

# Numerical Heat Transfer

## Chapter 13 Application examples of fluent for flow and heat transfer problem



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# 数值传热学

## 第 13 章 求解流动换热问题的Fluent软件应用举例



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## 13. A3 Multiphase flow using VOF

采用**流体体积法**研究多相流

**Focus:** in this example, first the **background of multiphase flow** is introduced, and then **Volume of Fluid method** is discussed in detail.

## 13. A3 Numerical simulation of multiphase flow using volume of fraction (VOF) method

- Problem description:** The computational domain is a 2D channel. Air with velocity of 5 m/s flows into the channel from the left inlet; and water with velocity of  $u=0.1\text{m/s}$  enters the channel from a micro-pore at the bottom.

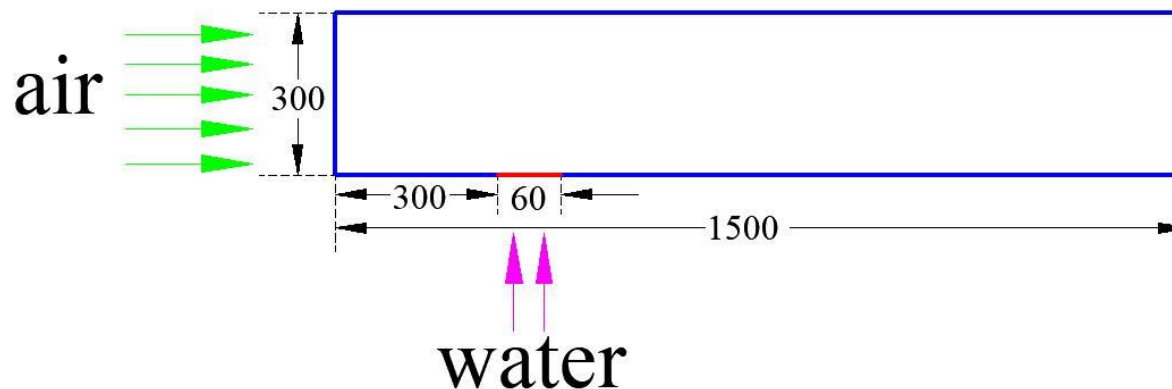
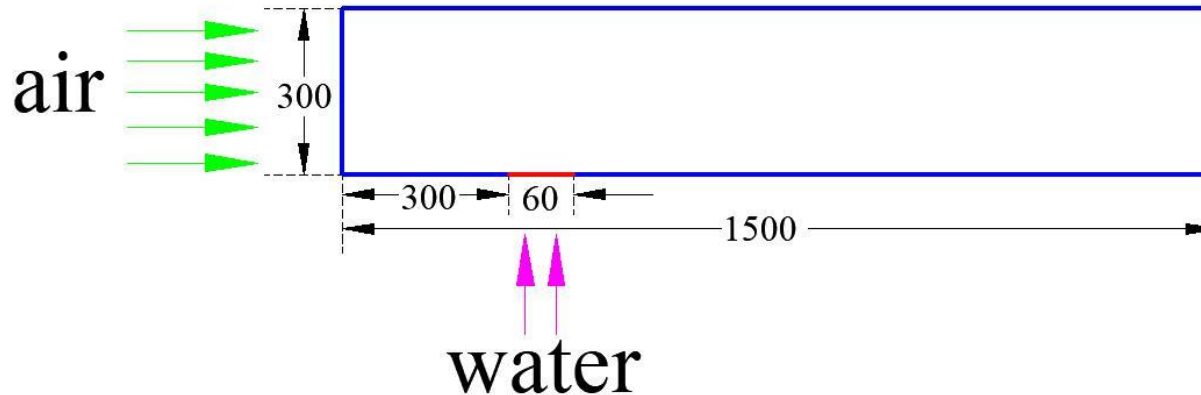


Fig.1 Computational domain and geometry sizes ( $\mu\text{m}$ ) 3/76

- **Find:** water dynamic behavior, pressure drop, and saturation in the channel;

The boundary conditions are as follows:



	Fluid flow
Air inlet	Velocity inlet
Water inlet	Velocity inlet
Outlet	Outflow
Bottom	Wall, 140°
Up	Wall, 60°

# 1. Background of Multiphase flow

**Multiphase fluid flows** are widely encountered in natural, scientific and engineering systems

A **phase** refers to gas, liquid or solid state of matter. A multiphase flow is the flow of a mixture of phases, such as gas (bubbles) in a liquid, or liquid (droplets) in a gas, and so on.

**Same component** (单组分多相流)

Liquid water and water vapor system

$H_2O$

**Multiple components** (多组分多相流)

Liquid water and air system,  $H_2O$ ,  $N_2$ ,  $O_2$ ...



Crown

## 2. Fundamental definitions

**Surface tension:** refers to the tensile force exists at the phase interface separating two fluids, due to a mutual attraction between molecules near the interface

**unit:** N/m **Typical value:** water-air: 0.0725 N/m



Water striders stay on top of water  
(水面上的水黾)

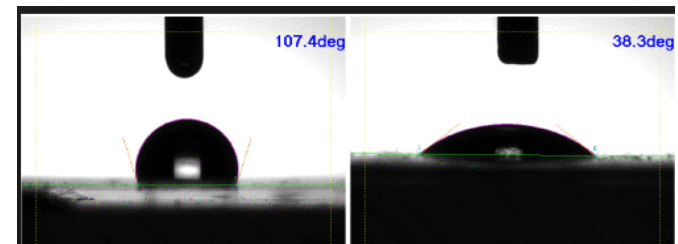
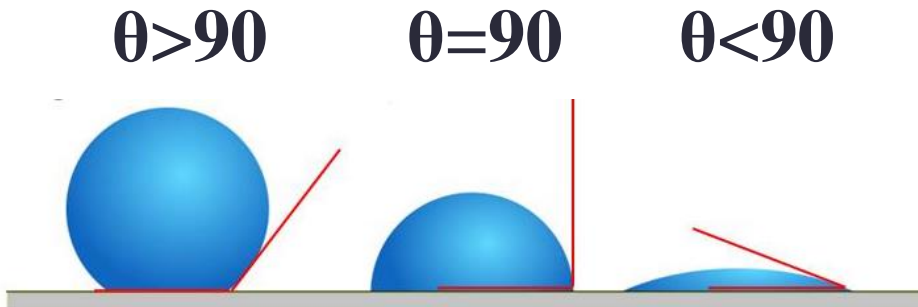


Lotus effect (荷叶效应)



## Contact angle

measurement of the surface wettability. The angle of the triple-phase line. **Hydrophilic** surface (亲水) with angle less than 90, liquid tends to spread. **Hydrophobic surface** (疏水) with angle higher than 90, liquid tends to form droplet. **Neutral surface** with angle as 90.

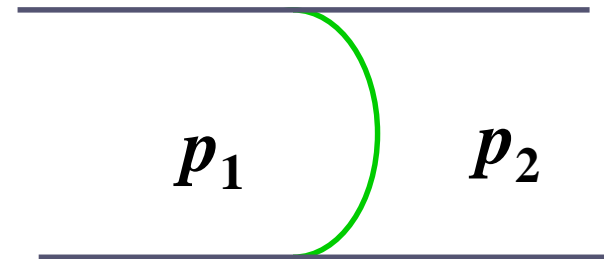




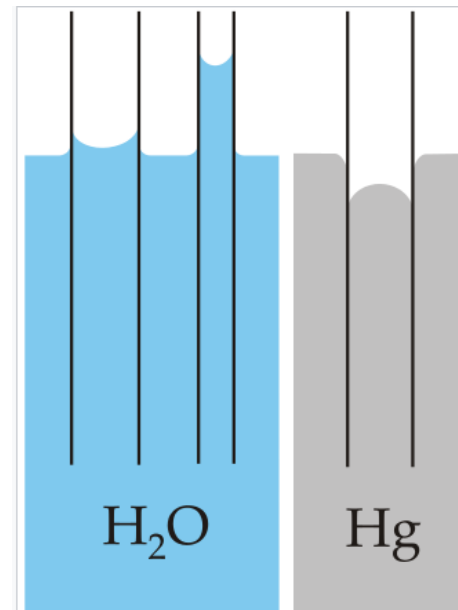
## Capillary pressure

pressure difference across a phase interface, related to the surface tension force

$$P_C = P_1 - P_2 = \frac{\sigma \cos \theta}{r}$$



Because of the capillary pressure, a liquid can flow in narrow spaces without the assistance of, or even in opposition to, external forces like gravity.



$$h = \frac{2\gamma \cos \theta}{\rho g r}$$

mercury

## 2. Different methods for multiphase flow

### Macroscopic

Volume of Fluid (VOF) 流体体积法

Level Set (LS) 水平集法

Phase-field 相场方法

Front tracking 前沿跟踪方法

} VOSET  
by NHT group

### Mesososcopic

Lattice Boltzmann Method, Smooth Particle Hydrodynamics  
(格子Boltzmann 方法, 光滑粒子方法)

### Microscopic

Molecular dynamics (分子动力学)

### 3. Volume of Fluid (VOF)

Proposed by Hirt and Nichols in 1981.

JOURNAL OF COMPUTATIONAL PHYSICS 39, 201–225 (1981)

#### Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries\*

Volume of fluid (VOF) method for the dynamics of free boundaries

CW Hirt, BD Nichols - Journal of computational physics, 1981 - Elsevier

Several methods have been previously used to approximate free boundaries in finite-difference numerical simulations. A simple, but powerful, method is described that is based on the concept of a fractional **volume of fluid** (VOF). This method is shown to be more flexible ...

☆ 99 被引用次数: 12539 相关文章 所有 17 个版本

Several methods have been previously used to approximate free boundaries in finite-difference numerical simulations. A simple, but powerful, method is described that is based on

**In fact, VOF is one of the most popular methods for multiphase flow. It has been successfully adopted for a wide range of problems, and is still being improved and enhanced.**

**Volume of fraction (体积分数):** the basic variable in VOF

The volume fraction of each fluid in a computational cell

$$C_m = \frac{V_m}{V_{\text{cell}}}$$

$$\sum C_m = 1$$

For two-phase flow: **primary phase(主相)** and **secondary phase (次相)**。

$$C_1 = 1$$

The cell is filled with the primary phase

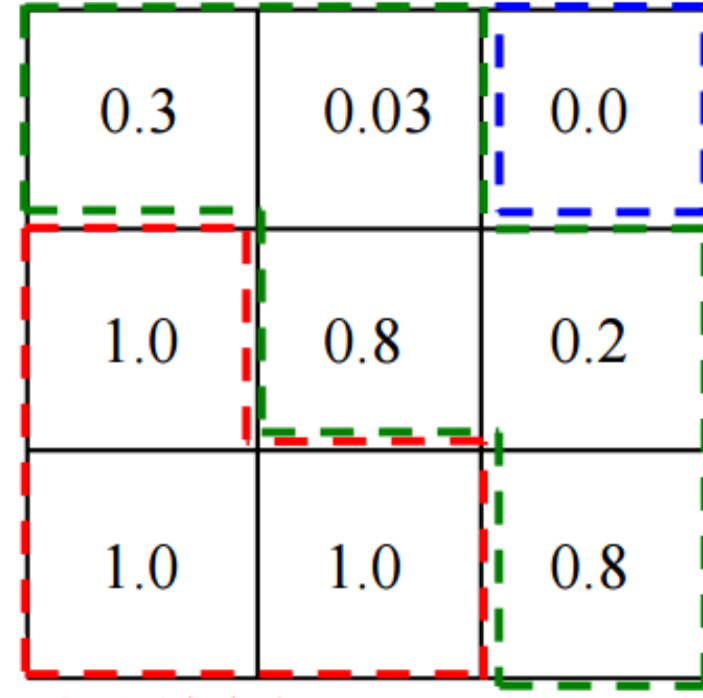
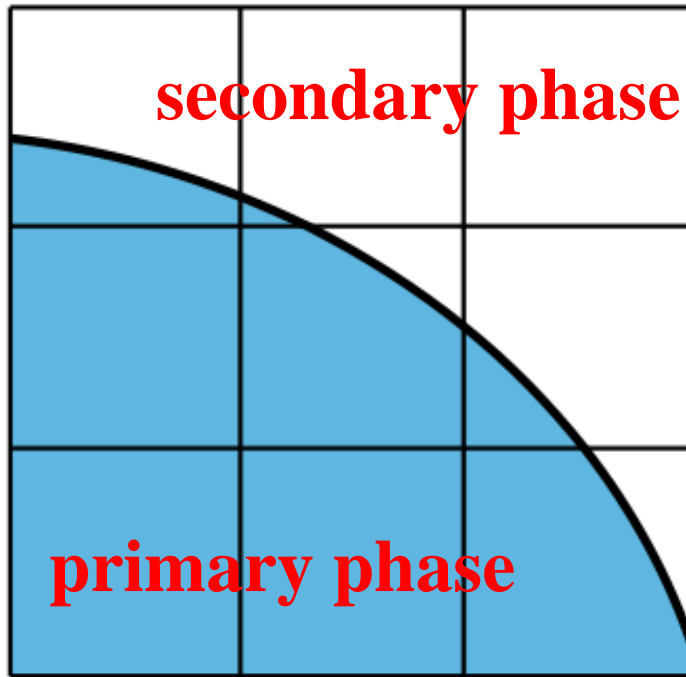
$$C_1 = 0$$

The cell is free of primary phase

$$C_1 \in (0, 1)$$

The cell is partially filled with primary phase

# Schematic of 2D two-phase flow system



$C_1 = 1$

The cell is filled with the primary phase

$C_1 = 0$

The cell is free of primary phase

$C_1 \in (0, 1)$

The cell is partially filled with primary phase

## Governing equation of $C$

1. The change of  $C$  is due to the flow in/out of the corresponding phase into a cell.
2.  $C$  is evolved according to local velocity obtained from solving the N-S equations.

$$\frac{\partial C_m}{\partial t} + \mathbf{u} \cdot \nabla C_m = 0$$

Unsteady term

Convection term

Convection-diffusion type equation

The two phases are not soluble (互溶), so there is no diffusion term. When there is chemical reaction or phase change, source term is not zero.

# The governing equations for multiphase phase flow using VOF

$$\frac{\partial(\rho)}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

Surface tension force

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

$\mathbf{u}$  from NS equation

$$\frac{\partial C_m}{\partial t} + \mathbf{u} \cdot \nabla C_m = 0$$

$$\rho = C_1 \rho_1 + C_g \rho_g \quad \mu = C_1 \mu_1 + C_g \mu_g$$

$$\mathbf{F} = 2\sigma k \frac{\rho \nabla C_1}{(\rho_1 + \rho_g)}$$

**CSF model**

Two-way coupled with each other.



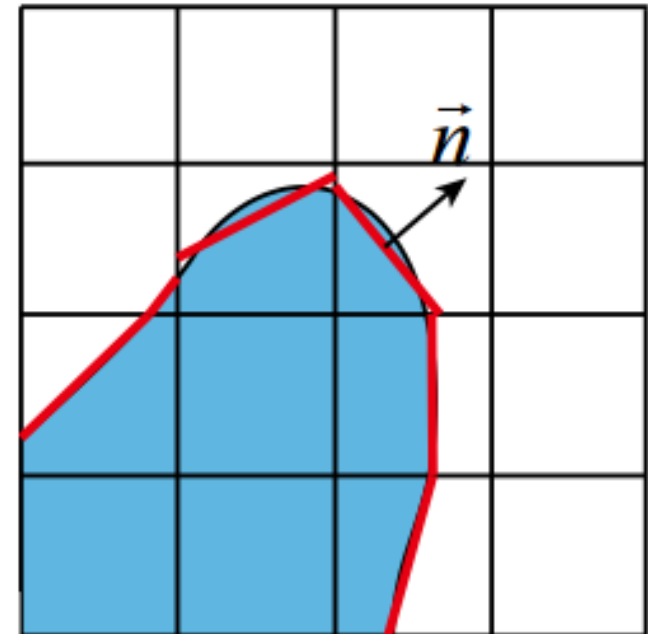
## Continuum surface force (CSF) model

The form of volumetric force is required in NS equation. However, surface tension force is a kind of surface force, rather than volumetric force.

CSF transfer the **surface tension force** to **volumetric force**

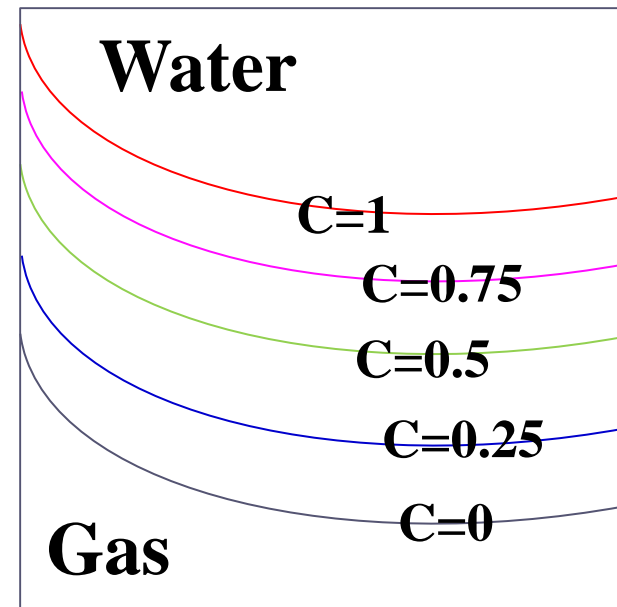
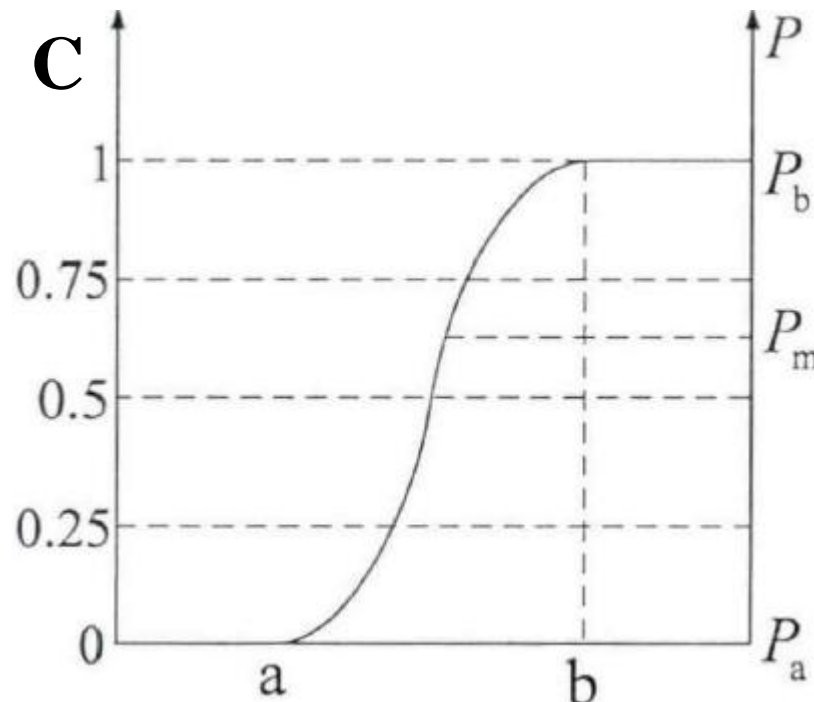
### ✓ Smooth C

- VOF in fact is a sharp-interface model.
- The **thickness of the interface is zero.**
- $C$  is sharply changed from 1 to 0 across the interface.



In microscopic, however, the interface is not sharp, it has a finite thickness, for example, of a few nanometers. Therefore, transition from phase 1 to phase 2 is smooth.

The purpose of smoothing  $C$  is to make  $C$  changes gradually from 1 to 0.



The following function is adopted to smooth  $C$

$$\tilde{C}_{i,j} = \sum_{m,n} C_{m,n} K(|\mathbf{r}_{i,j} - \mathbf{r}_{m,n}|, \varepsilon)$$

$\varepsilon$  Smoothed one

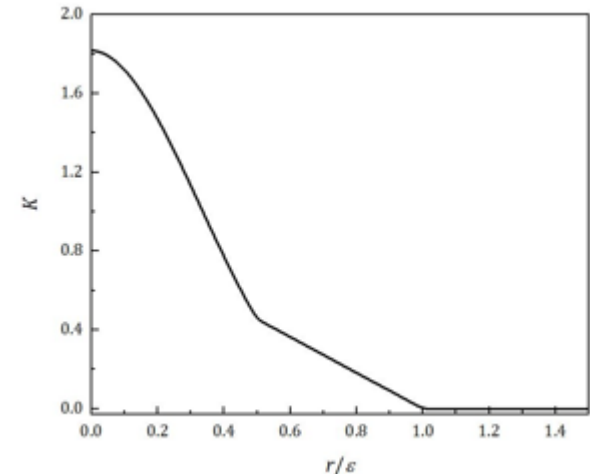
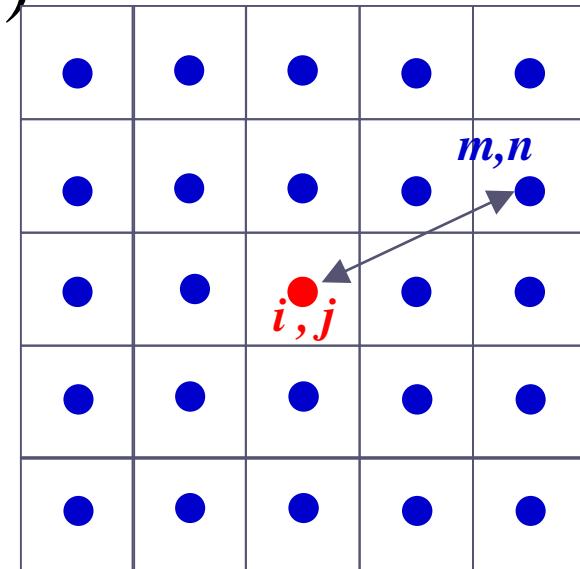
Control the thickness of the interface!  $3\Delta$

$$|\mathbf{r}_{i,j} - \mathbf{r}_{m,n}|$$

Distance between two points (i,j) and (m,n)

$K$  Smooth integration kernel

$$K(r, \varepsilon) = \begin{cases} (40/7\pi)(1 - 6(r/\varepsilon)^2 + 6(r/\varepsilon)^3) & (r/\varepsilon < 1/2) \\ (80/7\pi)(1 - r/\varepsilon) & (1/2 \leq r/\varepsilon < 1) \\ 0 & (r/\varepsilon > 1) \end{cases}$$



Smoothed  $C$ , namely  $\tilde{C}$ , is adopted to calculate force

$$\mathbf{n} = \nabla \tilde{C}$$

interface mean curvature

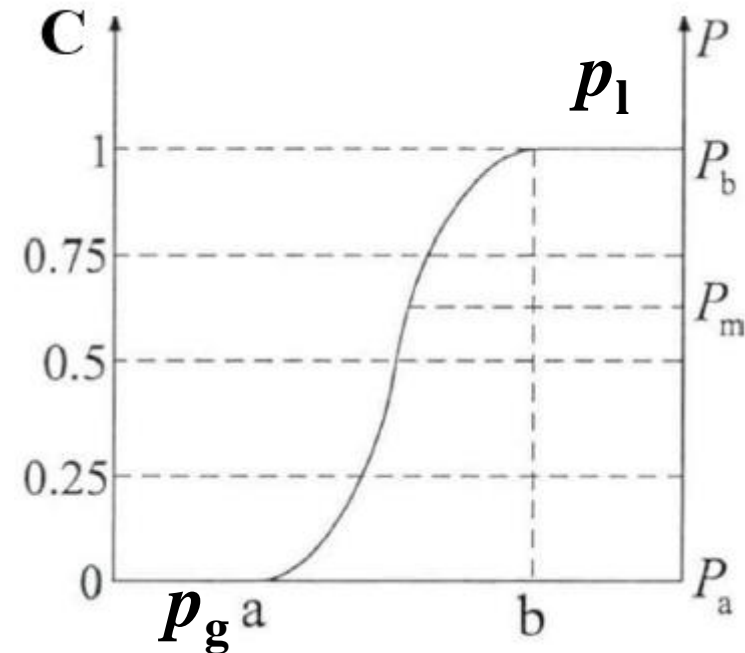
$$k = \frac{1}{r} = \nabla \cdot \left( \frac{\nabla \tilde{C}_1}{|\nabla \tilde{C}_1|} \right)$$

pressure in the transition region is

$$P_x = P_g + \sigma k (C_x - C_g) = P_g + \sigma k C_x$$

$$\begin{aligned} \mathbf{F} &\sim \nabla (P_x - P_g) = \nabla (\sigma k (C_x - C_g)) \\ &= \sigma k \nabla C \end{aligned}$$

Suppose local  $k$  is constant.

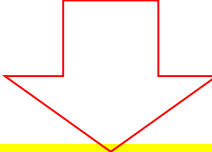


$$\mathbf{F} = 2\sigma k \frac{\rho \nabla C_1}{(\rho_1 + \rho_g)}$$

# How to solve the VOF equation?

$$\frac{\partial C_m}{\partial t} + \mathbf{u} \cdot \nabla C_m = 0$$

**Conservation form**


$$\frac{\partial C_m}{\partial t} + \nabla(\mathbf{u}C_m) = 0$$

**1. This is a convection-diffusion equation without diffusion term, and can be solved using schemes (such as QUICK) introduced in NHT.**

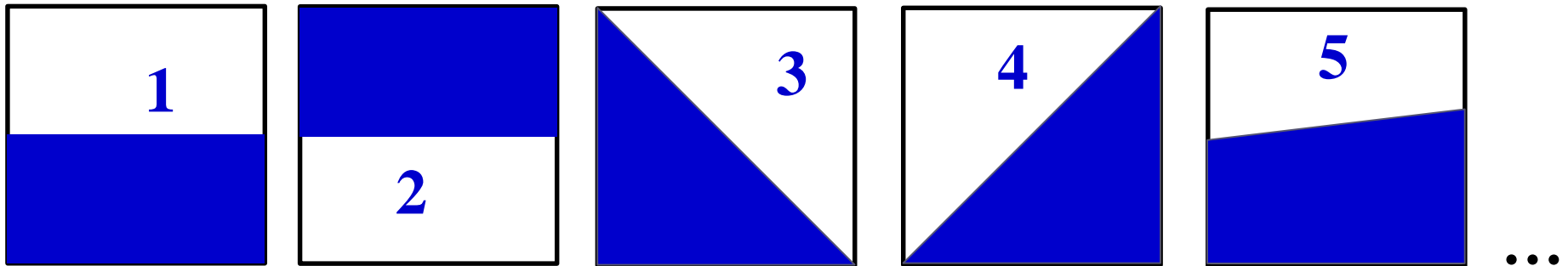
However, because  $C$  is not a continuous function. Such method may result in false diffusion, leading to gradually increasing thickness of the interface.

## 2. Reconstruction method

### Step 1. Interface reconstruction

For a value of  $C$  in a computational cell, the pattern of interface should be determined first.

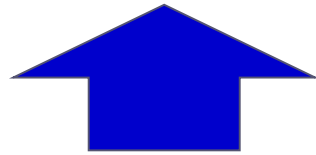
For example, for  $C=0.5$ , the interface may be as follows.



**Then which one is the right interface?**

There are totally 16 kinds of interface pattern, depending on local  $C$  and normal direction ( $nx, ny$ )

1.  $nx > 0, ny > 0$



2.  $nx > 0, ny < 0$

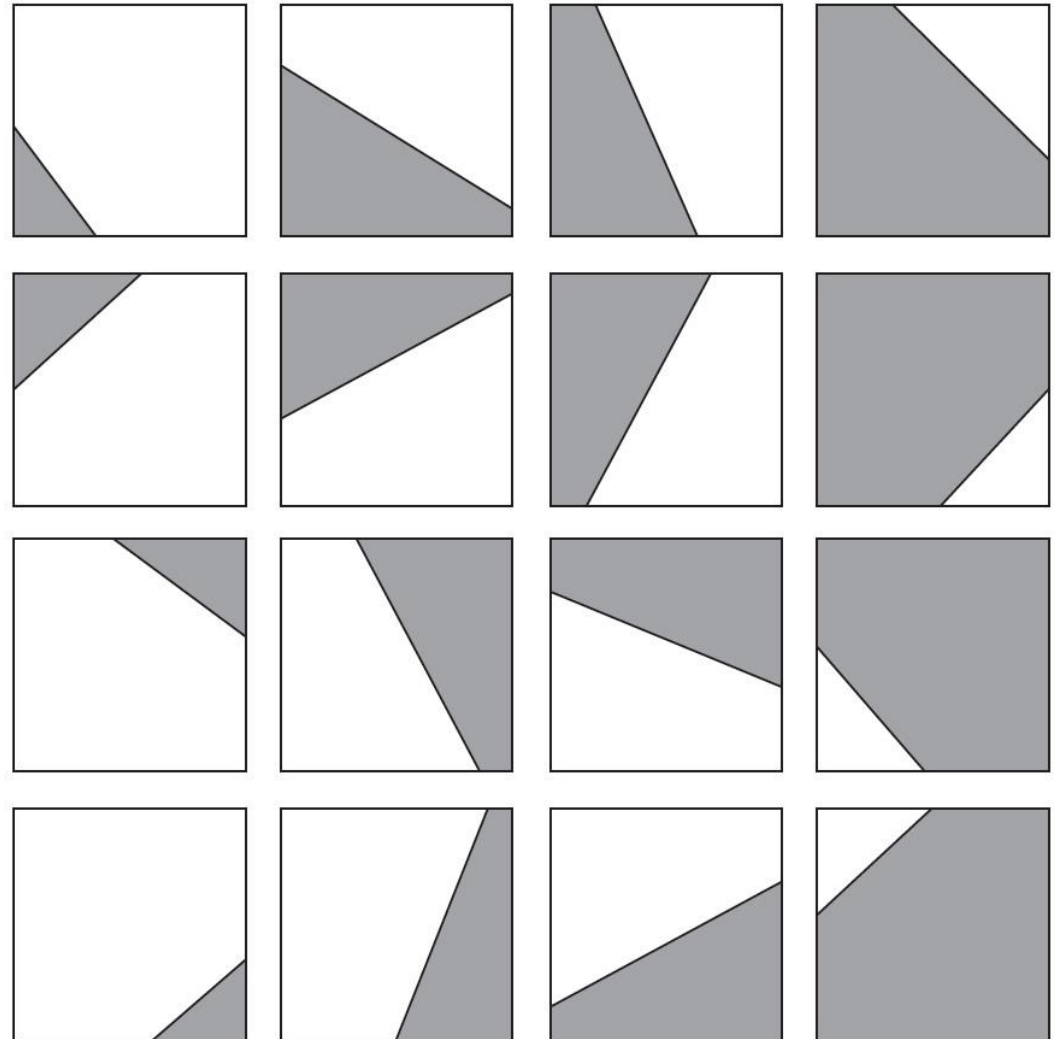
rotate

3.  $nx < 0, ny < 0$

translation

4.  $nx < 0, ny > 0$

mirroring





## Normal direction of the interface

$$n_{i,j}^x = (C_{i+1,j+1} + 2C_{i+1,j} + C_{i+1,j-1} - C_{i-1,j+1} - 2C_{i-1,j} - C_{i-1,j-1}) / \delta x$$

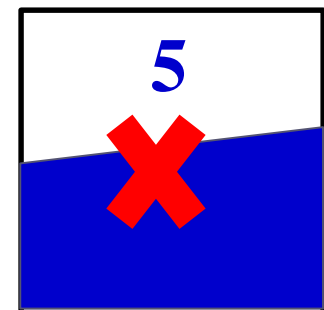
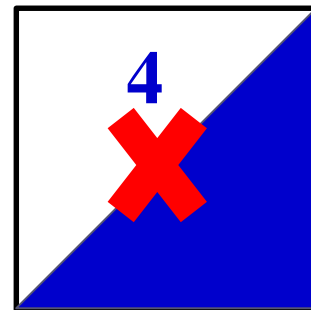
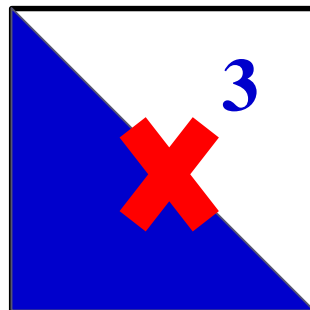
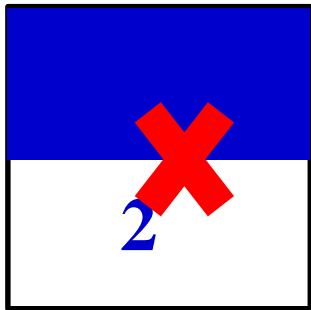
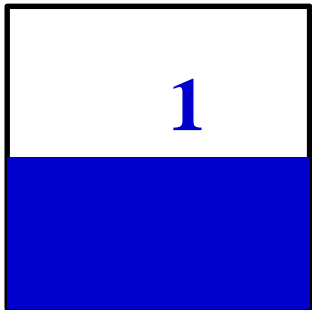
$$n_{i,j}^y = (C_{i+1,j+1} + 2C_{i,j+1} + C_{i-1,j+1} - C_{i+1,j-1} - 2C_{i,j-1} - C_{i-1,j-1}) / \delta y$$

Interface normal direction

Volume of fraction

Interface is reconstructed!

For example, for  $C=0.5$ ,  $n_x=0$ ,  $n_y=1$



...

## Normal direction of the interface

$$n_{i,j}^x = (\tilde{C}_{i+1,j+1} + 2\tilde{C}_{i+1,j} + \tilde{C}_{i+1,j-1} - \tilde{C}_{i-1,j+1} - 2\tilde{C}_{i-1,j} - \tilde{C}_{i-1,j-1}) / \delta x$$

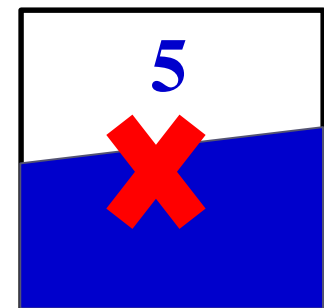
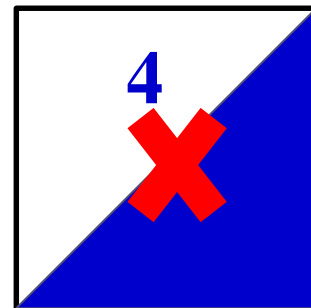
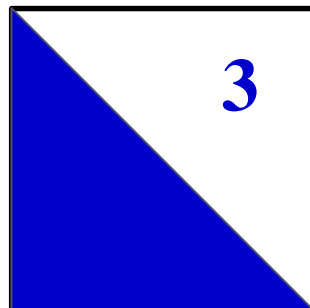
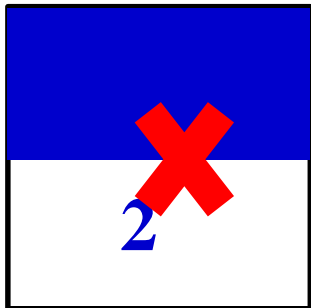
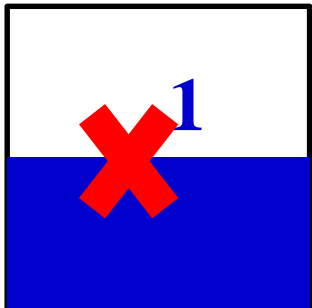
$$n_{i,j}^y = (\tilde{C}_{i+1,j+1} + 2\tilde{C}_{i,j+1} + \tilde{C}_{i-1,j+1} - \tilde{C}_{i+1,j-1} - 2\tilde{C}_{i,j-1} - \tilde{C}_{i-1,j-1}) / \delta y$$

Interface normal direction

Volume of fraction

Interface is reconstructed!

For example, for  $C=0.5$ ,  $n_x = 1/\sqrt{2}$ ,  $n_y = 1/\sqrt{2}$

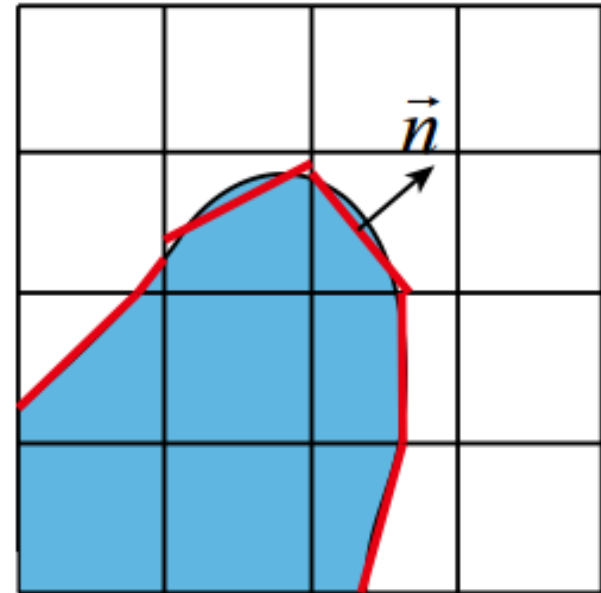


By the reconstruction scheme, the phase interface is determined in each computational cell.

## Piecewise linear interface calculation (PLIC)

The smooth interface is approximately described by a set of lines.

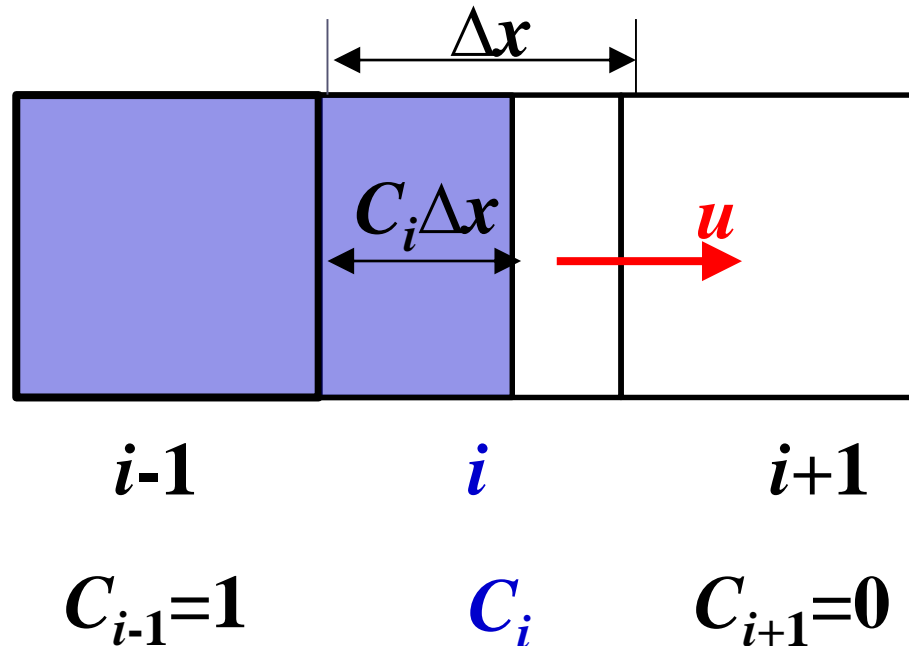
D.L. Youngs, Time-dependent multi-material flow with large fluid distortion, Numerical methods for Fluid Dynamics, 1982, 24(2), 273-285

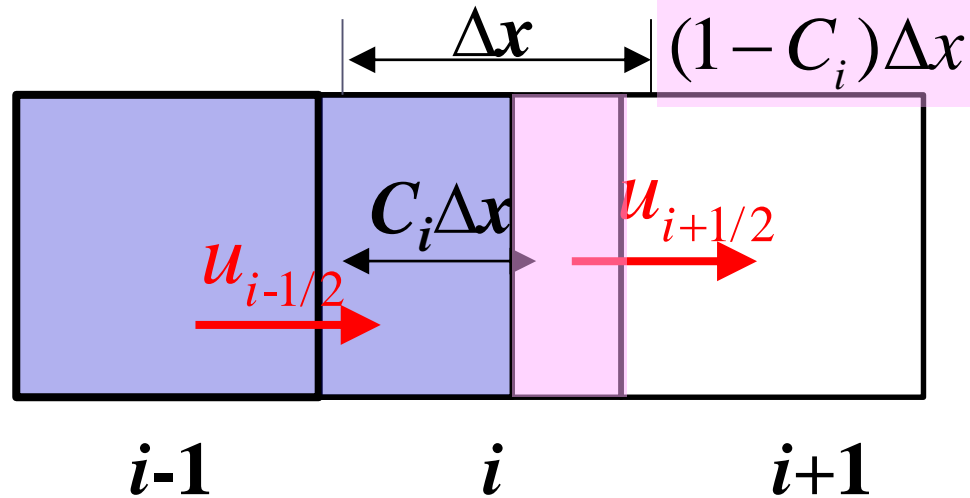


## Step 2. Interface advection in a given velocity field

Based on the reconstructed phase interface, calculate the variation of  $C$  according to local velocity field, and then update the  $C$  for next time step.

Taking 1D interface as example.





The volume that flows from  $i-1$  to  $i$  is

$$F_{i-1/2} = u_{i-1/2} \Delta t$$

The volume that flows from  $i$  to  $i+1$  is

$$F_{i+1/2} = \begin{cases} 0 & u_{i+1/2} \Delta t < (1 - C_i) \Delta x \\ u_{i+1/2} \Delta t - (1 - C_i) \Delta x & u_{i+1/2} \Delta t > (1 - C_i) \Delta x \end{cases}$$

Total volume is

$$C_i^{t+\Delta t} = C_i^t + (F_{i-1/2} - F_{i+1/2}) / \Delta x$$

## CFL condition

$$C_i^{t+\Delta t} = C_i^t + (F_{i-1/2} - F_{i+1/2}) / \Delta x$$

**Courant number**

$$u\Delta t / \Delta x$$

Because  $C$  should be smaller than 1, thus  $u\Delta t / \Delta x$  also should be smaller than 1. This is the CFL condition.

Therefore, during the numerical simulation, the time step should be sufficiently low that the CFL condition is satisfied, or **the Courant number  $< 1$** .

# The governing equations for multiphase phase flow using VOF

$$\frac{\partial(\rho)}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\mathbf{F} = 2\sigma k \frac{\rho \nabla C_1}{(\rho_1 + \rho_g)}$$

**CSF model**

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

$$\frac{\partial C_m}{\partial t} + \mathbf{u} \cdot \nabla C_m = 0$$

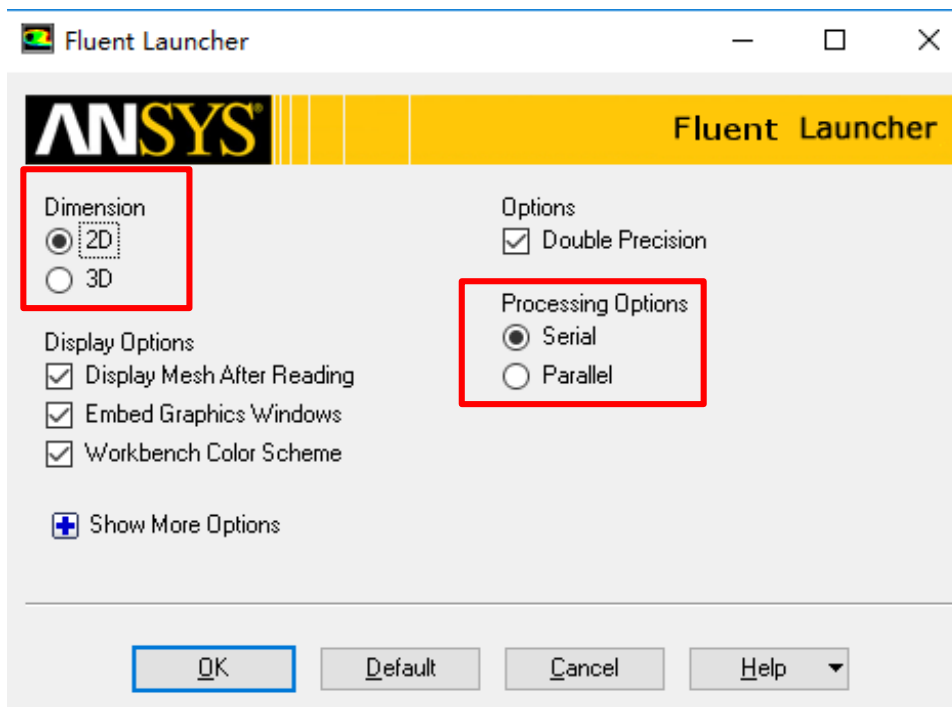
$$\rho = C_1 \rho_1 + C_g \rho_g \quad \mu = C_1 \mu_1 + C_g \mu_g$$

**Two-way coupled with each other.**



## 2 Process of simulation

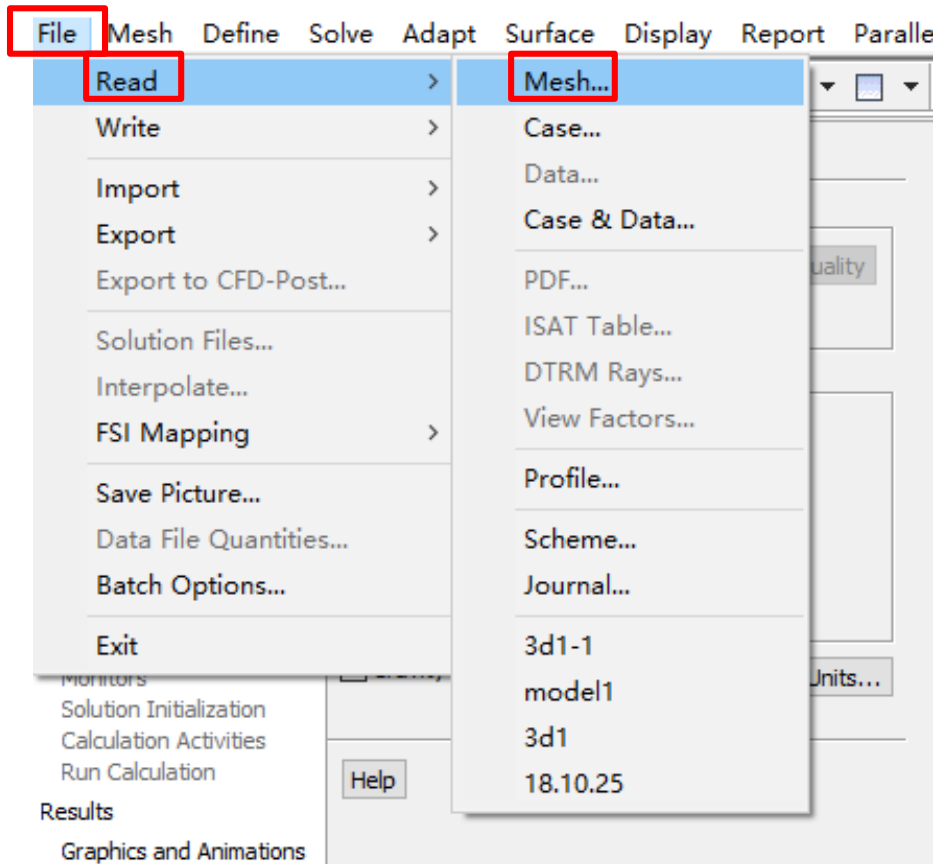
### 2.1 Launch ANSYS Fluent



- Choose **2-Dimension**
- Choose **Display Options**
- Choose **Double Precision**
- Choose **Serial Processing**

## 2.2 Read the mesh

### File → Read → Mesh



Building...

```

mesh
materials,
interface,
domains,
zones,
    water
    gdl
    wall
    air-in
    air-out
int_fluid
fluid
    
```

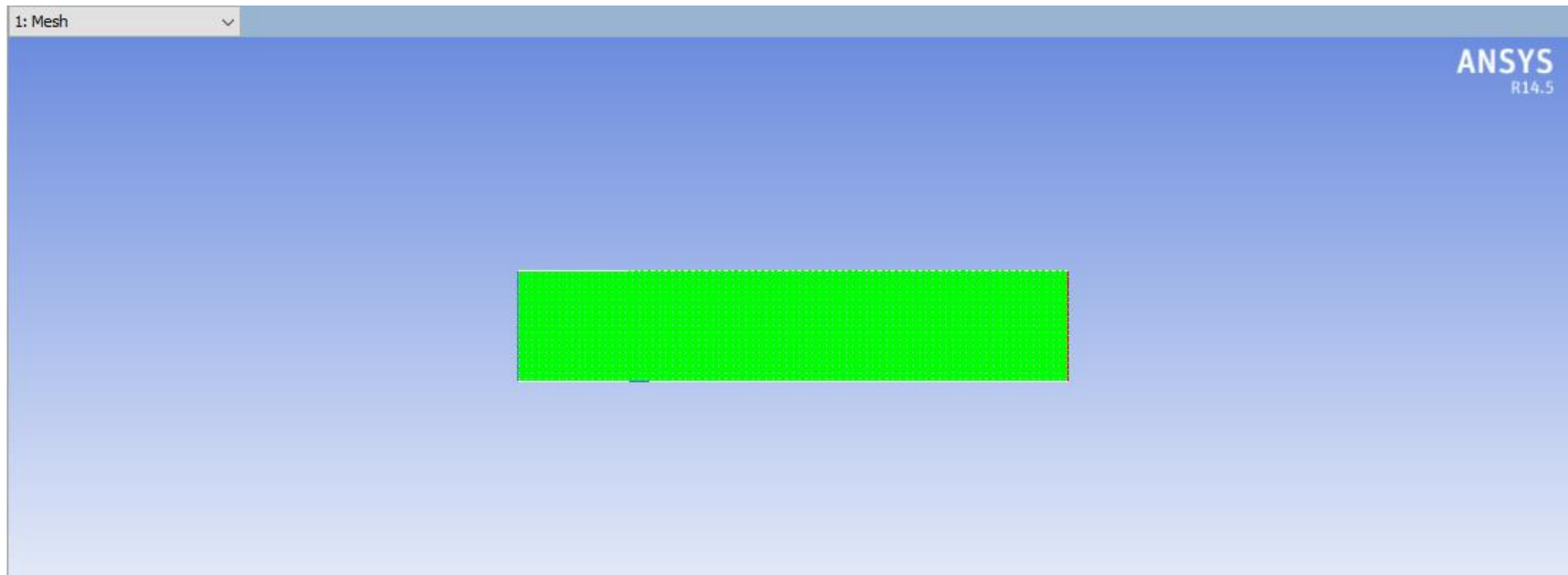
Done.

Preparing mesh for display...

Done.

## 2.3 Check the mesh

### General → Mesh → Check



#### Mesh Check

##### Domain Extents:

x-coordinate: min (m) = -3.300000e+02, max (m) = 1.170000e+03

y-coordinate: min (m) = 0.000000e+00, max (m) = 3.000000e+02

##### Volume statistics:

minimum volume (m3): 2.500000e+01

maximum volume (m3): 2.500000e+01

total volume (m3): 4.500000e+05

##### Face area statistics:

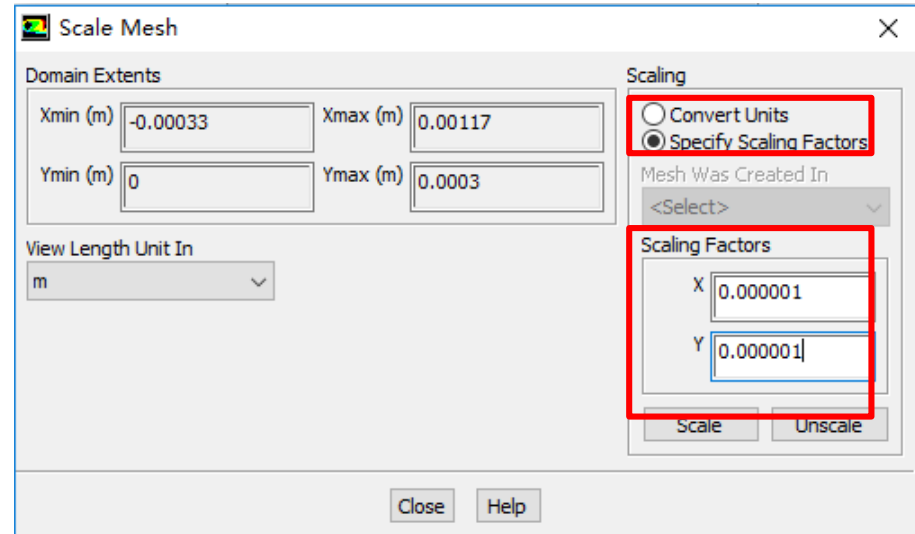
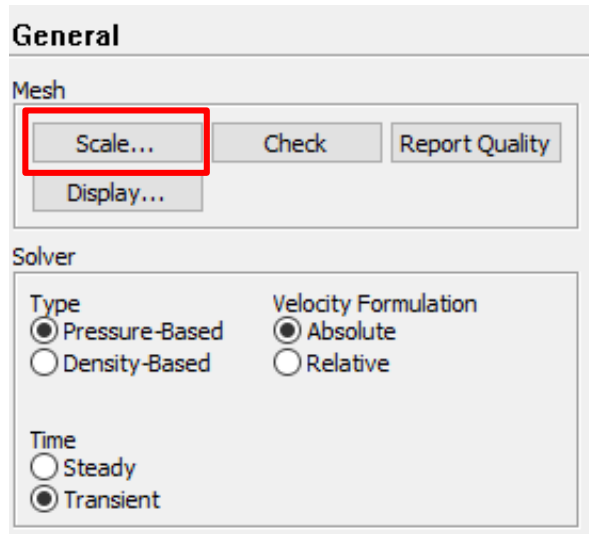
minimum face area (m2): 5.000000e+00

maximum face area (m2): 5.000000e+00

Checking mesh.....  
Done.

## 2.4 Scale the domain size

General → Mesh → Scale



- Choose **Specify Scaling Factor**

- Write **0.000001** in the **Scaling Factor** box to convert the unite from **m** to **μm**.

## 2.5 Choose the solver

### General → Solver

Solver

Type

Pressure-Based

Density-Based

Velocity Formulation

Absolute

Relative

Time

Steady

Transient

Gravity

Units...

Gravitational Acceleration

X (m/s<sup>2</sup>) 0

Y (m/s<sup>2</sup>) -9.8

Z (m/s<sup>2</sup>) 0

- Choose **Transient**

The dynamic behaviors of water is to be studied.

- Select **Gravity**

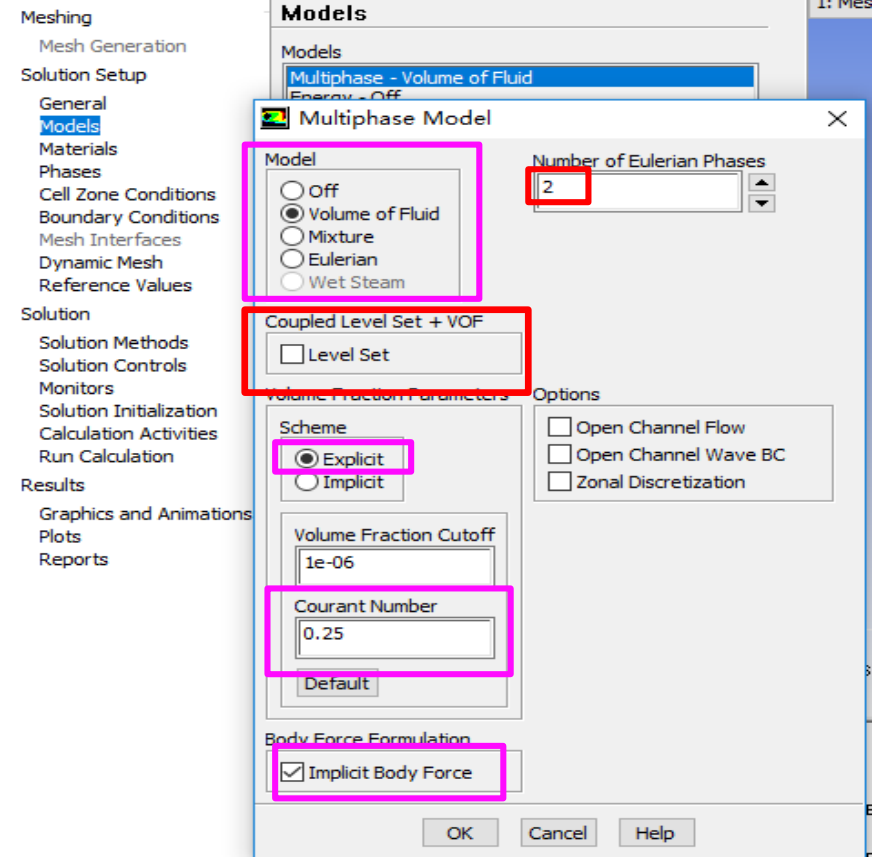
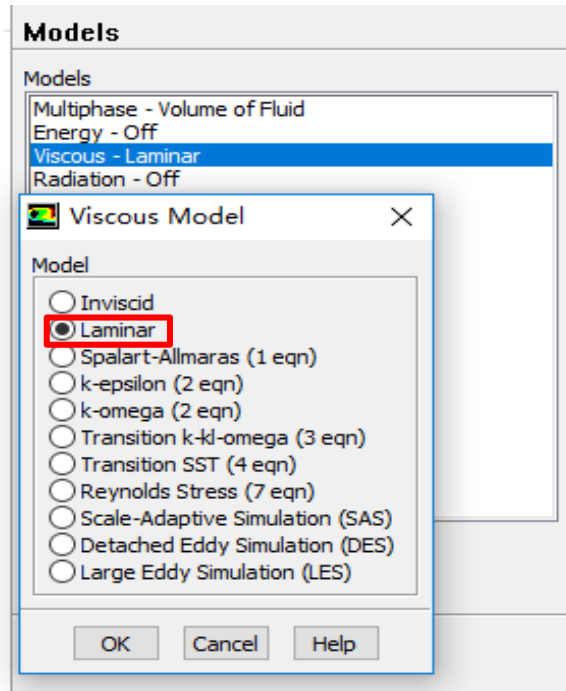
- Write **-9.8** in the Gravitational Acceleration box of Y.

**Density-based method cannot be used for VOF.**

## 2.6 Choose the models

### Solution Setup → Models

Meshing  
 Mesh Generation  
 Solution Setup  
 General  
**Models**  
 Materials  
 Phases  
 Cell Zone Conditions  
 Boundary Conditions  
 Mesh Interfaces  
 Dynamic Mesh  
 Reference Values  
 Solution  
 Solution Methods  
 Solution Controls  
 Monitors  
 Solution Initialization  
 Calculation Activities  
 Run Calculation  
 Results  
 Graphics and Animations  
 Plots  
 Reports



■ Choose **Volume of Fluid** as **Multiphase Model**

■ **Coupled Level set +VOF?**

## Coupled Level Set +VOF

**Spatial gradient (interface curvature and surface tension force)**

LS function is smooth and continuous, accurate!

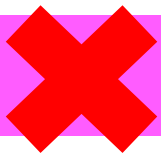
Advantages



VOF is discontinuous across the interface, not accurate



**Mass conservation**



LS is not good.

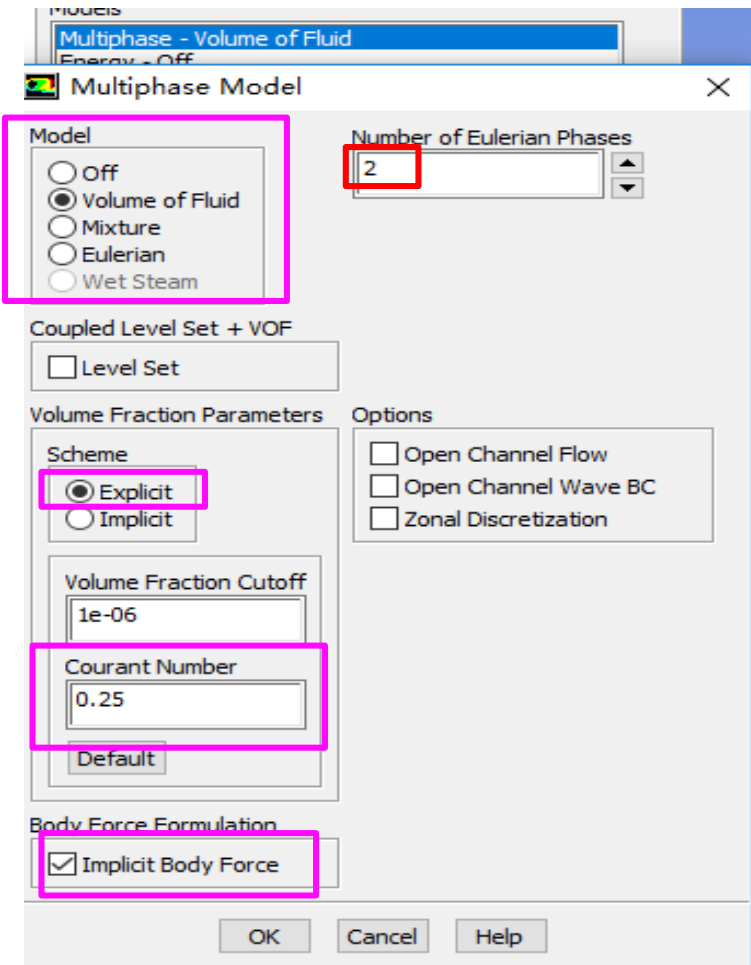
VOF is good.



Combining the advantages of LS and VOF

## 2.6 Choose the models

### Body force formulation



Large body forces (for example, gravity or surface tension forces) are included.

Implicit body force is adopted to improve solution convergence by accounting for the partial equilibrium of the pressure gradient and surface tension forces.



# Forces in Momentum equation

**Multiphase flow is controlled by a set of forces.**

**Inertial force**

**Viscous force**

**Body force**

$$\frac{\partial(\rho\mathbf{u})}{\partial t} + \nabla \cdot (\rho\mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot [\mu(\nabla\mathbf{u} + \nabla\mathbf{u}^T)] + \rho\mathbf{g} + 2\sigma k \frac{\rho\nabla C_1}{(\rho_1 + \rho_g)}$$

**Pressure**

**gravity**

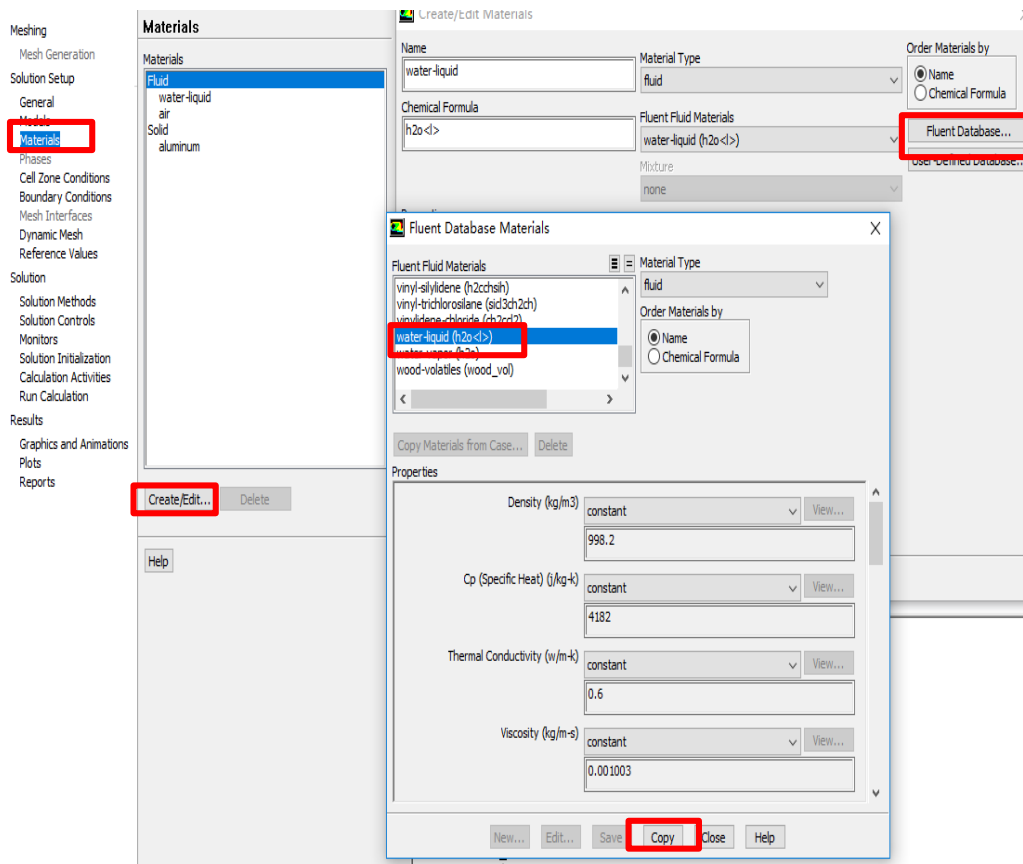
**Surface  
tension  
force**

\* Here surface tension force is converted to body force using CSF.

## 2.7 Define the materials

**Solution Setup → Materials → Create/Edit Material**

### ■ Create water-liquid



The screenshot shows the ANSYS Fluent interface. On the left, the 'Materials' panel is active, with 'Materials' highlighted. The 'Create/Edit Materials' dialog box is open, showing the following settings:

- Name: water-liquid
- Material Type: fluid
- Chemical Formula: h2o<->
- Fluent Fluid Materials: water-liquid (h2o<->)
- Mixture: none

The 'Fluent Database Materials' dialog box is also open, showing a list of materials. 'water-liquid (h2o<->)' is selected. The 'Properties' section shows the following values:

- Density (kg/m<sup>3</sup>): constant, 998.2
- Cp (Specific Heat) (J/kg-K): constant, 4182
- Thermal Conductivity (W/m-K): constant, 0.6
- Viscosity (kg/m-s): constant, 0.001003

The 'Copy' button at the bottom of the 'Fluent Database Materials' dialog is highlighted.

1. Click **Fluent Database**
2. Choose **water-liquid**
3. Click **Copy**

## 2.8 Define the phases

### Solution Setup → Phases

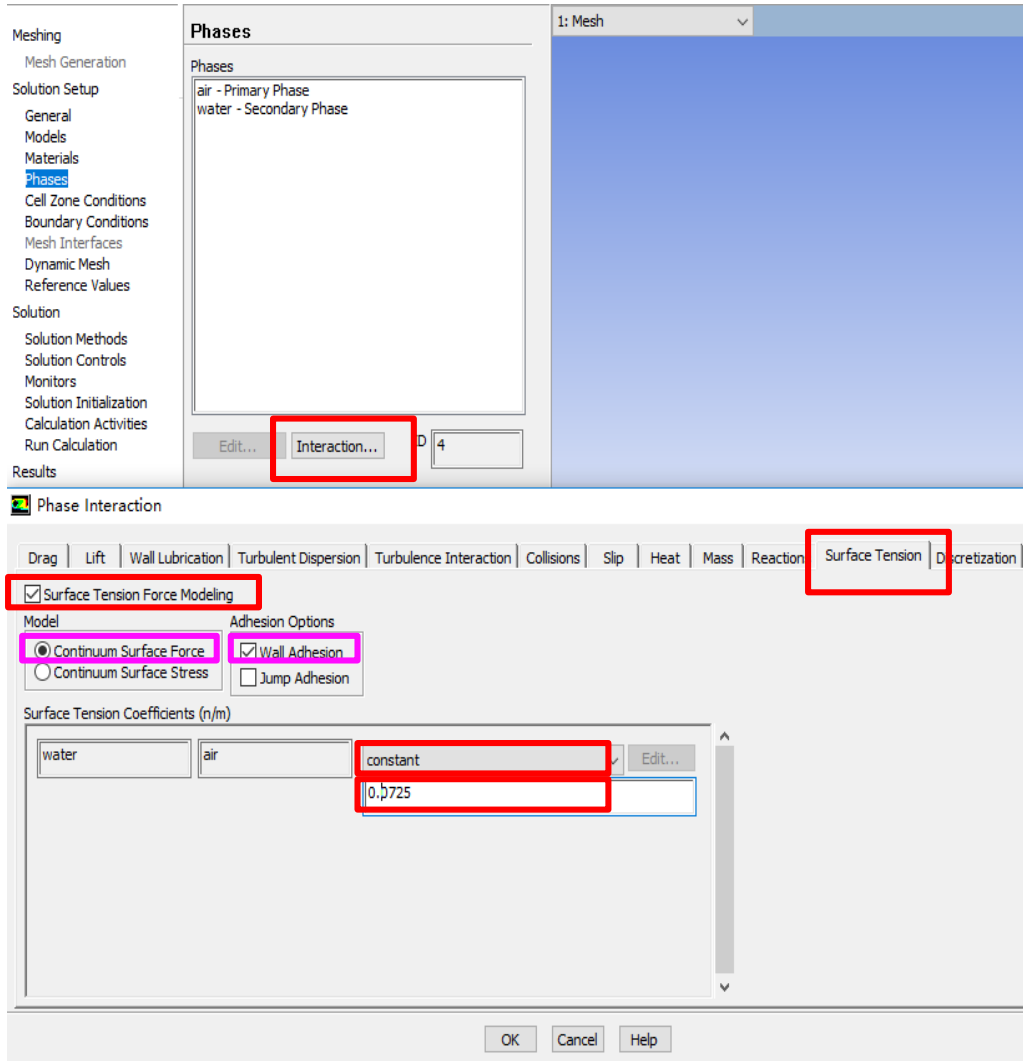
- Choose **air** as Primary Phase
- Choose **water-liquid** as Secondary Phase

The image displays two screenshots of the ANSYS Fluent software interface, specifically the 'Phases' dialog box. The left screenshot shows the 'Primary Phase' dialog with 'air' selected as the phase material. The right screenshot shows the 'Secondary Phase' dialog with 'water' as the name and 'water-liquid' as the phase material. Red boxes highlight the relevant fields in both dialog boxes.

**Primary phase is usually set as the one dominated in the computational domain.**

## 2.8 Define the phases

### Define surface tension force

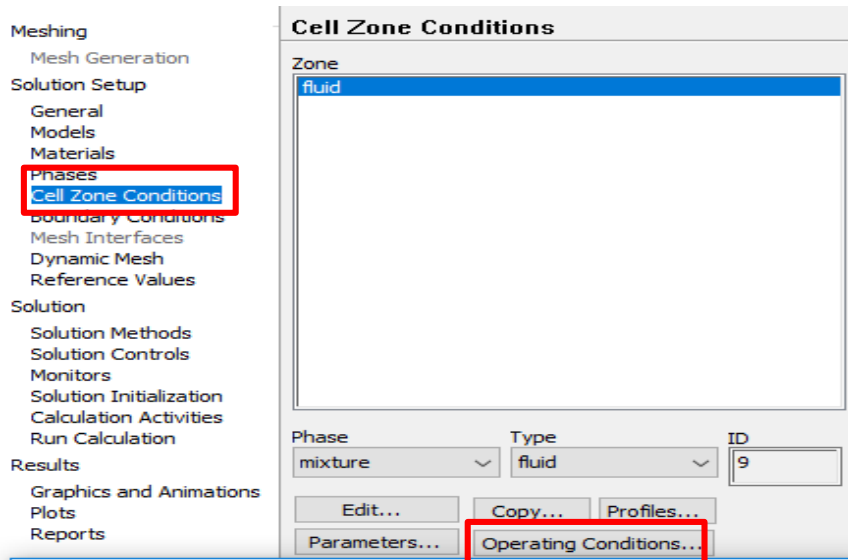


The screenshot shows the ANSYS Fluent interface. In the 'Phases' panel, 'air - Primary Phase' and 'water - Secondary Phase' are listed. The 'Interaction...' button is highlighted with a red box. Below, the 'Phase Interaction' panel is shown with 'Surface Tension' selected in the top bar. The 'Surface Tension Force Modeling' checkbox is checked. Under 'Model', 'Continuum Surface Force' is selected. Under 'Adhesion Options', 'Wall Adhesion' is checked. In the 'Surface Tension Coefficients (n/m)' section, 'constant' is selected for the model, and the value '0.0725' is entered in the text box.

1. Click Interaction
2. Click Surface Tension
3. Select Surface Tension Force Modeling
4. Choose Continuum Surface Force and Wall Adhesion.
5. Choose constant and write 0.0725.

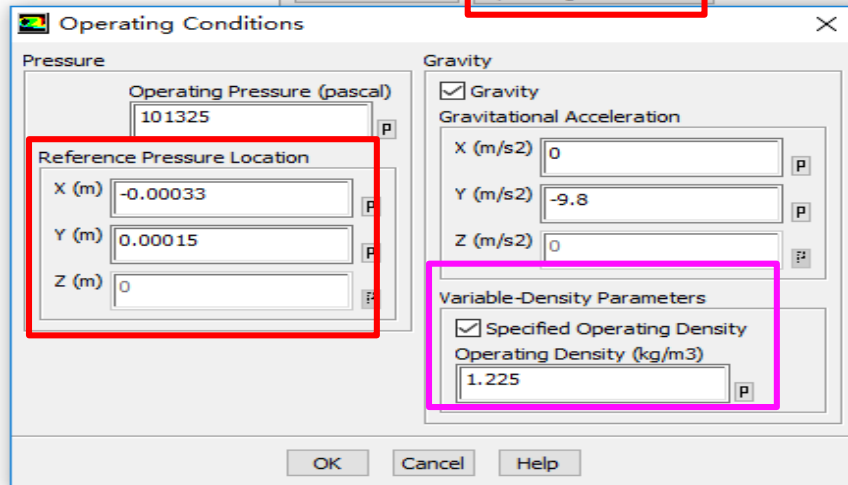
## 2.9 Define cell zone conditions

Solution Setup → Cell Zone Condition → Operating Conditions



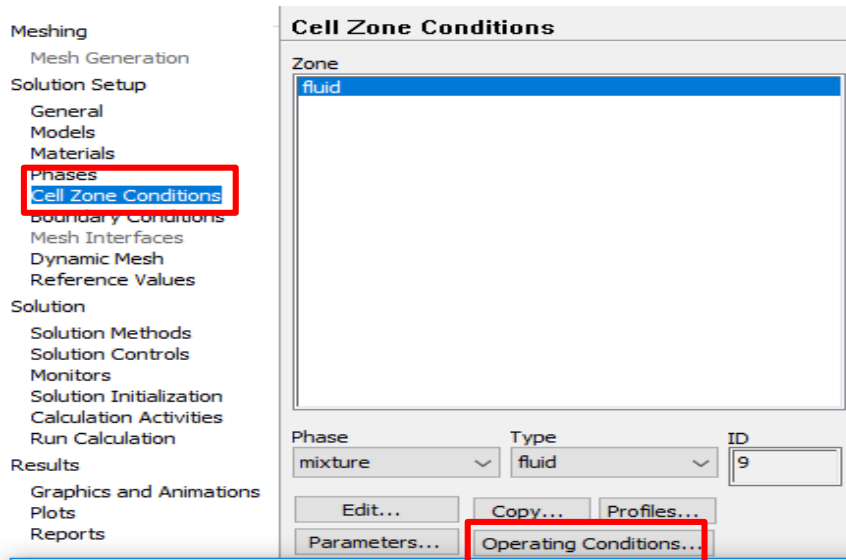
**Operating pressure**

- In Fluent, operating pressure is the same as reference pressure.
- Input location and value of operating pressure.



## 2.9 Define cell zone conditions

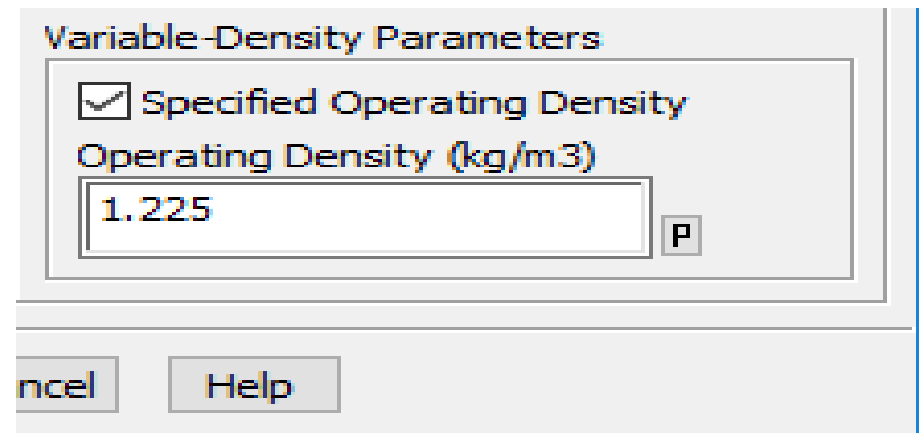
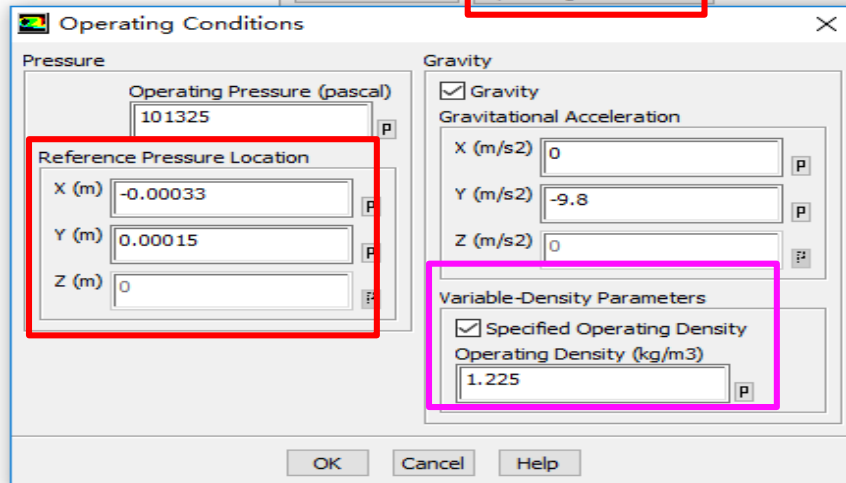
**Solution Setup → Cell Zone Condition → Operating Conditions**



**Specified operating density**

**Set the operating density to be the density of the lightest phase.**

**Here input the density of the air.**



## 2.10 Define the boundary conditions

### Solution Setup → Boundary Condition

Phase	Type	ID
mixture	velocity-inlet	12

**Velocity Inlet**

Zone Name: air-in      Phase: mixture

Momentum | Thermal | Radiation | Species | DPM | Multiphase | UDS

Velocity Specification Method: Magnitude, Normal to Boundary

Reference Frame: Absolute

Velocity Magnitude (m/s): 5      constant

Supersonic/Initial Gauge Pressure (pascal): 0      constant

OK    Cancel    Help

- For the left inlet, pure air flows into the domain.
- Velocity inlet is adopted for the mixture.
- Volume fraction of each phase should be given.

Phase	Type	ID
water	velocity-inlet	12

**Velocity Inlet**

Zone Name: air-in      Phase: water

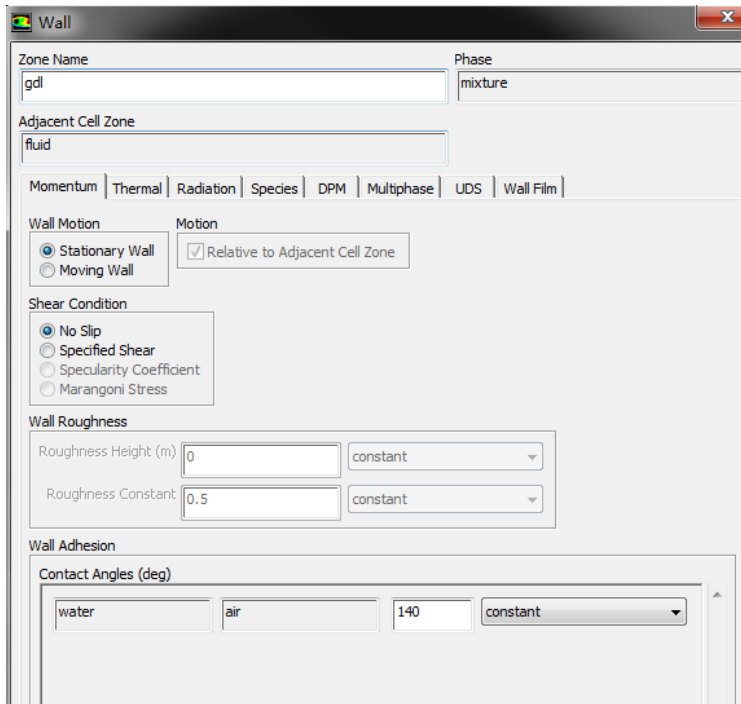
Momentum | Thermal | Radiation | Species | DPM | Multiphase | UDS

Volume Fraction: 0      constant

OK    Cancel    Help

## 2.10 Define the boundary conditions

For the top and bottom surface, Define contact angle



- Choose wall as Type
- Input value of the contact angle 140°
- The angle is measured by water here.

### Wall Adhesion

#### Contact Angles (deg)

water

air

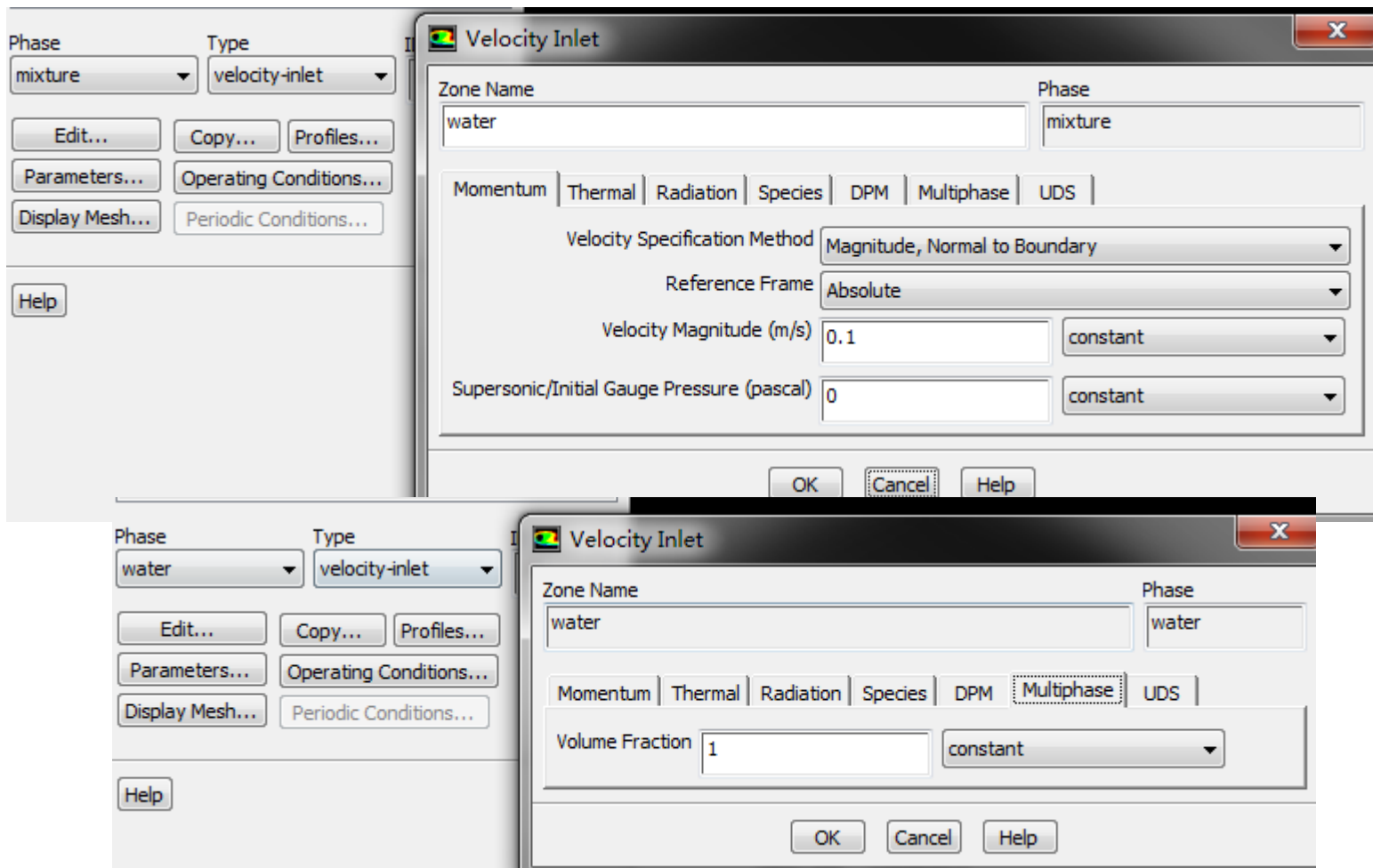
140

constant



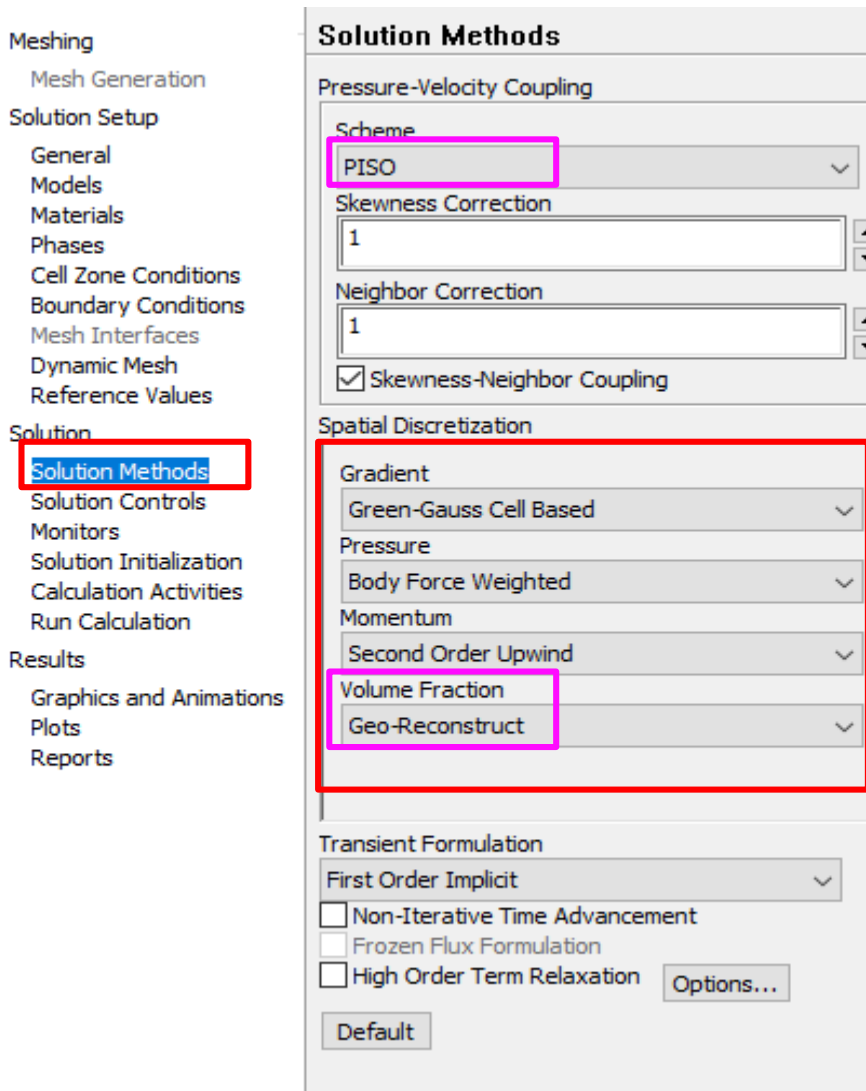
## 2.10 Define the boundary conditions

For the water inlet, define velocity inlet condition; define the volume fraction of water as 1.



## 2.11 Choose the solution methods

### Solution → Solution Methods



The screenshot shows the ANSYS Fluent 'Solution Methods' dialog box. The 'Solution' tab is selected in the left-hand tree. The 'Scheme' dropdown is set to 'PISO'. The 'Skewness Correction' and 'Neighbor Correction' are both set to '1', and 'Skewness-Neighbor Coupling' is checked. The 'Spatial Discretization' section is highlighted with a red box, showing 'Gradient' set to 'Green-Gauss Cell Based', 'Pressure' set to 'Body Force Weighted', 'Momentum' set to 'Second Order Upwind', and 'Volume Fraction' set to 'Geo-Reconstruct'. The 'Transient Formulation' section is set to 'First Order Implicit'.

- Choose PISO (Scheme)
- Choose Green-Gauss Cell Based (Gradient)
- Choose Body Force Weighted (Pressure)
- Choose Second Order Upwind (Momentum)
- Choose Geo-Reconstruct (Volume Fraction)

# The Pressure-Implicit with Splitting of Operators (PISO)

The PISO also belongs to the family of SIMPLE.

There are **one time of prediction step (预估)** and **correction step (校正)** in SIMPLEC.

**Prediction step:** determine  $u^*$  and  $v^*$  based on  $u^0$  and  $v^0$

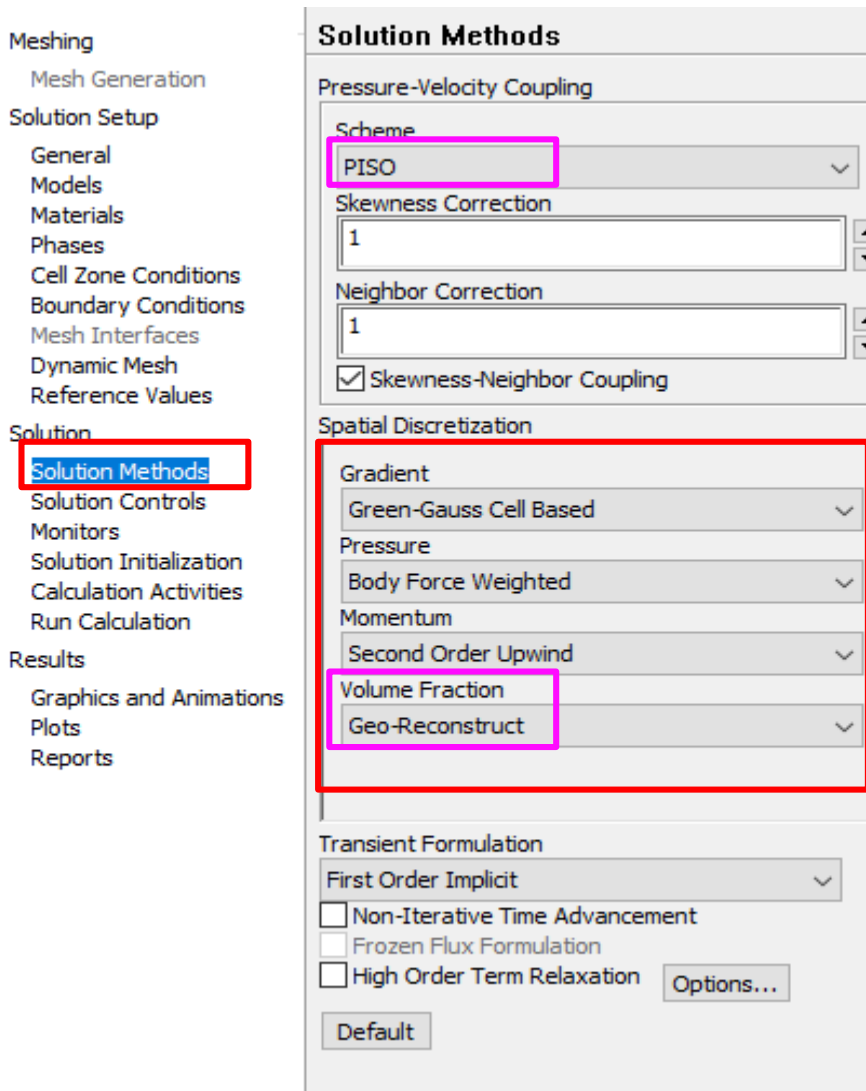
**Correction step:** solve pressure correction, obtain  $u$  and  $v$  that satisfying the Mass Conservation Equation.

In PISO, two times of correction steps are conducted, thus improving the convergence.

**PISO is recommended for transient problem.**

## 2.11 Choose the solution methods

### Solution → Solution Methods



The screenshot shows the ANSYS Fluent 'Solution Methods' dialog box. The 'Solution' tab is selected in the left-hand tree. The 'Scheme' dropdown is set to 'PISO'. The 'Skewness Correction' and 'Neighbor Correction' are both set to '1'. The 'Skewness-Neighbor Coupling' checkbox is checked. The 'Spatial Discretization' section is highlighted with a red box, and the 'Volume Fraction' dropdown is highlighted with a pink box. The 'Transient Formulation' section is at the bottom, with 'First Order Implicit' selected and 'Non-Iterative Time Advancement', 'Frozen Flux Formulation', and 'High Order Term Relaxation' unchecked.

- Choose PISO (Scheme)
- Choose Green-Gauss Node Based (Gradient)
- Choose Body Force Weighted (Pressure)
- Choose Second Order Upwind (Momentum)
- Choose Geo-Reconstruct (Volume Fraction)

## Gradient calculation

1. **Green-Gauss Cell-Based (格林-高斯基于单元法)**
2. **Green-Gauss Node-Based (格林-高斯基于节点法)**
3. **Least-Squares Cell Based 基于单元体的最小二乘法**

**It is the default scheme for gradient calculation.**

**The former two are based on Green-Gauss Theory**

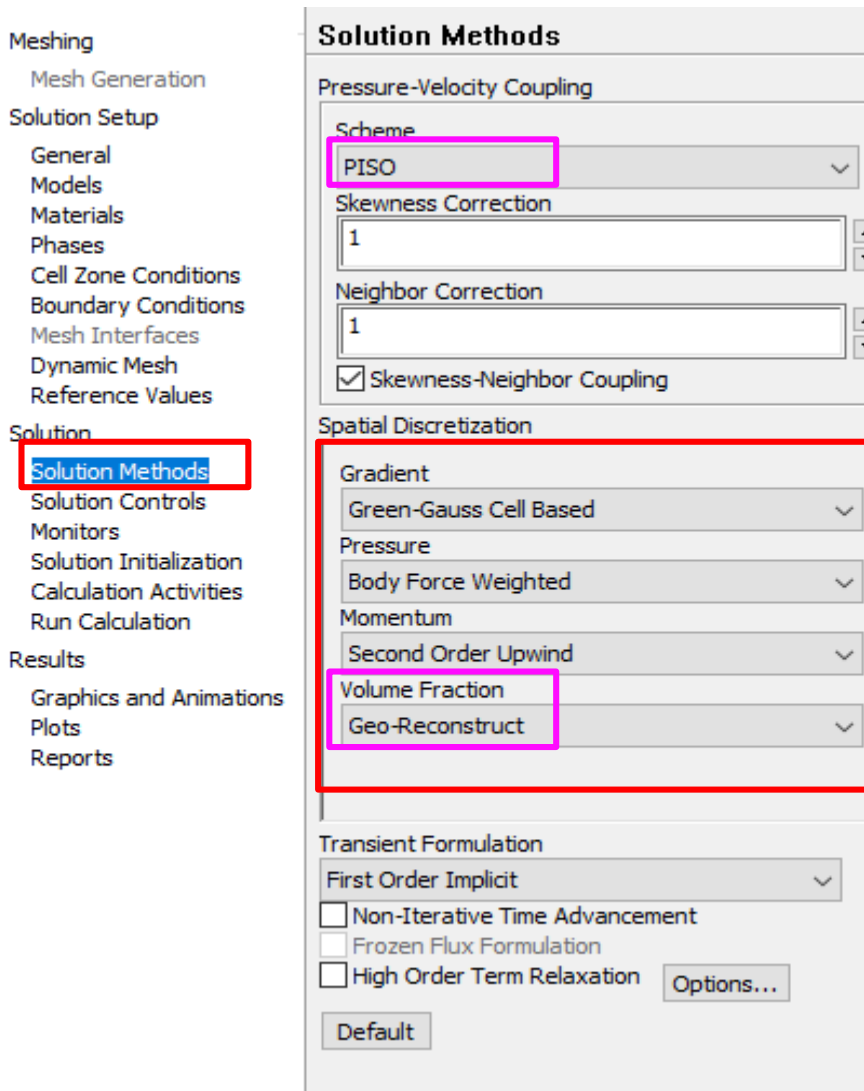
$$\langle \nabla \phi \rangle = \frac{1}{V_C} \int_{V_C} \nabla \phi dV = \frac{1}{V_C} \int \phi \cdot \mathbf{n} dS = \sum \phi_f \cdot \mathbf{n} S$$

**The least-square cell based is based on**

$$\xi = \sum_{i=1}^N \left\{ w_i \left( \phi_{Ci} - \phi_{C0} - \left[ \frac{\partial \phi}{\partial x} \Delta x_i + \frac{\partial \phi}{\partial y} \Delta y_i + \frac{\partial \phi}{\partial z} \Delta z_i \right] \right)^2 \right\}$$

## 2.11 Choose the solution methods

### Solution → Solution Methods



The screenshot shows the ANSYS Fluent Solution Methods panel. The left sidebar has 'Solution Methods' highlighted in red. The main panel is divided into sections: Pressure-Velocity Coupling, Spatial Discretization, and Transient Formulation. In the Pressure-Velocity Coupling section, 'Scheme' is set to 'PISO' (highlighted in pink), 'Skewness Correction' is '1', 'Neighbor Correction' is '1', and 'Skewness-Neighbor Coupling' is checked. In the Spatial Discretization section, 'Gradient' is 'Green-Gauss Cell Based', 'Pressure' is 'Body Force Weighted', 'Momentum' is 'Second Order Upwind', 'Volume Fraction' is 'Geo-Reconstruct' (highlighted in pink), and 'Geo-Reconstruct' is also highlighted in pink. In the Transient Formulation section, 'First Order Implicit' is selected, and 'Non-Iterative Time Advancement', 'Frozen Flux Formulation', and 'High Order Term Relaxation' are unchecked.

- Choose PISO (Scheme)
- Choose Green-Gauss Node Based (Gradient)
- Choose Body Force Weighted (Pressure)
- Choose Second Order Upwind (Momentum)
- Choose Geo-Reconstruct (Volume Fraction)

# Pressure calculation

1. Linear scheme

2. Standard scheme

3. Second Order

4. Body Force Weighted scheme

Calculate the pressure according to the body force.

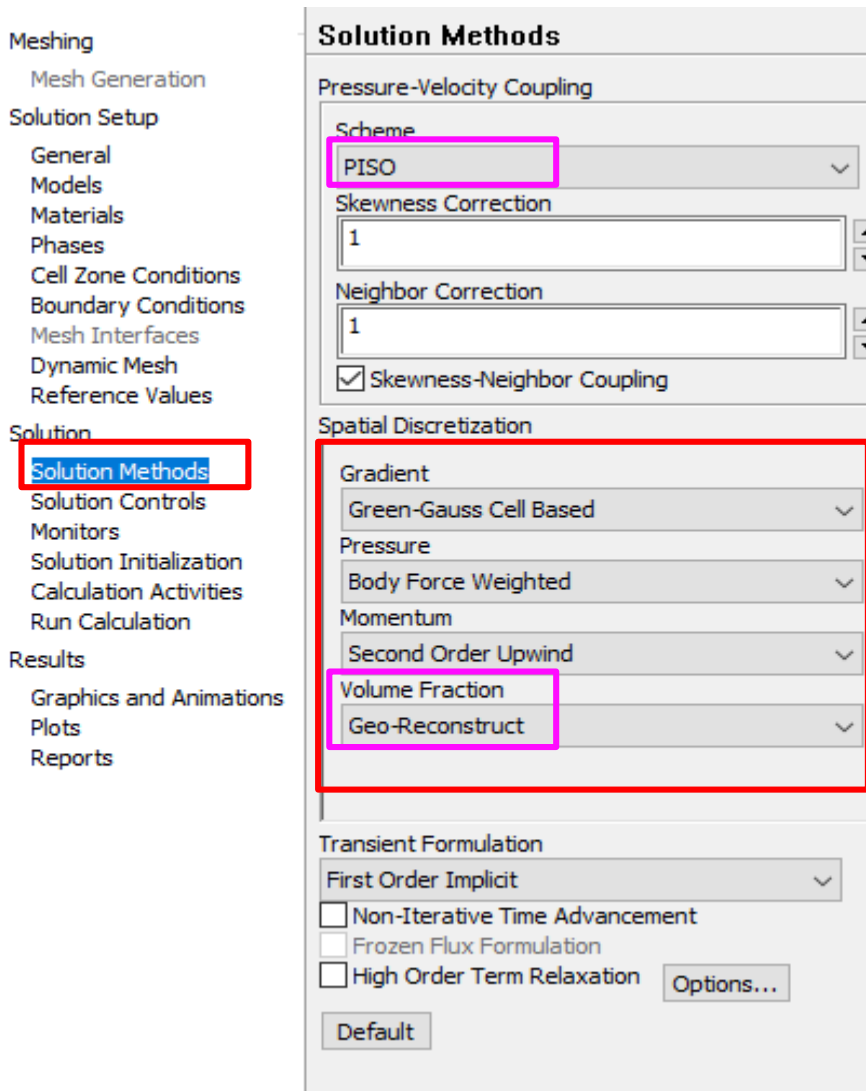
- ✓ Multiphase flow such as VOF (Volume of Fluid, 体积分函数法) or LS (Level Set, 水平集): **recommended.**
- ✓ For porous media: **not recommended!**

5. **PRESTO!** (Pressure Staggering Option) scheme

For problem with high pressure gradient.

## 2.11 Choose the solution methods

### Solution → Solution Methods



The screenshot shows the ANSYS Fluent 'Solution Methods' panel. The 'Solution' menu item is highlighted in red. The 'Solution Methods' sub-menu is also highlighted in red. The 'Scheme' dropdown is set to 'PISO'. The 'Skewness Correction' and 'Neighbor Correction' are both set to '1'. The 'Skewness-Neighbor Coupling' checkbox is checked. The 'Spatial Discretization' section is highlighted in red, with 'Volume Fraction' and 'Geo-Reconstruct' highlighted in pink. The 'Transient Formulation' section is also visible, with 'First Order Implicit' selected and 'Non-Iterative Time Advancement', 'Frozen Flux Formulation', and 'High Order Term Relaxation' unchecked.

- Choose PISO (Scheme)
- Choose Green-Gauss Node Based (Gradient)
- Choose Body Force Weighted (Pressure)
- Choose Second Order Upwind (Momentum)
- Choose Geo-Reconstruct (Volume Fraction)



## Solving methods for VOF equation

The geometric reconstruction interpolation scheme is recommended when time-accurate transient behaviors of the multiphase are required. In other words, it can accurately predict the sharp interface.

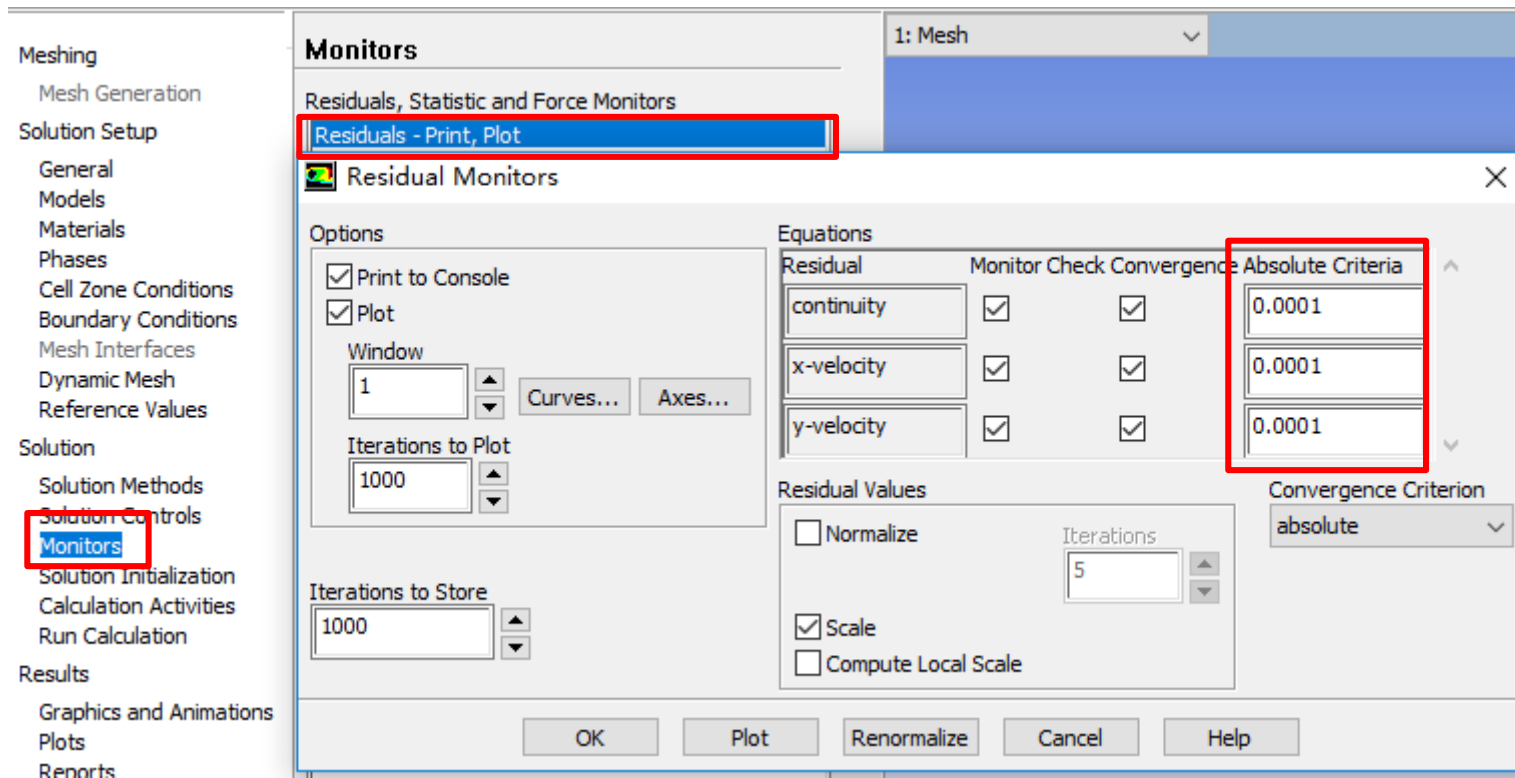
This scheme is the most accurate and is applicable for general unstructured meshes.

Modified HRIC, Compressive, and CICSAM schemes are less computationally expensive than the Geo-Reconstruct scheme, the interface between phases will not be as sharp as the geometric reconstruction interpolation scheme.

## 2.12 Define the monitors

### Solution → Monitors

- Define the **Residuals Monitor** and write **0.0001** in the **Absolute Criteria** box



The screenshot shows the ANSYS Fluent interface with the **Monitors** dialog box open. The **Residuals - Print, Plot** option is selected in the **Monitors** list. The **Residual Monitors** dialog box is also open, showing the following settings:

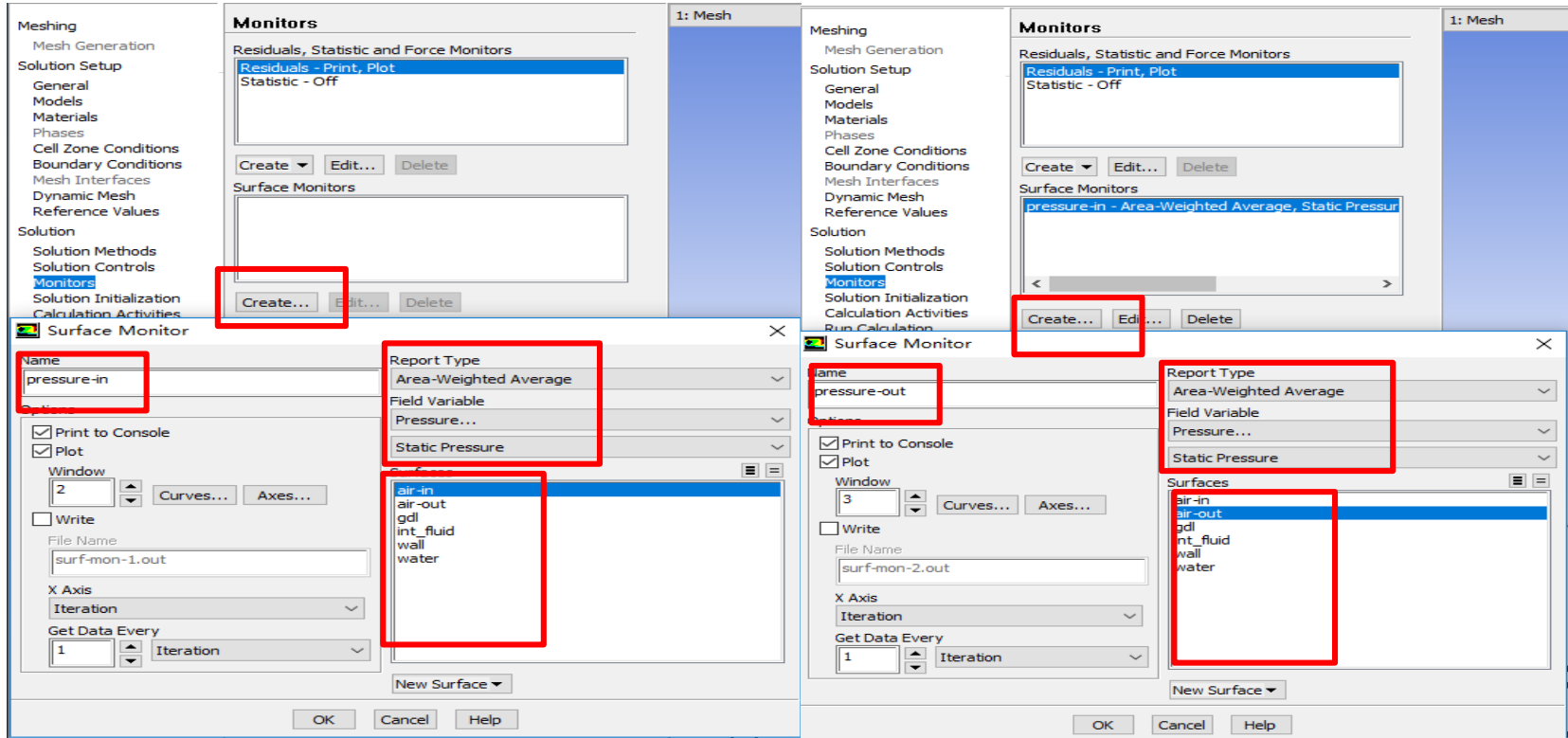
- Options:**
  - Print to Console
  - Plot
  - Window: 1
  - Iterations to Plot: 1000
  - Iterations to Store: 1000
- Equations:**

Residual	Monitor	Check	Convergence	Absolute Criteria
continuity	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	0.0001
x-velocity	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	0.0001
y-velocity	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	0.0001
- Residual Values:**
  - Normalize
  - Scale
  - Compute Local Scale
  - Iterations: 5
- Convergence Criterion:** absolute

The **Absolute Criteria** values for continuity, x-velocity, and y-velocity are all set to 0.0001, which is highlighted with a red box in the image.

## 2.12 Define the monitors

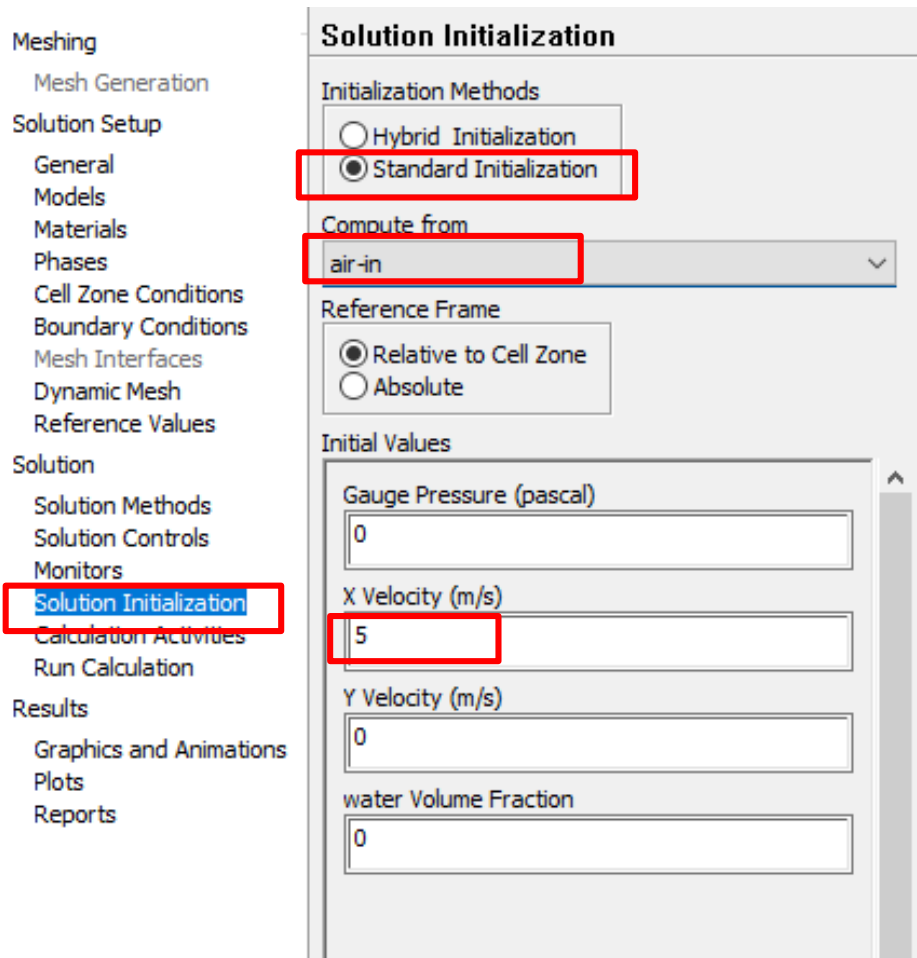
### ■ Create the Surface Monitor



1. Change the **Name**
2. Choose the **Report Type** and **Surface**

## 2.13 Initialize

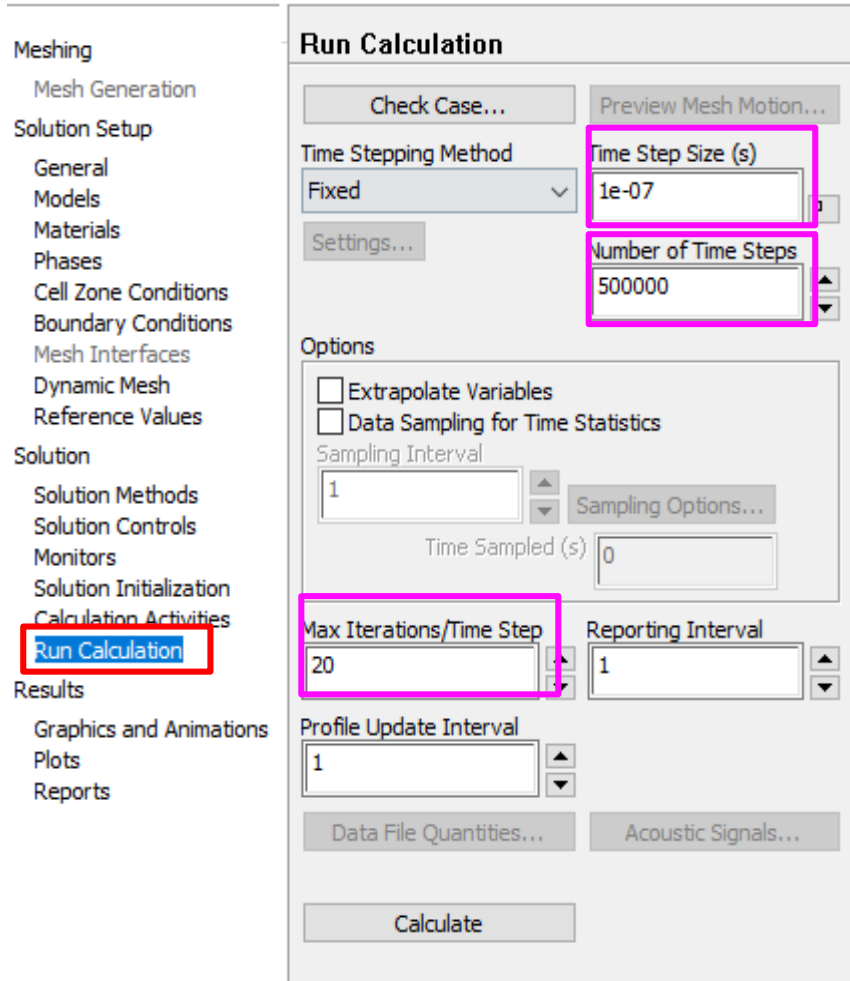
### Solution → Solution Initialization



- Choose Standard Initialization
- Choose air-in
- Click Initialize

## 2.14 Run calculation

### Solution → Run Calculation



- Write **Number** in **Time Step Size** box
- Write **Number** in **Number of Time Step** box according to situations
- Write **Number** in **Max Iterations** according to situations

## 2.14 Run calculation

- **Time Step Size(s)** sets the magnitude of the (physical) time step  $\Delta t$ . **Courant number  $< 1$  should be satisfied.**
- **Number of Time Steps** sets the number of time steps to be performed.
- **Max Iterations/Time Step** sets the maximum number of iterations to be performed per time step. If the convergence criteria are met before this number of iterations is performed, the solution will advance to the next time step.

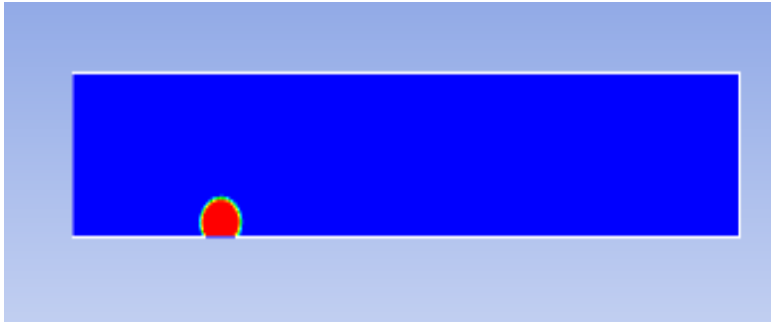
# Summary

- 1.Read mesh**
- 2.Check mesh**
- 3.Scale domain**
- 4.Choose solver (transient, gravity)**
- 5.Choose model (VOF, explicit, courant number, implicit body force)**
- 6.Define material (water-liquid)**
- 7.Define phase (primary phase, secondary phase, interaction, surface tension, wall adhesion)**

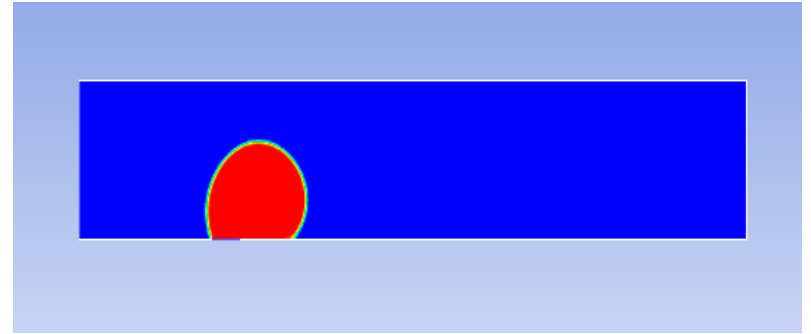
- 8. Define operating condition (reference pressure location, specified operating density)**
- 9. Define boundary condition (volume fraction, contact angle)**
- 10. Choose solution method (PISO, Green-Gauss cell based, Body force weighted )**
- 11. Define monitor (residuals monitor, surface monitor)**
- 12. Initialize (standard initialization)**
- 13. Run the simulation (time step size)**
- 14. Post-process**



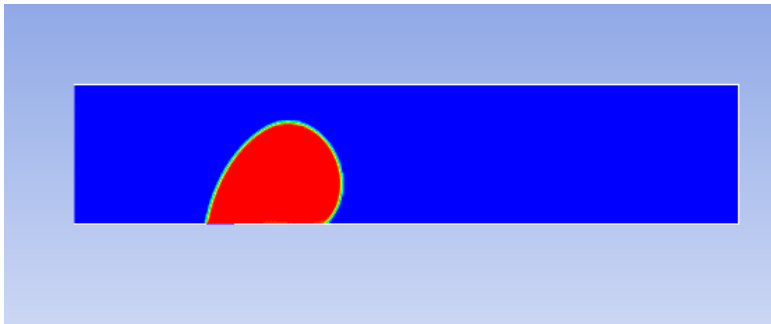
# 3 Results



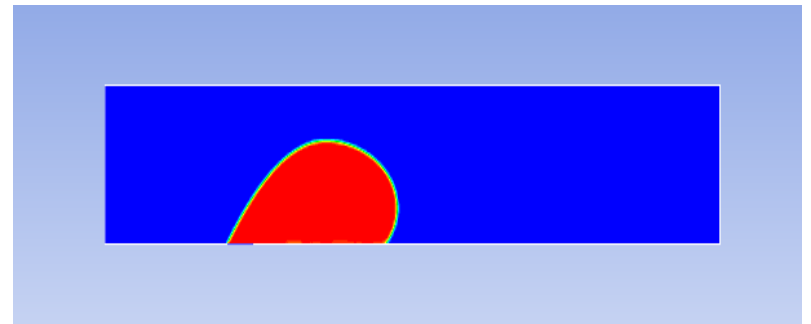
$T=8.868e-4$



$T=5.7064e-3$



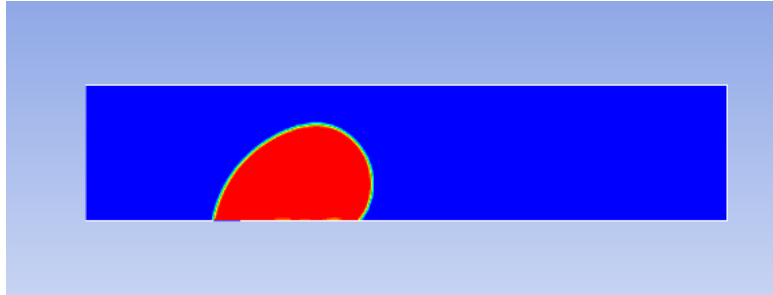
$T=8.5285e-3$



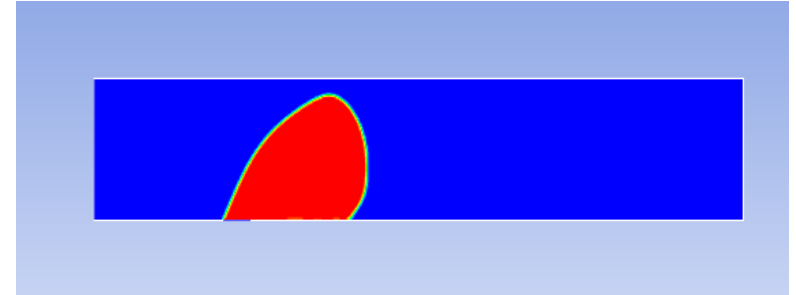
$T=9.9285e-3$

**Fig.2 water behavior**

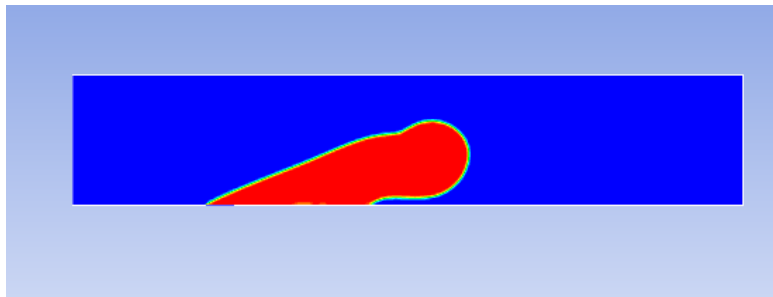
### 3 Results



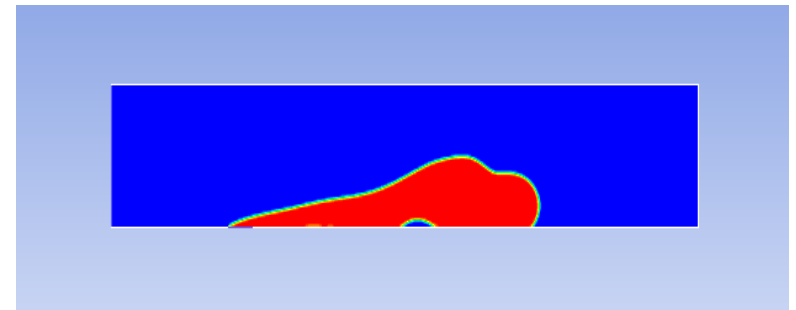
$T=1.1028e-2$



$T=1.0328e-2$

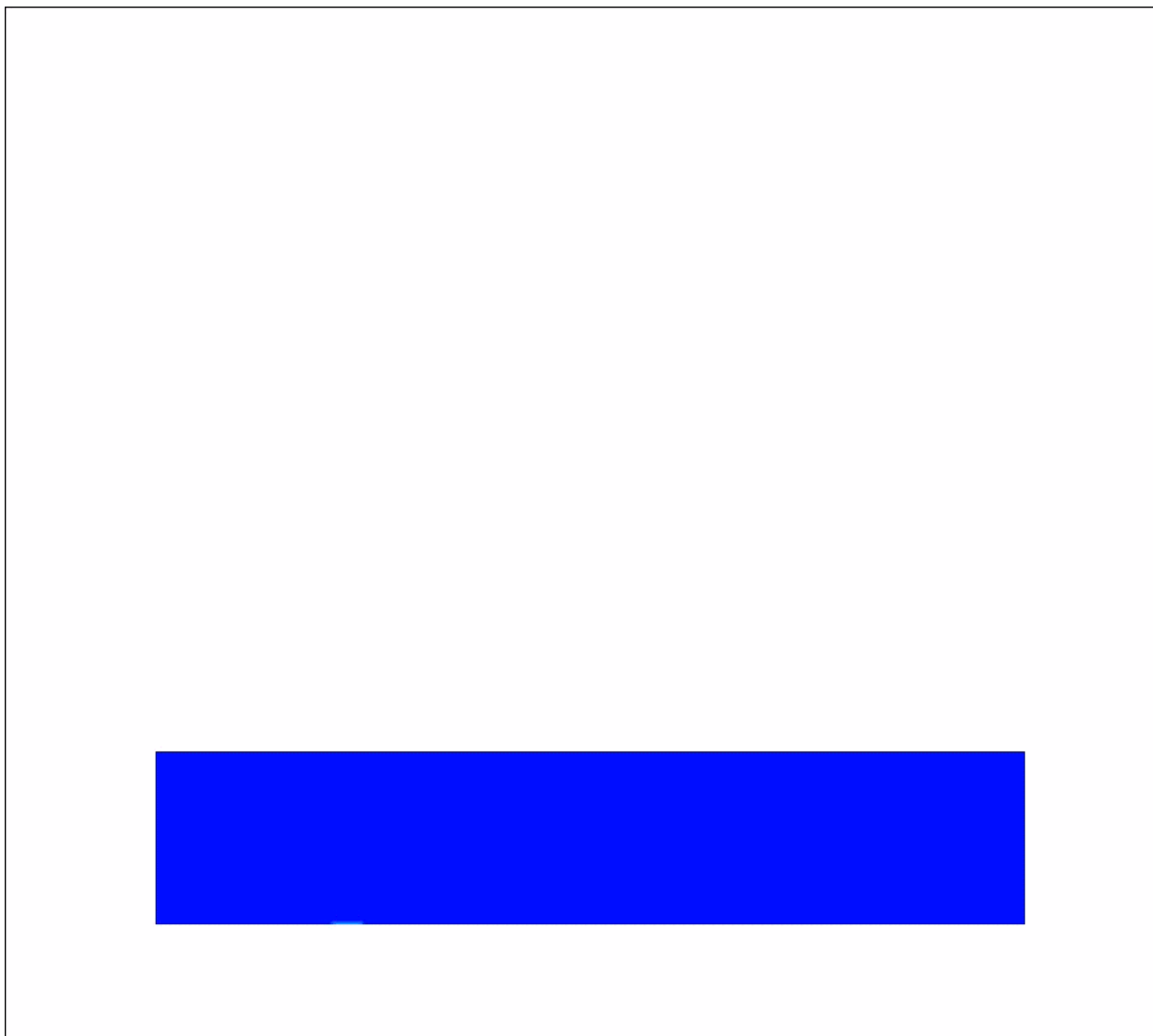


$T=1.0529e-2$

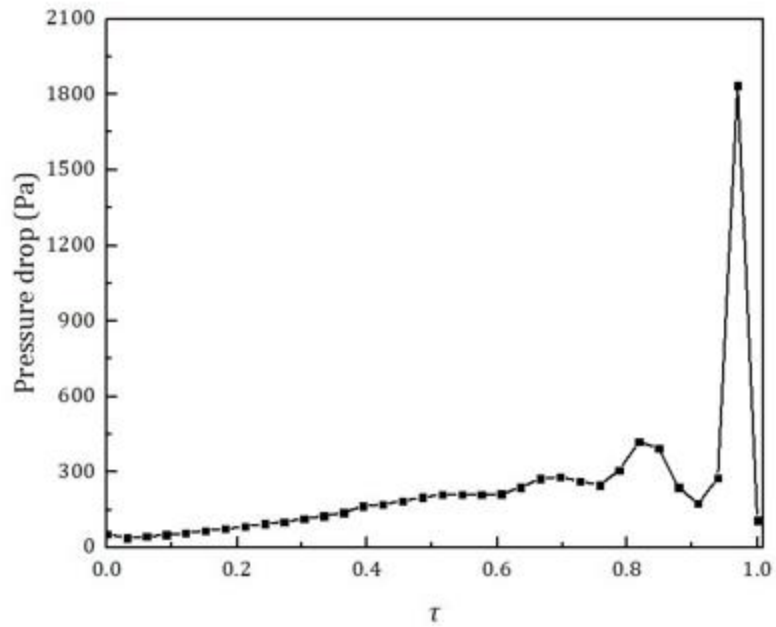


$T=1.0729e-2$

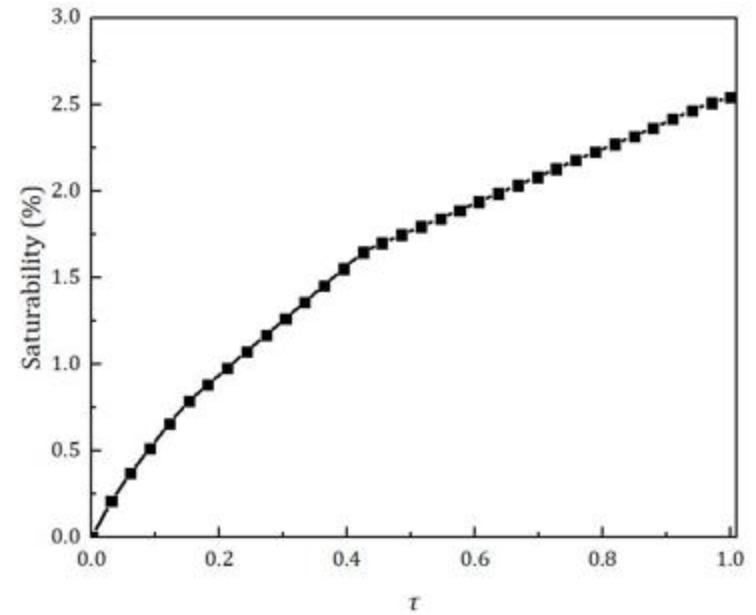
**Fig.2 water behavior**



## Pressure drop

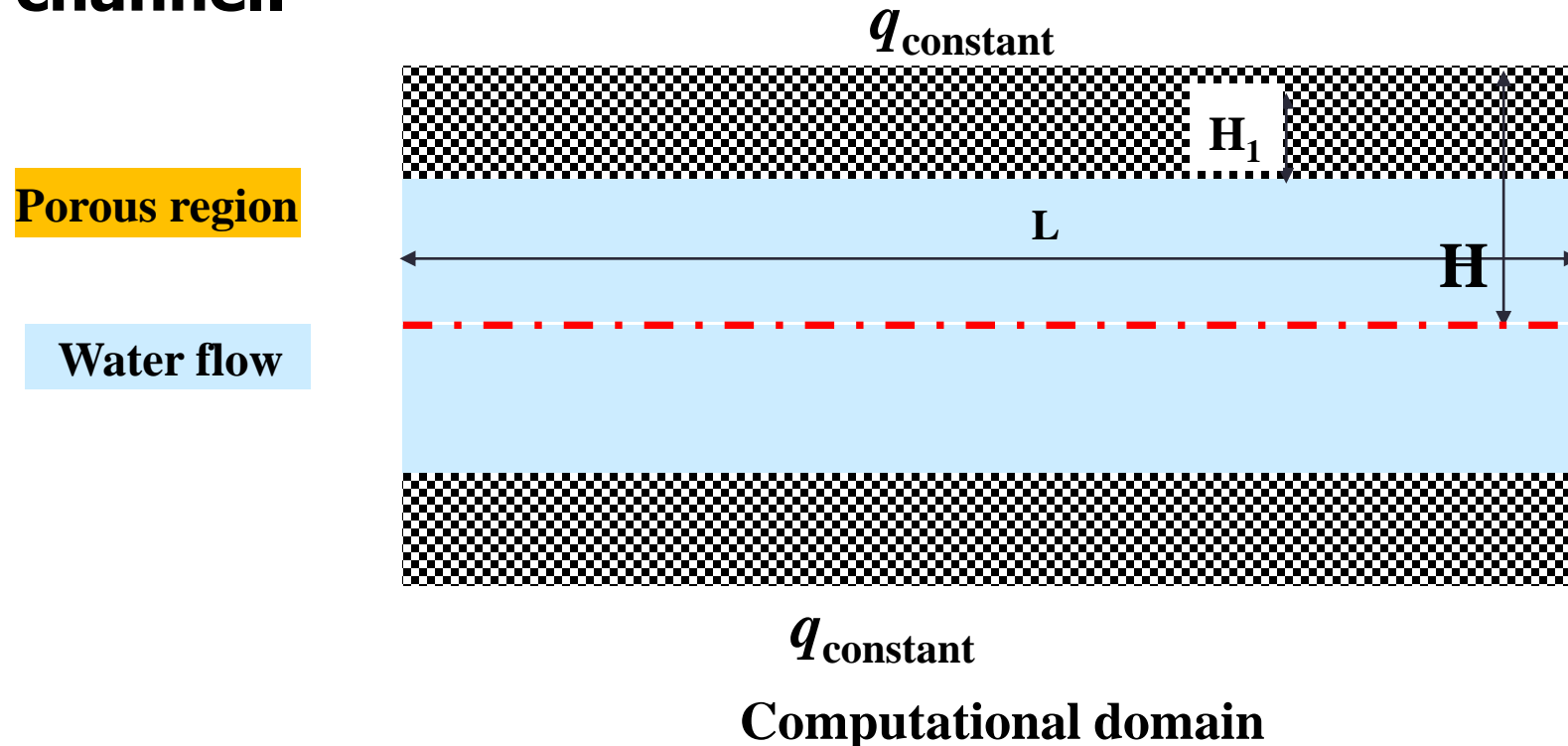


## Saturation



# Homework

**Known:** Porous medium is partially inserted into an 2D channel to enhance the heat transfer. The fluid is water and the porous region is aluminum metal foam. The porous region is attached to the outer wall of the channel.



Parameter	H	L	$\rho_{\text{water}}$	$\eta_{\text{water}}$	$c_{p \text{ water}}$	$\lambda_{\text{water}}$	$\varepsilon$
Value (Unit)	0.06 (m)	3 (m)	998.2 ( $\text{kg}\cdot\text{m}^{-3}$ )	$998\times 10^{-6}$ ( $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ )	4182 ( $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ )	0.597 ( $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ )	0.9

## Assumptions:

constant physical properties, steady, laminar flow

## Boundary conditions

Boundary	Condition
$x=0$	$v_x=U_{\text{in}}, T=300 \text{ K}$
$x=L$	$p=0 \text{ Pa}, T_{\text{backflow}}=300 \text{ K}$
$y=0$	symmetry
$y=H$	$v_x=v_y=0, q=500 \text{ Wm}^{-2}$
Porous region	Thermal-equilibrium model

**Solve:**

$$PN = \frac{Nu / Nu_{\text{base case}}}{\Delta p / \Delta p_{\text{base case}}}$$

Simulate the heat transfer and laminar flow based on above conditions. Analyze the  $Nu$ , pressure drop ( $\Delta P$ ) and  $PN$  at different  $Re$  and permeabilities (every one in the same group will run totally 16 cases). Thermal-equilibrium model is adopted for porous medium region. KC equation is adopted to calculate the permeability.

$$Re = \frac{\rho u_{\text{inlet}} H}{\mu} \quad k = \frac{D_p^2 \varepsilon^3}{150(1 - \varepsilon)^2}$$

## Traffic control in Xi'an

In each working day, cars with two values of tail number are not allowed on road.

**Monday: 1, 6**

**Tuesday: 2, 7**

**Wednesday: 3, 8**

**Thursday: 4, 9**

**Friday: 5, 0**





# Homework

The homework is divided into **5** groups based on different **tail numbers of student ID**.



## Tail numbers of student ID: 1, 6

<b>Group 1</b>	<b>Thickness of porous region <math>H_1</math></b>
	<b>0.02 (m)</b>

$D_p \backslash Re$	<b>Re=100</b>	<b>Re=200</b>	<b>Re=300</b>	<b>Re=400</b>
<b>0.0025</b>	<b>0.0025</b>	<b>0.0025</b>	<b>0.0025</b>	<b>0.0025</b>
<b>0.00079</b>	<b>0.00079</b>	<b>0.00079</b>	<b>0.00079</b>	<b>0.00079</b>
<b>0.00025</b>	<b>0.00025</b>	<b>0.00025</b>	<b>0.00025</b>	<b>0.00025</b>
<b>0.000079</b>	<b>0.000079</b>	<b>0.000079</b>	<b>0.000079</b>	<b>0.000079</b>

## Base case

$D_p$  is the diameter of particles

## Tail numbers of student ID: 2, 7

<b>Group 2</b>	<b>Thickness of porous region <math>H_1</math></b>
	<b>0.03 (m)</b>

<b><math>D_p</math> \ Re</b>	<b>Re=100</b>	<b>Re=200</b>	<b>Re=300</b>	<b>Re=400</b>
<b>0.0025</b>	<b>0.0025</b>	<b>0.0025</b>	<b>0.0025</b>	<b>0.0025</b>
<b>0.00079</b>	<b>0.00079</b>	<b>0.00079</b>	<b>0.00079</b>	<b>0.00079</b>
<b>0.00025</b>	<b>0.00025</b>	<b>0.00025</b>	<b>0.00025</b>	<b>0.00025</b>
<b>0.000079</b>	<b>0.000079</b>	<b>0.000079</b>	<b>0.000079</b>	<b>0.000079</b>

## Base case

$D_p$  is the diameter of particles

## Tail numbers of student ID: 3, 8

<b>Group 3</b>	<b>Thickness of porous region <math>H_1</math></b>
	<b>0.04 (m)</b>

<b>Re</b>	<b>Re=100</b>	<b>Re=200</b>	<b>Re=300</b>	<b>Re=400</b>
<b><math>D_p</math></b>				
<b>0.0025</b>	<b>0.0025</b>	<b>0.0025</b>	<b>0.0025</b>	<b>0.0025</b>
<b>0.00079</b>	<b>0.00079</b>	<b>0.00079</b>	<b>0.00079</b>	<b>0.00079</b>
<b>0.00025</b>	<b>0.00025</b>	<b>0.00025</b>	<b>0.00025</b>	<b>0.00025</b>
<b>0.000079</b>	<b>0.000079</b>	<b>0.000079</b>	<b>0.000079</b>	<b>0.000079</b>

## Base case

$D_p$  is the diameter of particles

## Tail numbers of student ID: 4, 9

<b>Group 4</b>	<b>Thickness of porous region <math>H_1</math></b>
	<b>0.05 (m)</b>

$D_p \backslash Re$	<b>Re=100</b>	<b>Re=200</b>	<b>Re=300</b>	<b>Re=400</b>
<b>0.0025</b>	<b>0.0025</b>	<b>0.0025</b>	<b>0.0025</b>	<b>0.0025</b>
<b>0.00079</b>	<b>0.00079</b>	<b>0.00079</b>	<b>0.00079</b>	<b>0.00079</b>
<b>0.00025</b>	<b>0.00025</b>	<b>0.00025</b>	<b>0.00025</b>	<b>0.00025</b>
<b>0.000079</b>	<b>0.000079</b>	<b>0.000079</b>	<b>0.000079</b>	<b>0.000079</b>

## Base case

$D_p$  is the diameter of particles

## Tail numbers of student ID: 5, 0

<b>Group 1</b>	<b>Thickness of porous region <math>H_1</math></b>
	<b>0.055 (m)</b>

<b><math>D_p</math> \ Re</b>	<b>Re=100</b>	<b>Re=200</b>	<b>Re=300</b>	<b>Re=400</b>
<b>0.0025</b>	<b>0.0025</b>	<b>0.0025</b>	<b>0.0025</b>	<b>0.0025</b>
<b>0.00079</b>	<b>0.00079</b>	<b>0.00079</b>	<b>0.00079</b>	<b>0.00079</b>
<b>0.00025</b>	<b>0.00025</b>	<b>0.00025</b>	<b>0.00025</b>	<b>0.00025</b>
<b>0.000079</b>	<b>0.000079</b>	<b>0.000079</b>	<b>0.000079</b>	<b>0.000079</b>

## Base case

$D_p$  is the diameter of particles

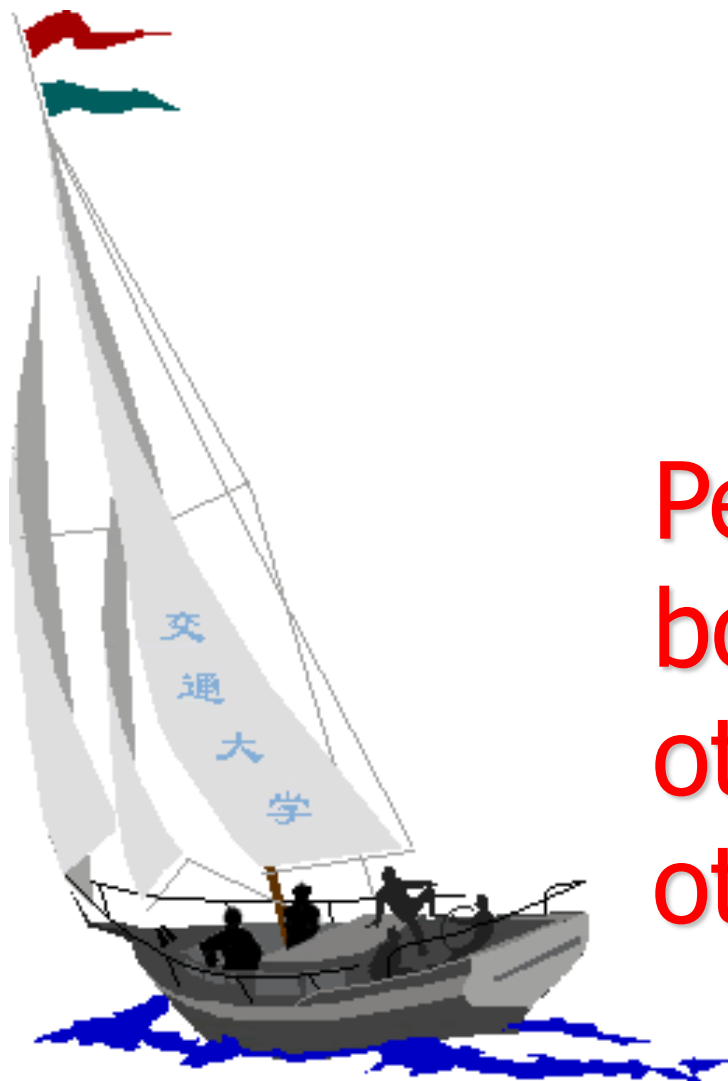
感谢各位同学  
感谢陶老师!

Happy New Year



*同舟共济渡彼岸!*

People in the same boat  
help each other to cross  
to the other bank,  
where....



# 同舟共济 渡彼岸!

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