CO_2 displacing H_2O, water in the big pores will be primarily displaced, and then the water in smaller pore will be displaced.

☐Signal Intensity

✓Denotes water saturation

✓During the process of CO_2 displacing H_2O ， Signal Intensity and water saturation decreases.

Experiment results Fissure defect effect

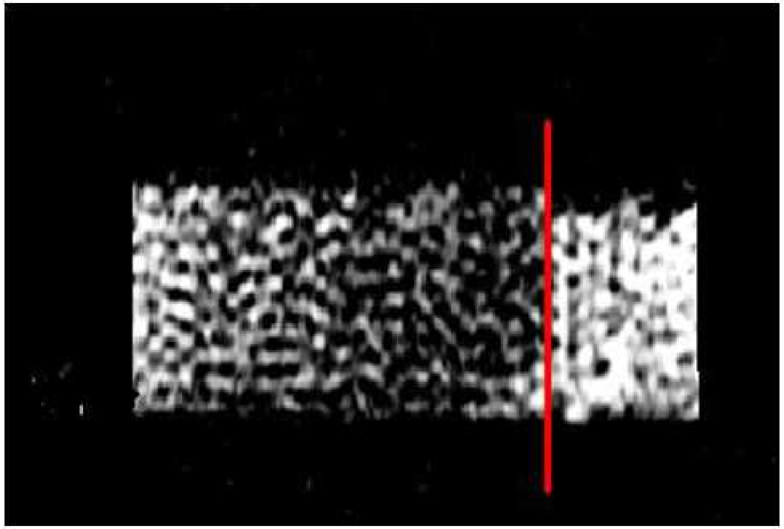


Fig.1 Fissure defect position image

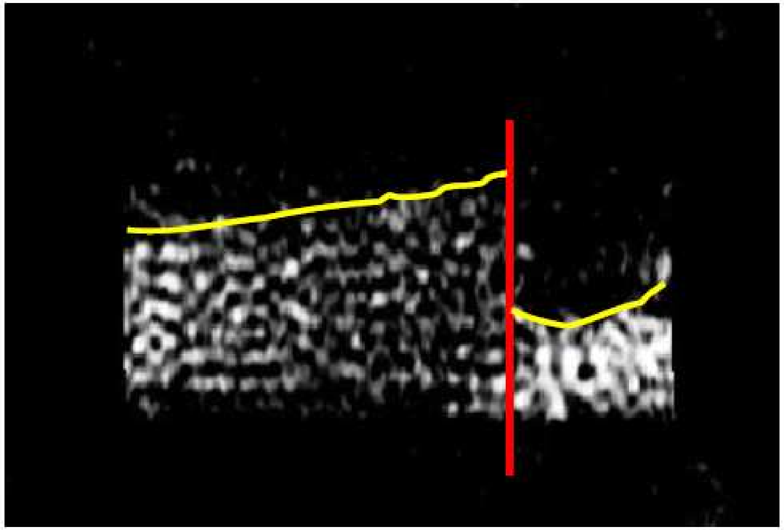


Fig.2 Water saturation gray image
（CO_2：H_2O=3：2）

- There is a vertical fissure near the outlet of the test section with significant influences on CO_2 distribution, more supercritical CO_2 will migrate to the top when encounters the fissure defect.
- In particular condition, more supercritical CO2 will migrate to the top when encounters the fissure defect, and therefore the cap rock has to withstand bigger pressure, which will results in reducing the safety of carbon geological storage.

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☐ **Conclusions**

Simulation Research Numerical model

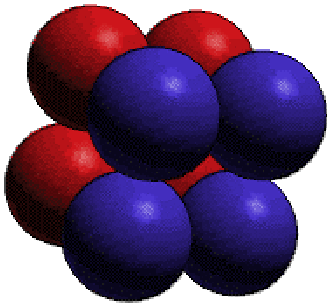


Fig.1 Simple Cubic Arrangement

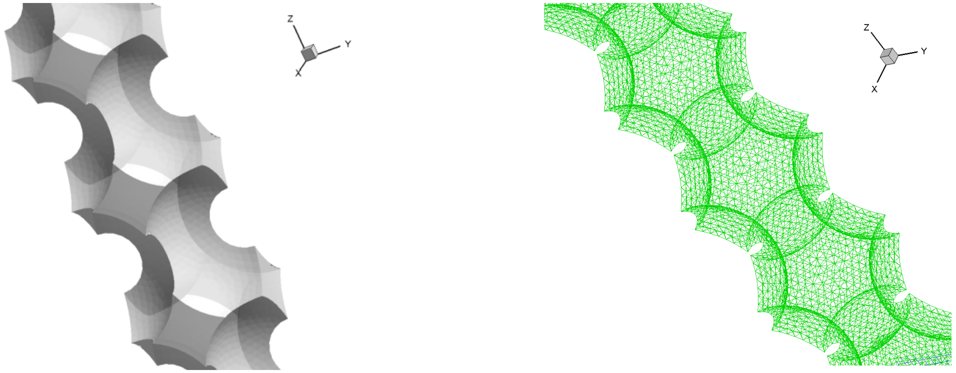


Fig.2 The calculation model and grids for the fluid domain

□ **The commercial software Gambit V2 and FLUENT V6 were respectively used as the grid generator and the CFD solver**

□ **Member of our research group, Xu and Jiang have discussed the influence of the different arrangement of the particles on the single phase fluid flow in porous media.**

□ **The diameter of particle is 120 μ m, porosity is 40%(agree with Abaci et al 1992）. For CO_2, simulation condition is 1500m depth underground, pressure is 15MPa, temperature is 60 ℃; for air, pressure is constant pressure, temperature is 290K.**

Control equations and boundary conditions

☐ **Continuity equation:**

$$\frac{1}{\rho_{\mathrm{q}}}=\frac{\partial}{\partial t}(\alpha_q\rho_q)+\nabla\cdot(\alpha_q\rho_q\vec{V}_q)=S_{\alpha_q}+\sum_{p=1}^{n}(\dot{m}_{pq}-\dot{m}_{qp})$$

☐ **Momentum equation:**

$$\frac{\partial}{\partial t}(\rho\vec{V})+\nabla\cdot(\rho\vec{V}\vec{V})=-\nabla\rho+\nabla\cdot[\mu(\nabla\vec{V}+\nabla\vec{V}^{T})]+\rho\vec{g}+\vec{F}$$

☐ **Capillary pressure equation:**

$$P_c=\frac{2\sigma\cos\theta}{r}$$

☐ **3-D unsteady VOF model was used, symmetrical boundary conditions were imposed on the boundaries of the computational domain. The inflow into the domain was set as the mass flow rate inlet with the outflow set as the pressure outlet boundary condition.**

Simulation result   Water and air

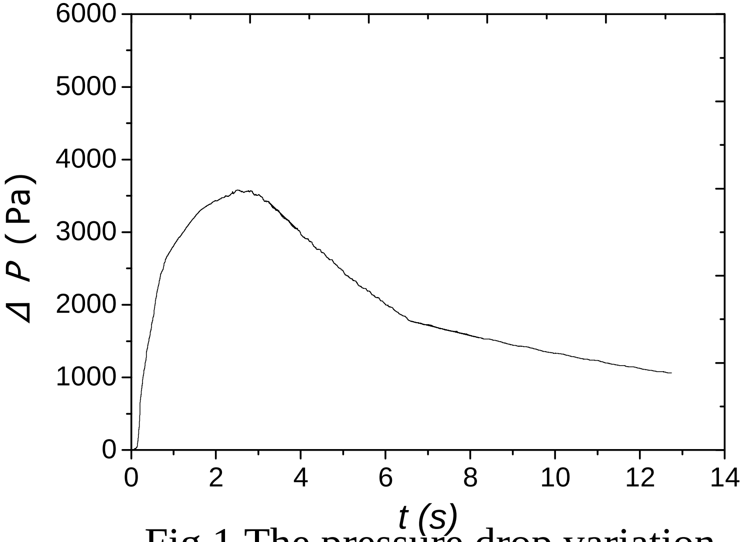


Fig.1 The pressure drop variation with injection time

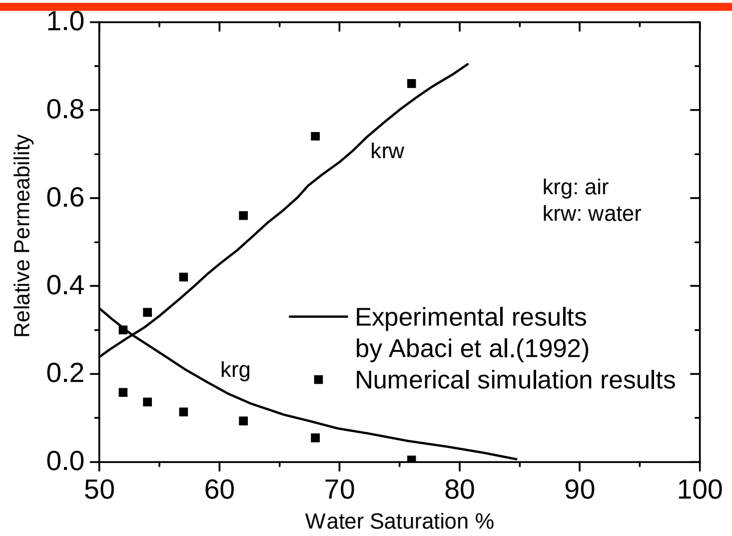


Fig.2 Relative permeability – saturation relation using air and water

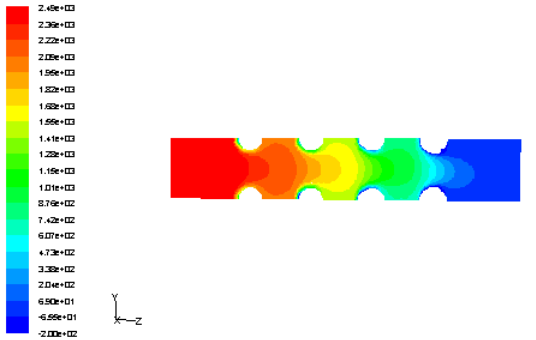


Fig.3 Pressure distribution in center cross section at (t=5s)

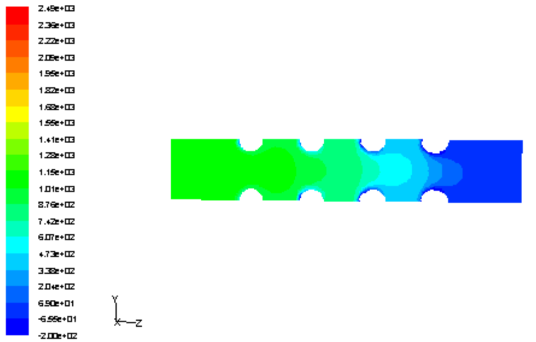
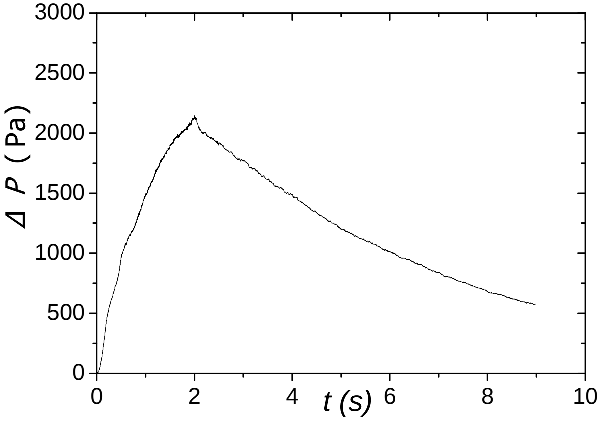


Fig.4 Pressure distribution in center cross section at (t=12s)

Simulation result Supercritical CO_2 and water



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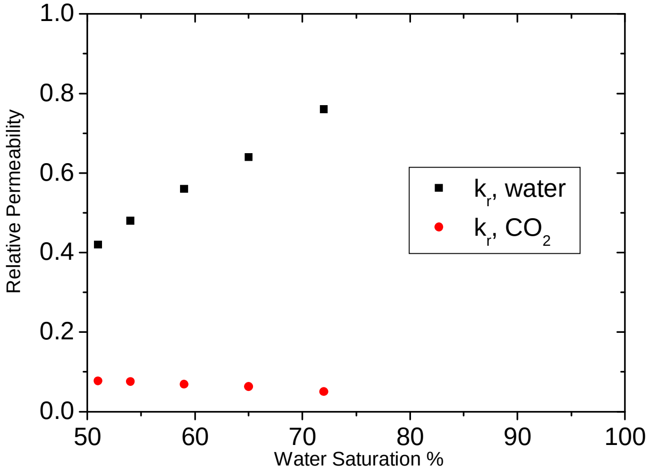

Fig.2 Relative permeability – saturation relation using supercritical CO2 and water

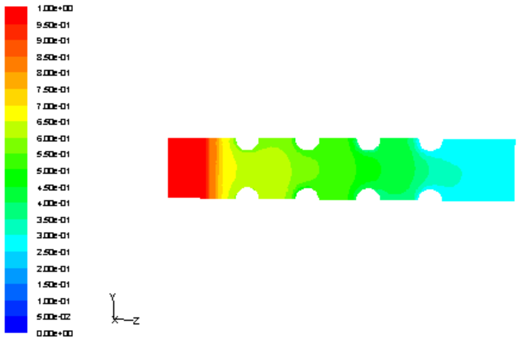

Fig.3 Volume fraction of water in center cross section at t=4s

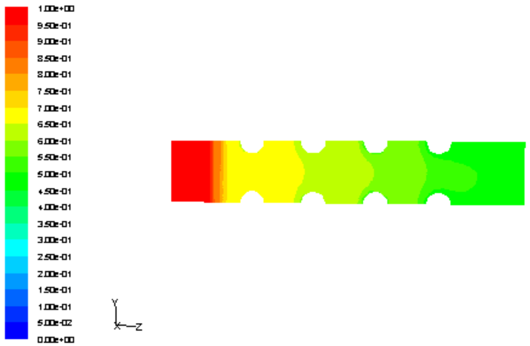

Fig.4 Volume fraction of water in center cross section at (t=9s)

- ✓**In this research, one numerical simulation method was provided to simulate the two phase flow in porous media by solving the Navier-Stokes equation directly.**
- ✓**The pore scale method could provide the fundamental understanding of the mechanism of trapping and CO_2 behavior after CO_2 injection into the saline aquifer.**

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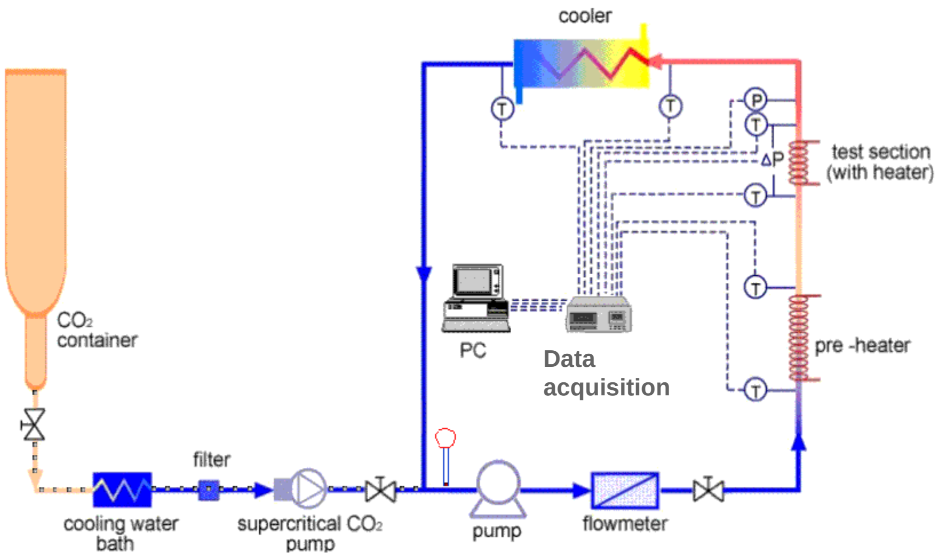
PART 3 Fluid Flow and Heat Transfer of CO_2 at Super-critical Pressures in Mini/micro Channels and Porous Media

- Fluid flow and convection heat transfer of CO_2 at supercritical pressures in vertical small/mini tubes, porous media and in multi-port minichannels; horizontal small tubes
- Heating and Cooling conditions
- Experimental research and numerical simulation
- The effects of inlet fluid temperature, pressure, heat flux, flow directions, buoyancy and thermal acceleration were investigated

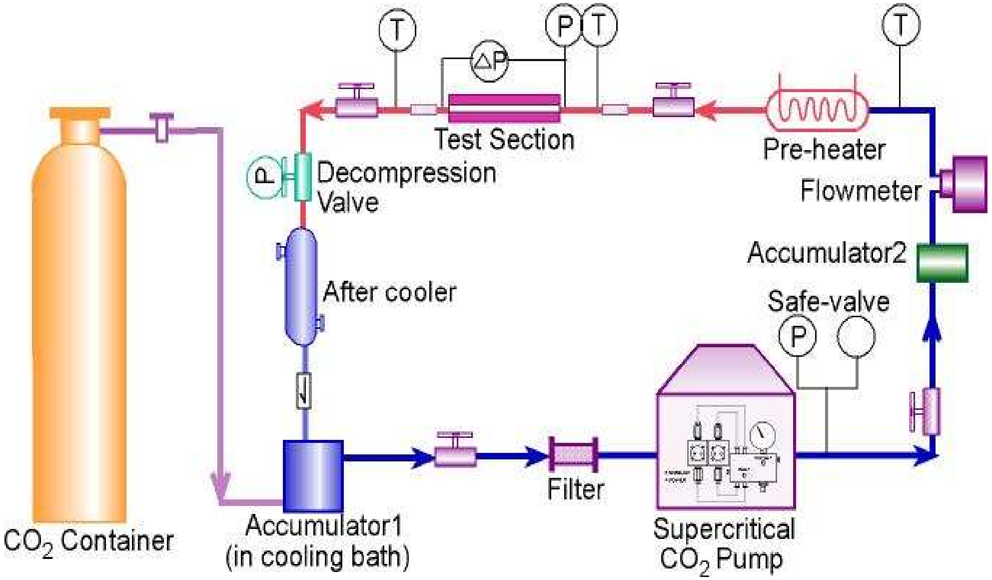
EXPERIMENTAL SYSTEM--No.1



Parameters for System No. 1

- Pump：12 MPa， 0~14 kg/h, 0.35 MPa
- Pressure gage transducer：0～14 MPa, 0.075％
- Coriolis-type mass flowmeter：0～65 kg/h, 0.1%

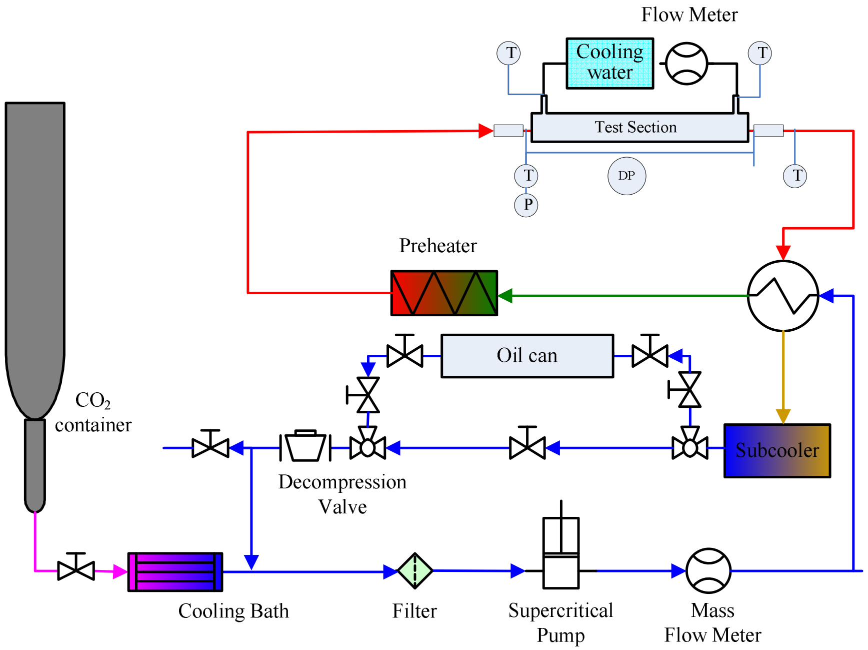
EXPERIMENTAL SYSTEM--No.2

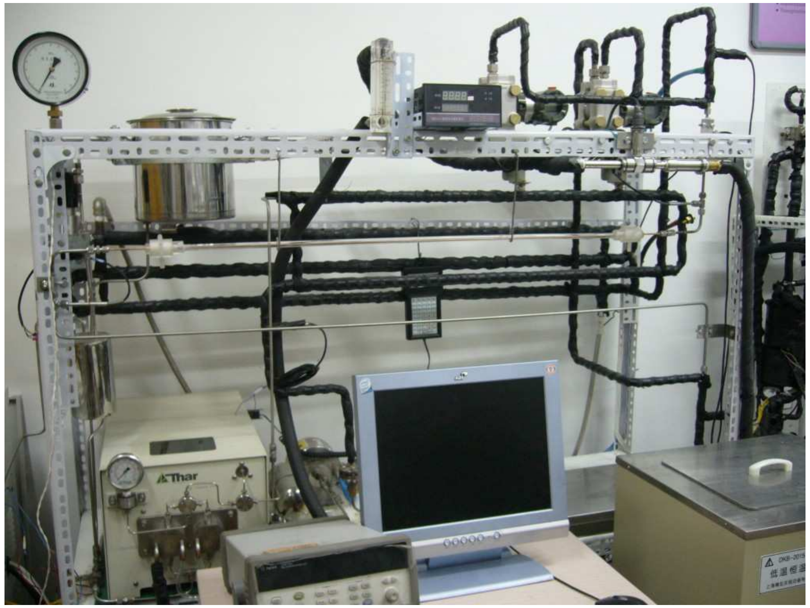


Parameters for System No. 2

- Pump：68.9 MPa， 0.06 ~ 3 kg/h
- Pressure gage transducer：0～14 MPa, 0.075％
- Coriolis-type mass flowmeter：0～65 kg/h, 0.1%

EXPERIMENTAL SYSTEM--No.3





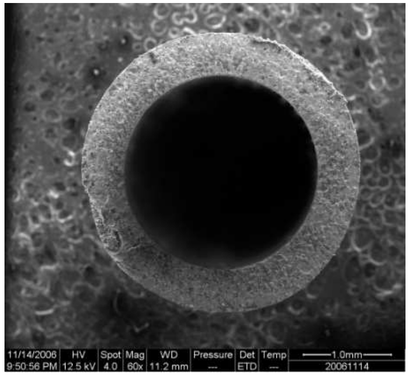
Parameters for System No. 3

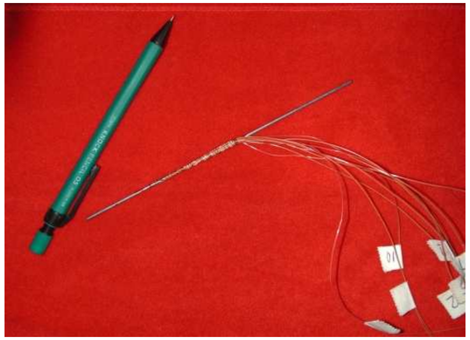
Pump： 35 MPa， 1.8 ~ 21 kg/h

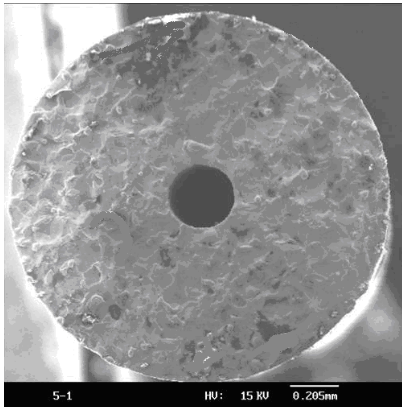
Pressure gage transducer： 0～25 MPa, 0.075％

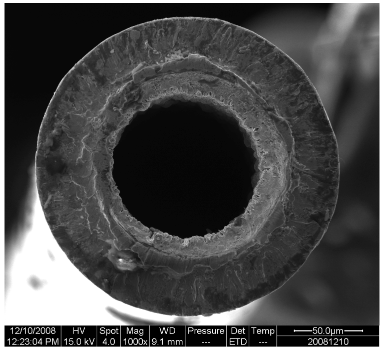
Coriolis-type mass flowmeter： 0～65 kg/h, 0.1%

Test Sections









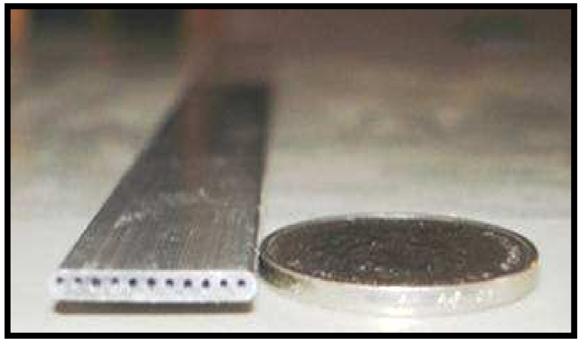
Tubes:

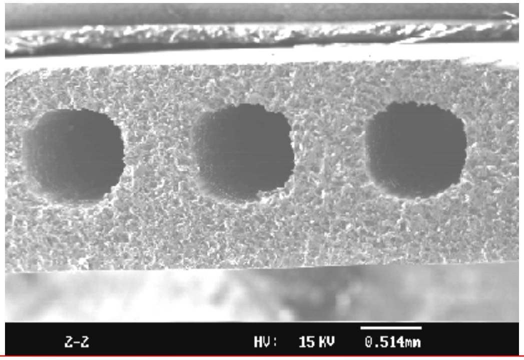
Inside diameter: 2.078mm, 0.948mm, 0.27mm, 0.0992mm

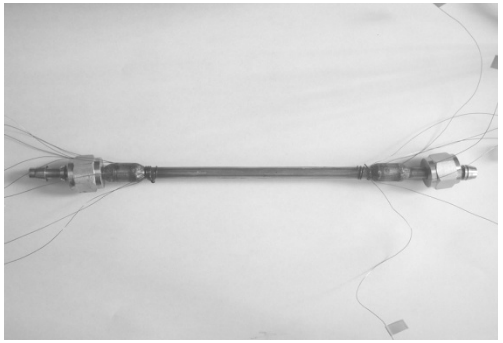
Outside diameter: 3.137mm, 1.729mm, 1.59 mm, 0.216 mm

Porous media: 4mm; 0.2~0.28 mm

Multi-port mini-channel: Inner diameter 0.82 mm







Results

- **Fluid flow and convection heat transfer of CO_2 at supercritical pressures in**

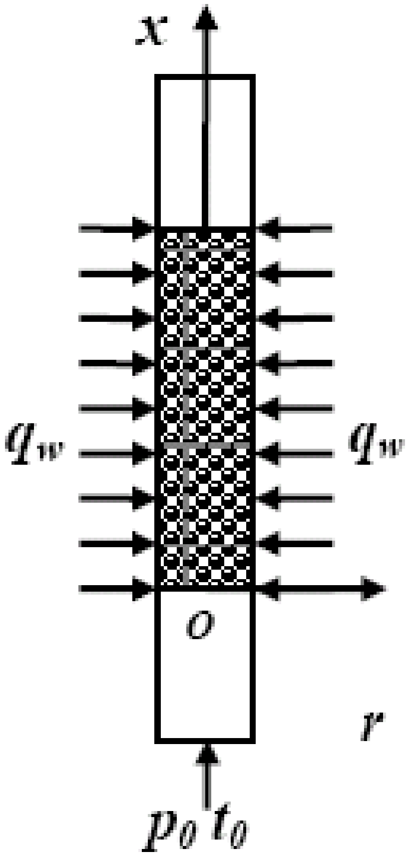
1) vertical tube with d_i=2.078 mm, d_o=3.14 mm; heating conditions

2) vertical tube with d_i=0.0992 mm, d_o=0.216mm heating conditions

3) porous media tube with porosity 0.45 and 0.4

- **Experiments and numerical simulation**
- Pei-Xue Jiang, et al,
- International Journal of Heat and Mass Transfer, Vol.52, No.21-22, pp.4748-4756, 2009；
- International Journal of Heat and Mass Transfer, Vol. 51, No. 25-26, pp. 6583-6293, 2008；
- Applied Thermal Engineering, Vol. 29, No. 5-6, pp. 1146–1152, 2009；
- Experimental Thermal and Fluid Science, Vol. 32, pp. 1628–1637, 2008；
- International Journal of Thermal Sciences, Vol. 47, No. 8, pp. 998–1011, 2008；
- International Journal of Heat and Mass Transfer, Vol. 51, No. 11-12, pp.3052-3056, 2008；
- The Journal of Supercritical Fluids, Vol. 38, pp.339-346, 2006

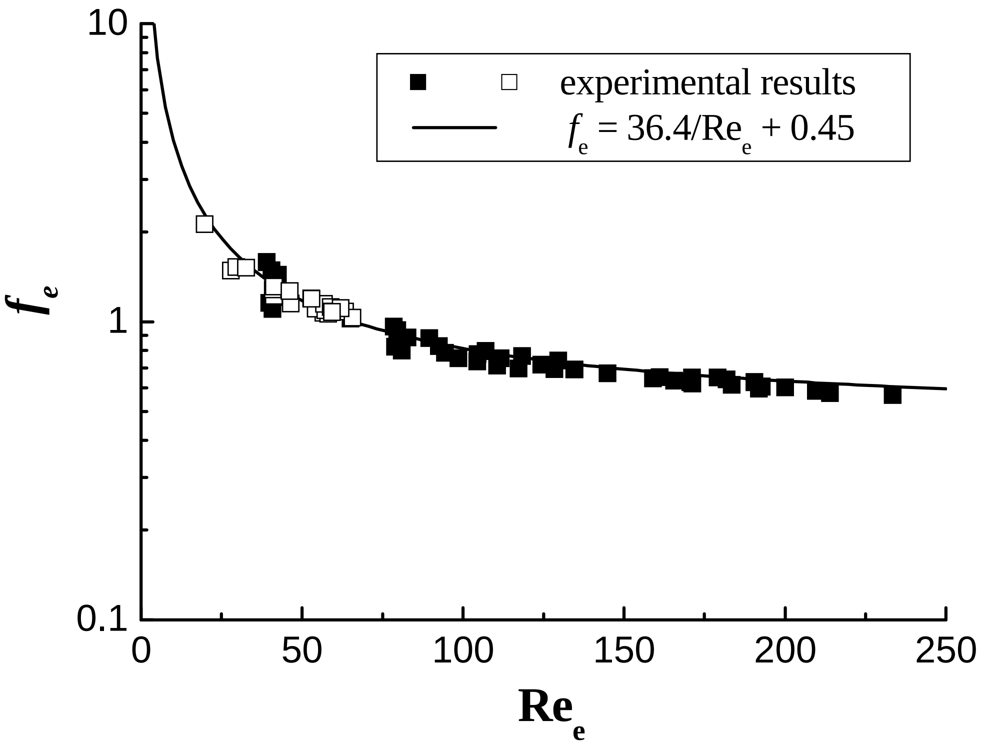
3) Results for Porous tube



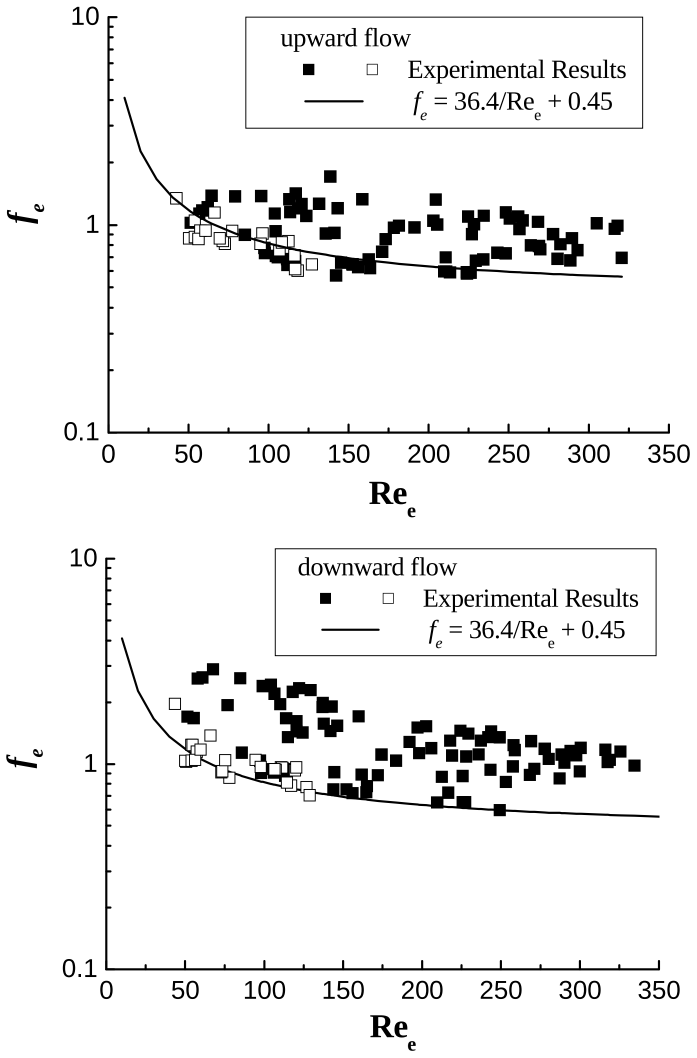
Porous tube（copper）
Sintered bronze particles

d_p mm	0.1-0.12	0.2-0.28
porosity	0.45	0.4
D_{in} mm	4	4
D_{out} mm	6	6
$L_{heating}$ mm	50	50
TC No.	8	8

Flow Resistance in porous tube



Un-heated cases



heated cases

$$\mathrm{Re}_e^{\ *} = \mathrm{Re}_e \left(\frac{\bar{\rho}_w}{\bar{\rho}_f}\right)^n \left(\frac{\bar{\mu}_w}{\bar{\mu}_f}\right)^m$$

For upward flow：

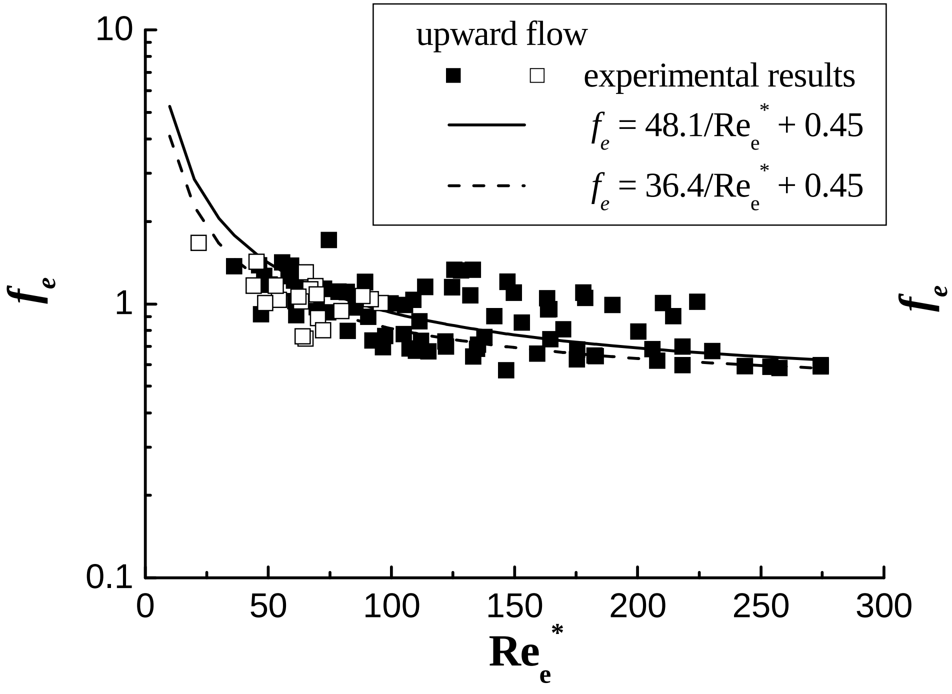
$n = 3.85$， $m = -3.55$

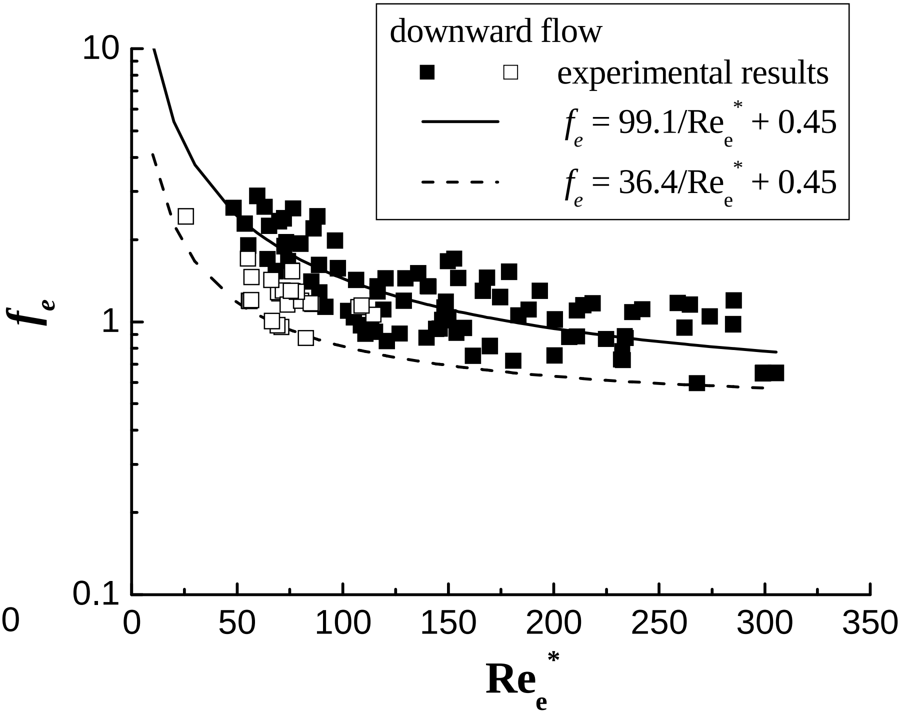
For downward flow：

$n = 3.47$， $m = -3.53$

$$f_e = \frac{48.1}{\mathrm{Re}_e^{\ *}} + 0.45$$

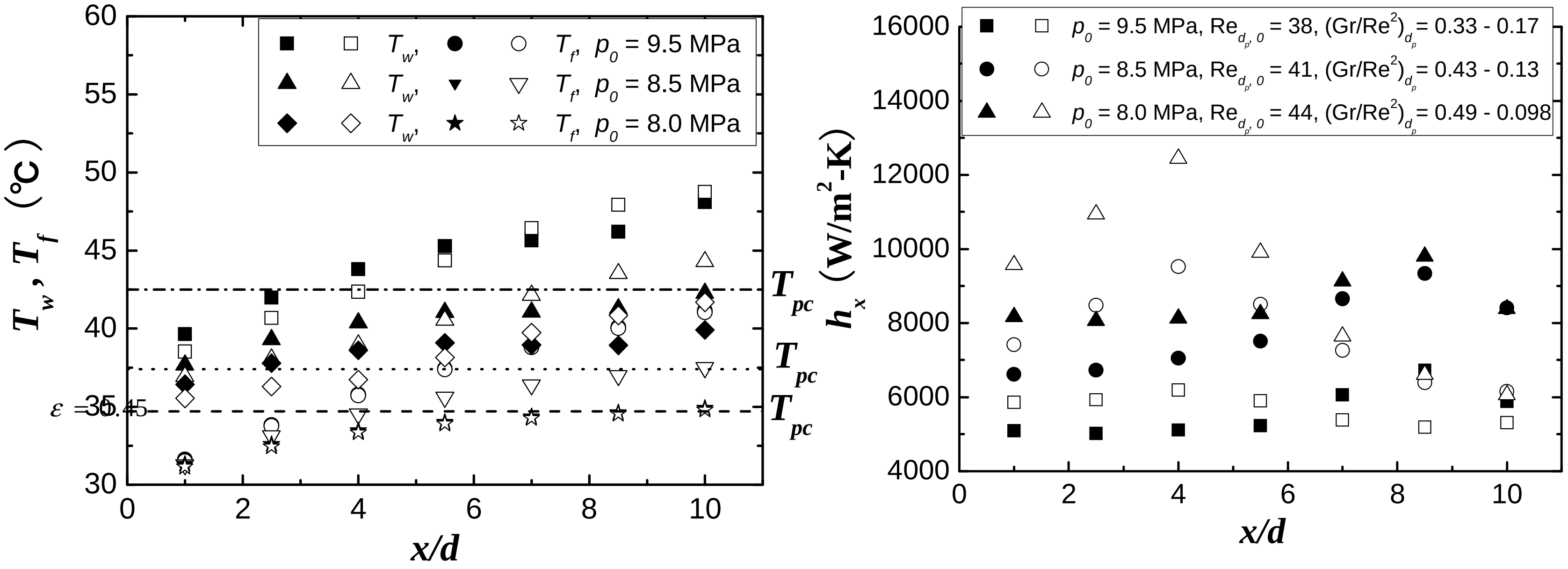
$$f_e = \frac{99.1}{\mathrm{Re}_e^{\ *}} + 0.45$$





Heat transfer in porous tube

different inlet temperatures, different heat fluxes, different mass flow rates, for different pressures



Local heat transfer coefficients and fluid and wall temperatures **for different pressures** in a porous tube

d=4 mm, d_p=0.1~0.12 mm,

G =1.0 kg/h, q_w=4.0×10^4 W/m^2, T_0=30 ℃

Solid symbols: upward flow, hollow symbols: downward flow

Ongoing Researches

- **The accurate measurement method of the relative permeability curve**
  - Provide to large-scale modelling
- **Heat transfer of SC CO_2 in porous media containing water**
  - CO_2 Impurity effection
- **CO_2 phase change combined with heat transfer during well injection process**
  - Various injection temperature, injection pressure, injection rate, etc.
- **Joule-Thomson cooling effect**
- **Risk assessment modelling**
- **EGS**
  - System design and parameters optimization
  - Heat transfer between hot rocks and working fluid
  - Heat transfer during injection process and producing process

Conclusions

- MRI can be used to understand the injection and flow characteristic more directly from pore-scale angle. MRI can also be used to measure the porosity and water saturation accurately. CO_2 saturation in test section will increase with the increase of CO_2 injection ratio.
- Supercritical CO_2 will migrate to the top of the test section under the effects of buoyancy and gravity forces.
- Behind the fissure defect, the influence of buoyancy becomes more significant. In particular condition, more supercritical CO_2 will migrate to the top when encounters the fissure defect, and therefore the cap rock has to withstand bigger pressure, which will results in reducing the safety of carbon geological storage.
- The pore scale could provide the fundamental understanding of the mechanism of trapping and CO_2 behavior after CO_2 injected into the saline aquifer.

Thank you for your attention!