A Simulation Tool for Coil-Wound Heat Exchanger in LNG Process

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Outlines

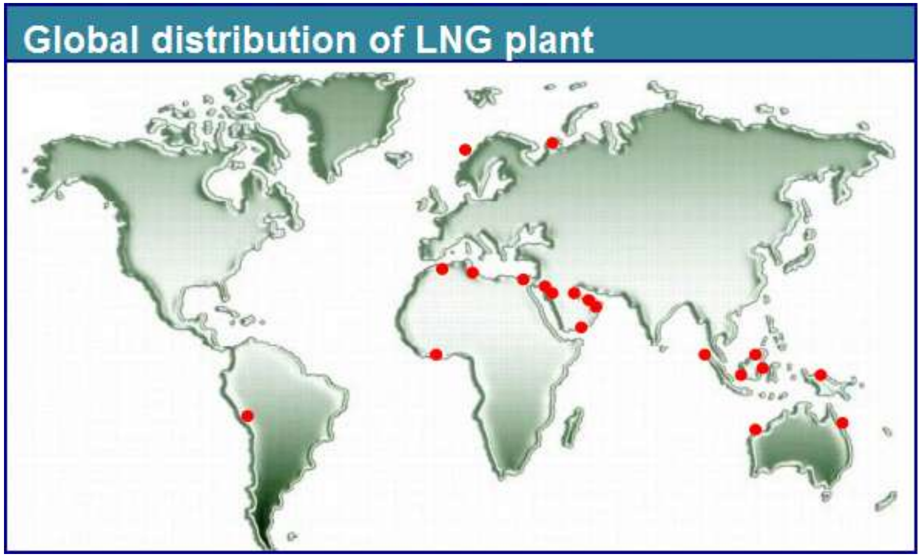
- Background
- CWHE Model and Algorithm
- Simulation Tool
- Conclusions

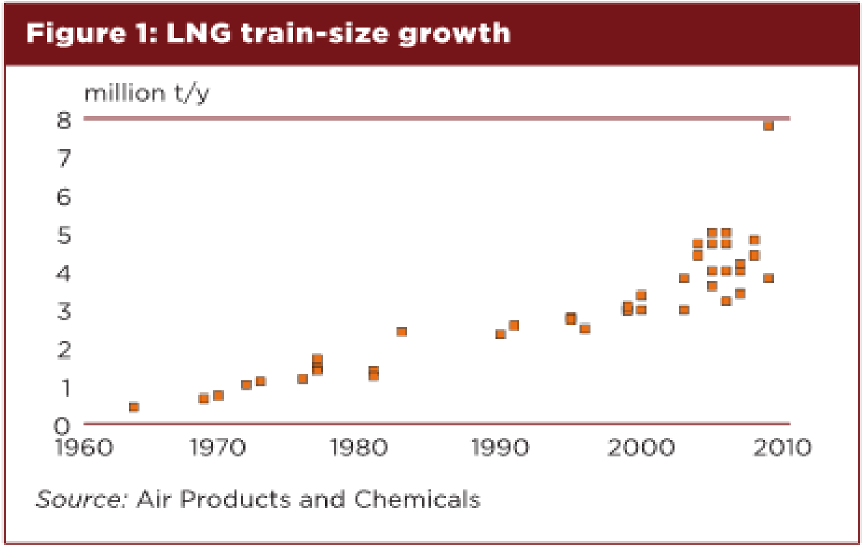
Background

Coil-Wound Heat Exchanger(CWHE)——main cryogenic HE in LNG process

Advantages：

- Compact structure
- Large operation range
- Multi-stream flow
- Large-scale oriented



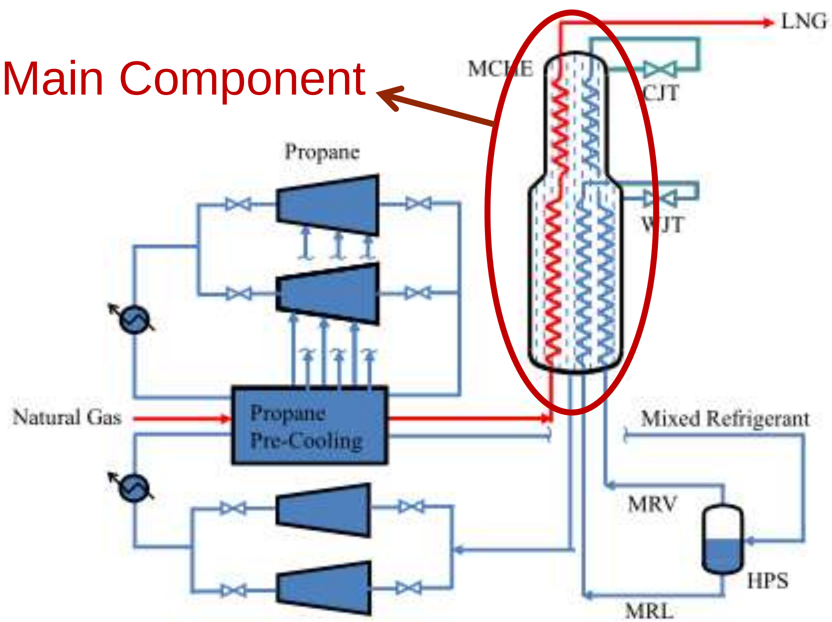


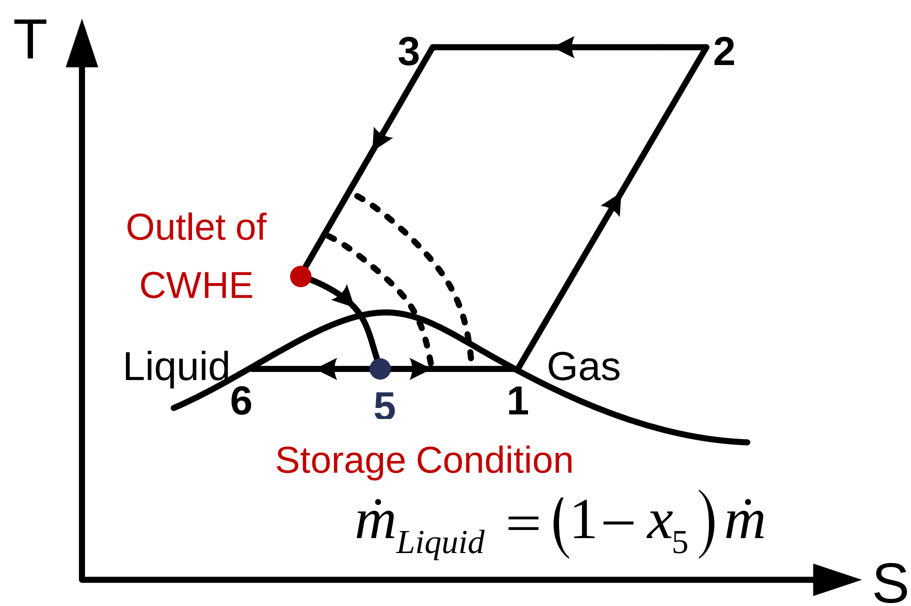
Background

The performance of CWHE is critically important

1 CWHE represents 20%~30% of the investment costs and about 25% of the total exergy lost.

2 The liquid production rate is sensitive to the effectiveness of CWHE.





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Background

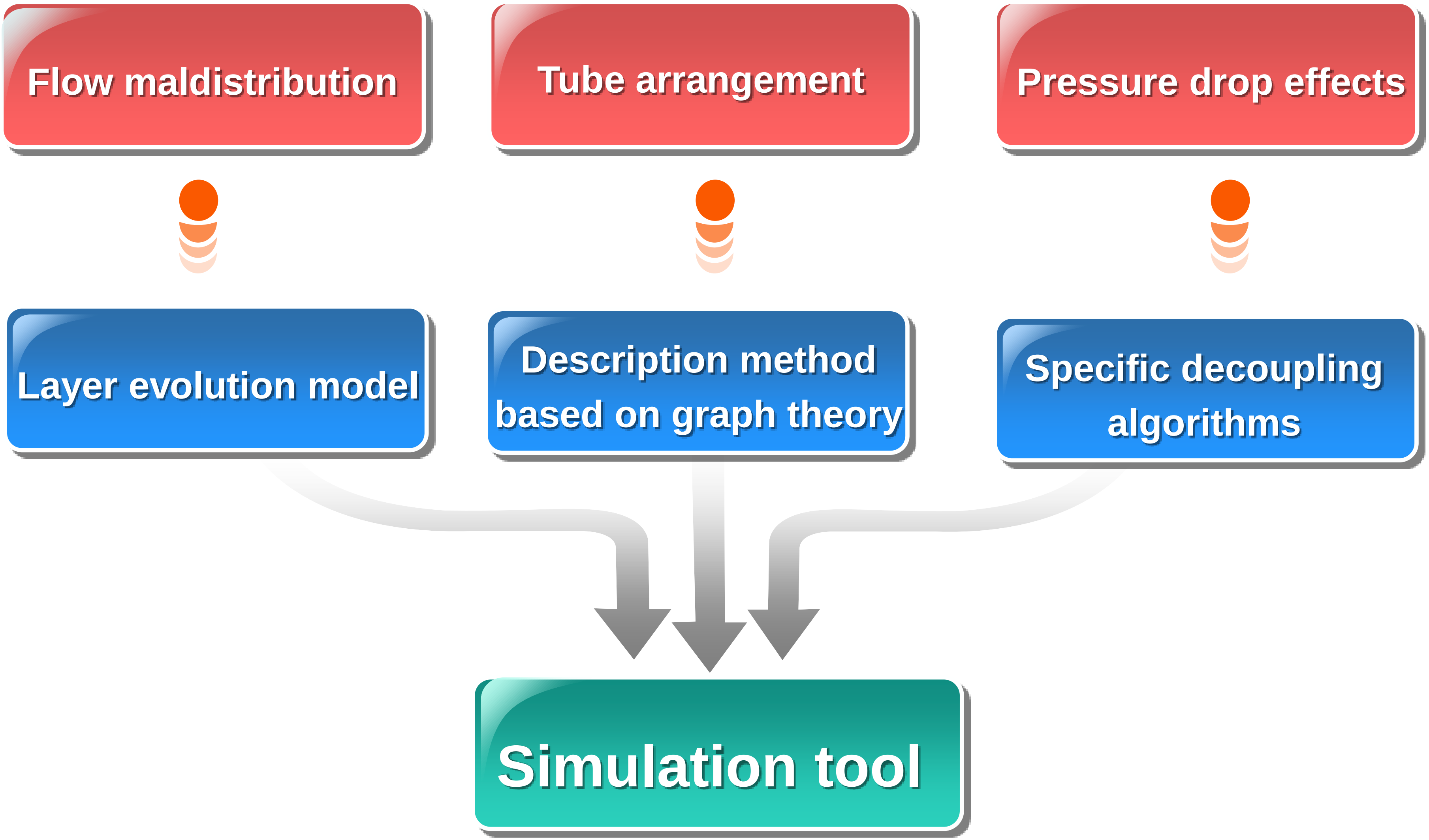
Existed models for CWHE heat exchanger

● Effect considered by model ○ Effect not considered by model

Effects	LPM	DPM		SEM
		Zones	Elements	
Single-phase flow	●	●	●	●
Two-phase flow	○	●	●	●
Change in fluid properties	○	○	●	●
Multiple streams	○	○	○	●
Flow maldistribution	○	○	○	○
Tube arrangement	○	○	○	○
Pressure drop coupling effects	○	○	○	○

Need to be considered for high-effectiveness CWHE design!

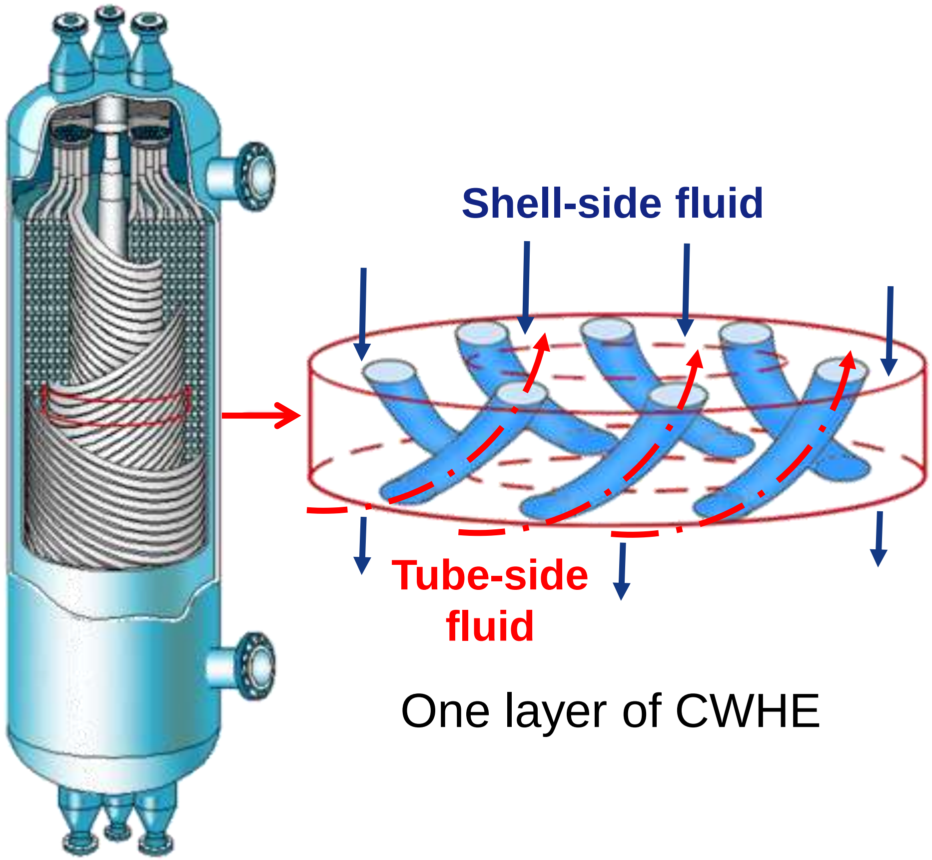
Approach



Flow maldistribution
Tube arrangement
Pressure drop effects
Layer evolution model
Description method based on graph theory
Specific decoupling algorithms
Simulation tool

CWHE Model

Layer evolution model



One layer of CWHE

Model characteristic

1.CV is divided layer-by-layer

- Model can evaluate the thermal hydraulic performance of each layer

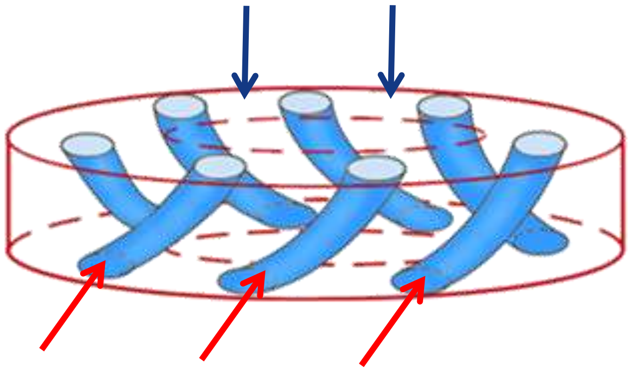
2.Fluid is simplified to one-dimensional flow

- Tube-side fluid is axial flow along tube
- Shell-side fluid is downward flow

3.The fluid vapor and liquid are in thermal equilibrium

CWHE Model

Governing equations



Tube-side fluid

Mass equation： $\nabla\cdot(\rho_t \mathbf{u}) = 0$

Momentum equation： $\nabla\cdot(\rho_t \mathbf{u}\mathbf{u}) = -\nabla p + \nabla\cdot(\ldots$

Shell-side fluid

Mass equation： $\nabla\cdot(\rho_s \mathbf{u}) = 0$

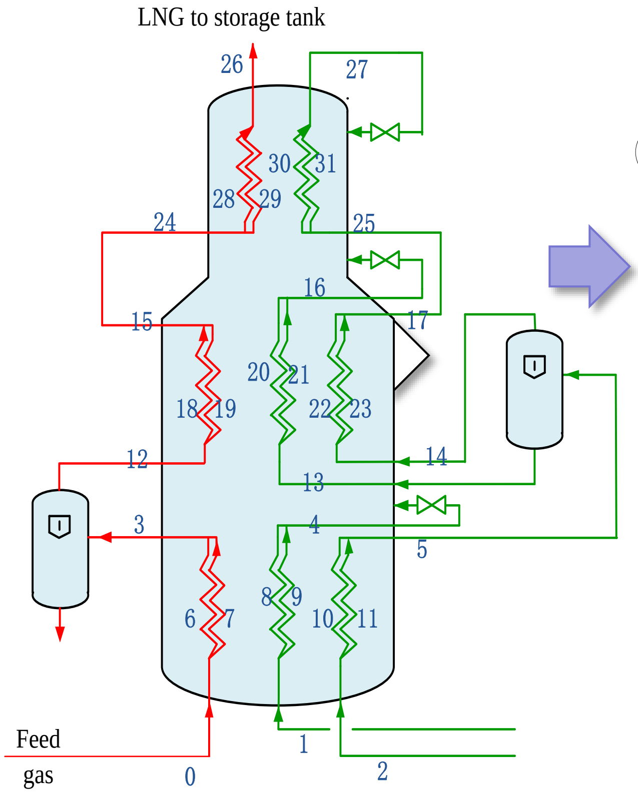
Momentum equation： $\nabla\cdot(\rho_s \mathbf{u}\mathbf{u}) = -\nabla p + \nabla\cdot(\ldots$

Energy conservation

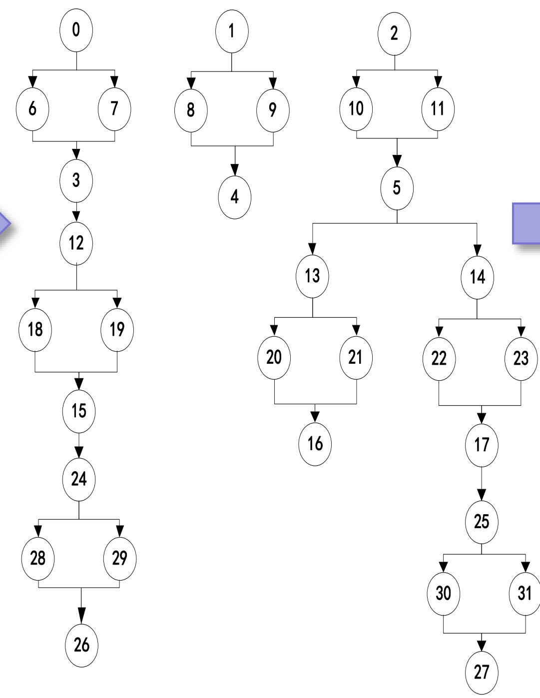
$$\sum_{i=1}^{N} G_{t,i}(h_{t,o,i} - h_{t,i,i}) = G_s(h_{s,i} - h_{s,o}) = \ldots$$

CWHE Model

Tube arrangement description method



Arbitrary tube arrangement



The directed graph

$$m_{i,j} = \begin{cases} 0 & \text{when No.j is not connected to No.i} \\ 1 & \text{when No.j is connected to No.i} \end{cases}$$

$$\begin{array}{c} \\ \boldsymbol{M} = \end{array} \begin{array}{c} \begin{array}{cccccccccccc} 1 & 2 & 3 & 4 & & 27 & 28 & 29 & 30 & 31 & 32 & \end{array} \\ \begin{bmatrix} 0 & 0 & 0 & 0 & & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & & 0 & 0 & 0 & 0 & 0 & 0 \\ & \vdots & \vdots & & & & & \vdots & \vdots & & \\ 0 & 0 & 0 & 0 & & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \end{array} \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ \\ 27 \\ 28 \\ 29 \\ 30 \\ 31 \\ 32 \end{array}$$

The adjacent matrix

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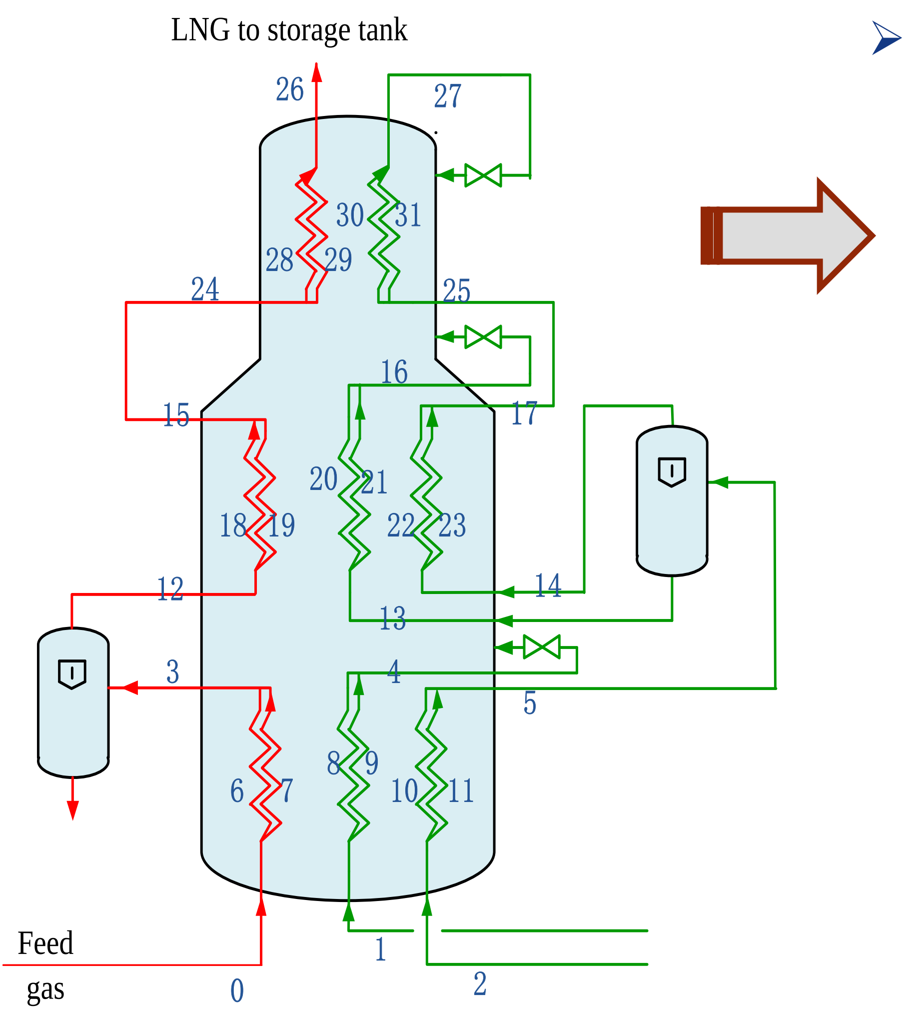
CWHE Model

Heat transfer path creation

- According to the broad first search algorithm
- Starts from one join point or split point, and ends at the next join point or split point



Inlet 0	Inlet 1	Inlet 2
0->6->3	1->8->4	2->10->5
0->7->3	1->9->4	2->11->5
3->12		5->13
12->18->15		13->20->16
12->19->15		13->21->16
15->24		5->14
24->28->26		14->22->17
24->29->26		14->23->17
		17->25
		25->30->27
		25->31->27

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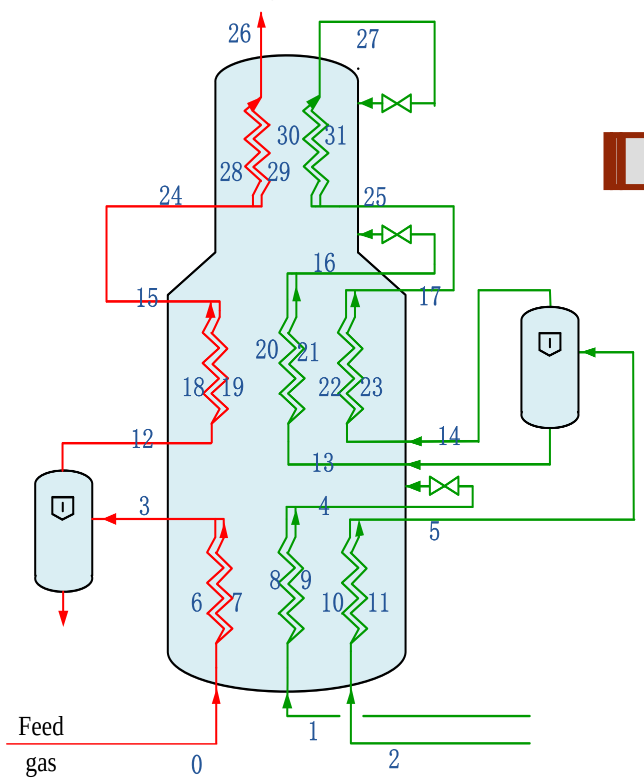
CWHE Model

Pressure drop path creation

- According to the depth first search algorithm
- Starts from one split point, and ends at the refrigerant outlet point



Inlet 0

- 0->6->3->12->18->15->24->28->26
- 0->7->3->12->18->15->24->28->26
- 3->12->18->15->24->28->26
- 12->18->15->24->28->26
- 12->19->15->24->28->26
- 15->24->28->26
- 24->28->26
- 24->29->26

Inlet 1

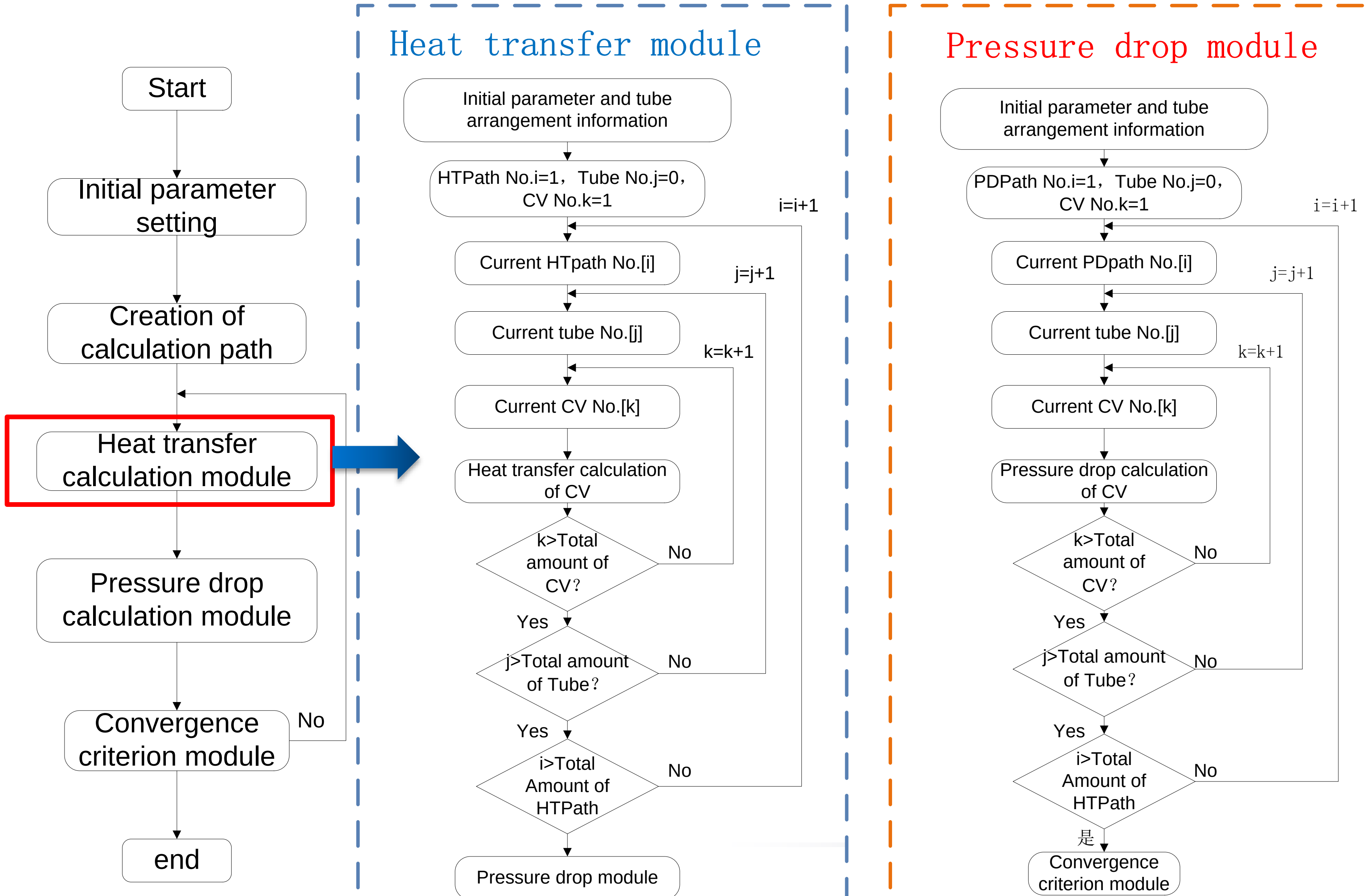
- 1->8->4
- 1->9->4

Inlet 2

- 2->10->5->13->20->16
- 2->11->5->13->20->16
- 5->13->20->16
- 5->14->22->17->25->30->27
- 13->20->16
- 13->21->16
- 14->22->17->25->30->27
- 14->23->17->25->30->27
- 17->25->30->27
- 25->30->27
- 25->31->27

Algorithm

Heat transfer and pressure drop alternative iteration algorithm



Algorithm

Mass flow rate distribution principle

- The value of *S* (equivalent flow resistance) and Δ*p* are updated
- The distribution of refrigerant mass flow rate is adjusted
- The inlet and outlet refrigerant pressure of each control volume are updated,
- The pressure drops of each path group become identical within a given tolerance.

Pressure drop of each path

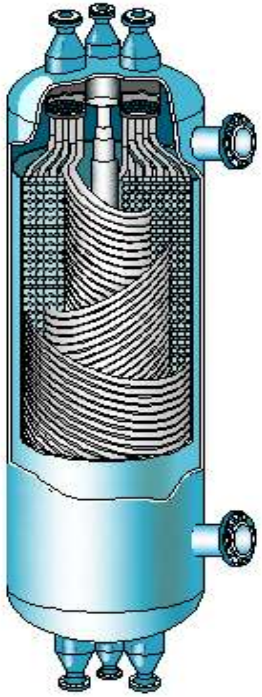
$$\Delta p = S_1 G_1^2 \quad \Delta p = S_2 G_2^2 \quad \dots \quad \Delta p = S_n G_n^2$$

Mass flow rate of each path

$$G_1 : G_2 : \cdots : G_n = \frac{1}{\sqrt{S_1}} : \frac{1}{\sqrt{S_2}} : \cdots : \frac{1}{\sqrt{S_n}}$$

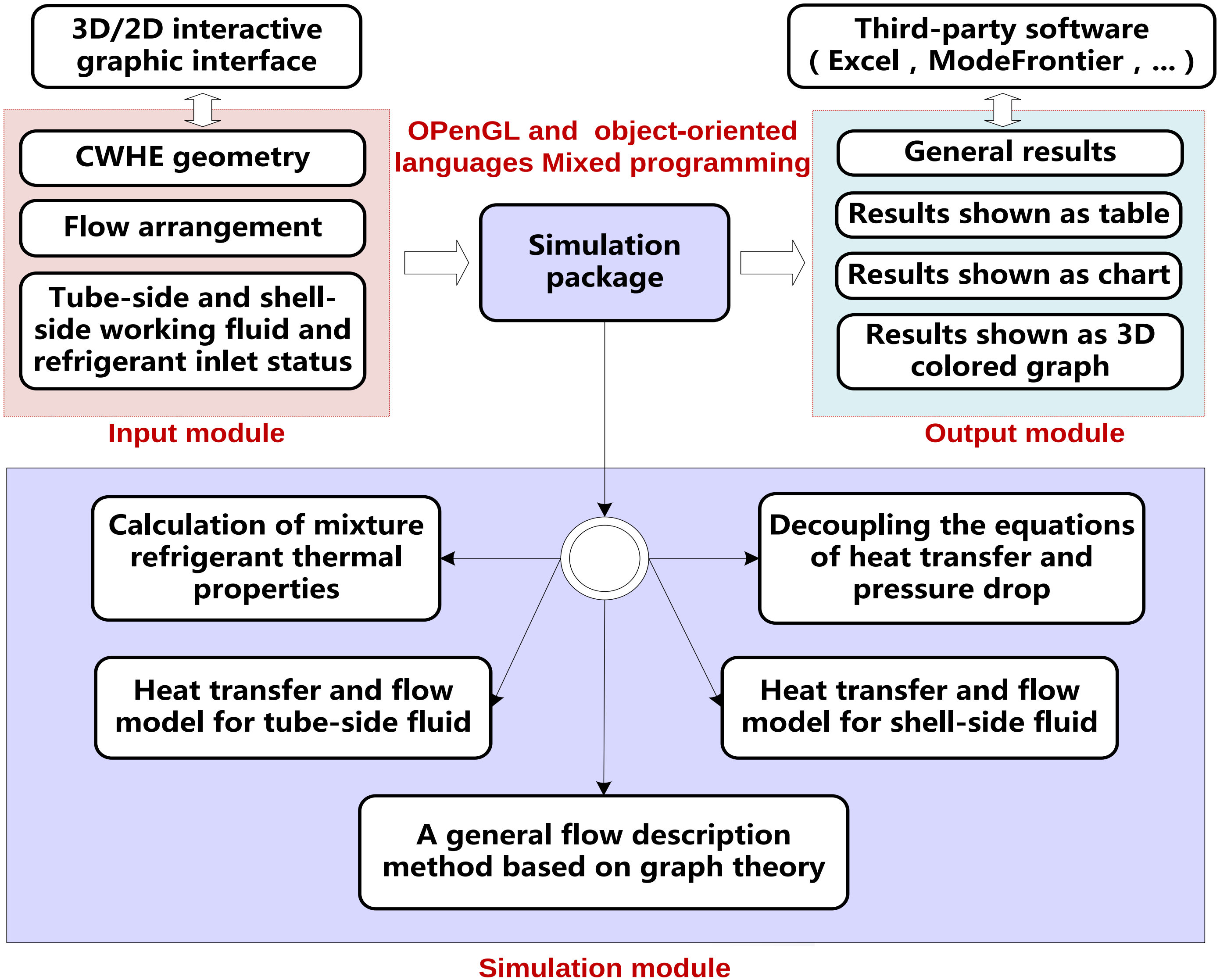
Normalization of mass flow rate：

$$G_1^{'} : G_2^{'} : \cdots : G_n^{'} = \frac{1/\sqrt{S_1}}{\sum_{i=1}^{n} 1/\sqrt{S_i}} : \frac{1/\sqrt{S_2}}{\sum_{i=1}^{n} 1/\sqrt{S_i}} : \cdots : \frac{1/\sqrt{S_n}}{\sum_{i=1}^{n} 1/\sqrt{S_i}}$$



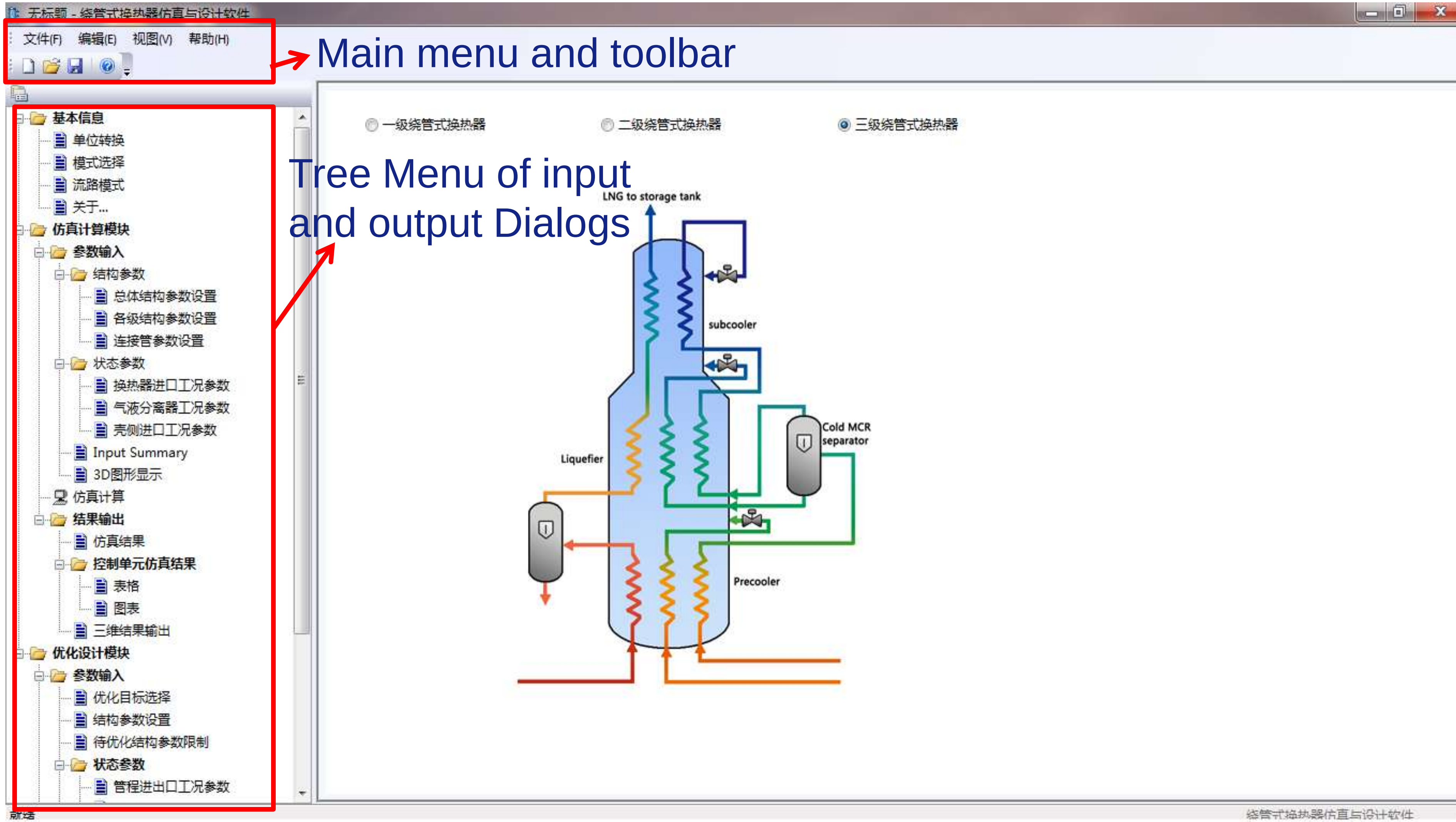
Simulation tool

Framework of Simulation tool

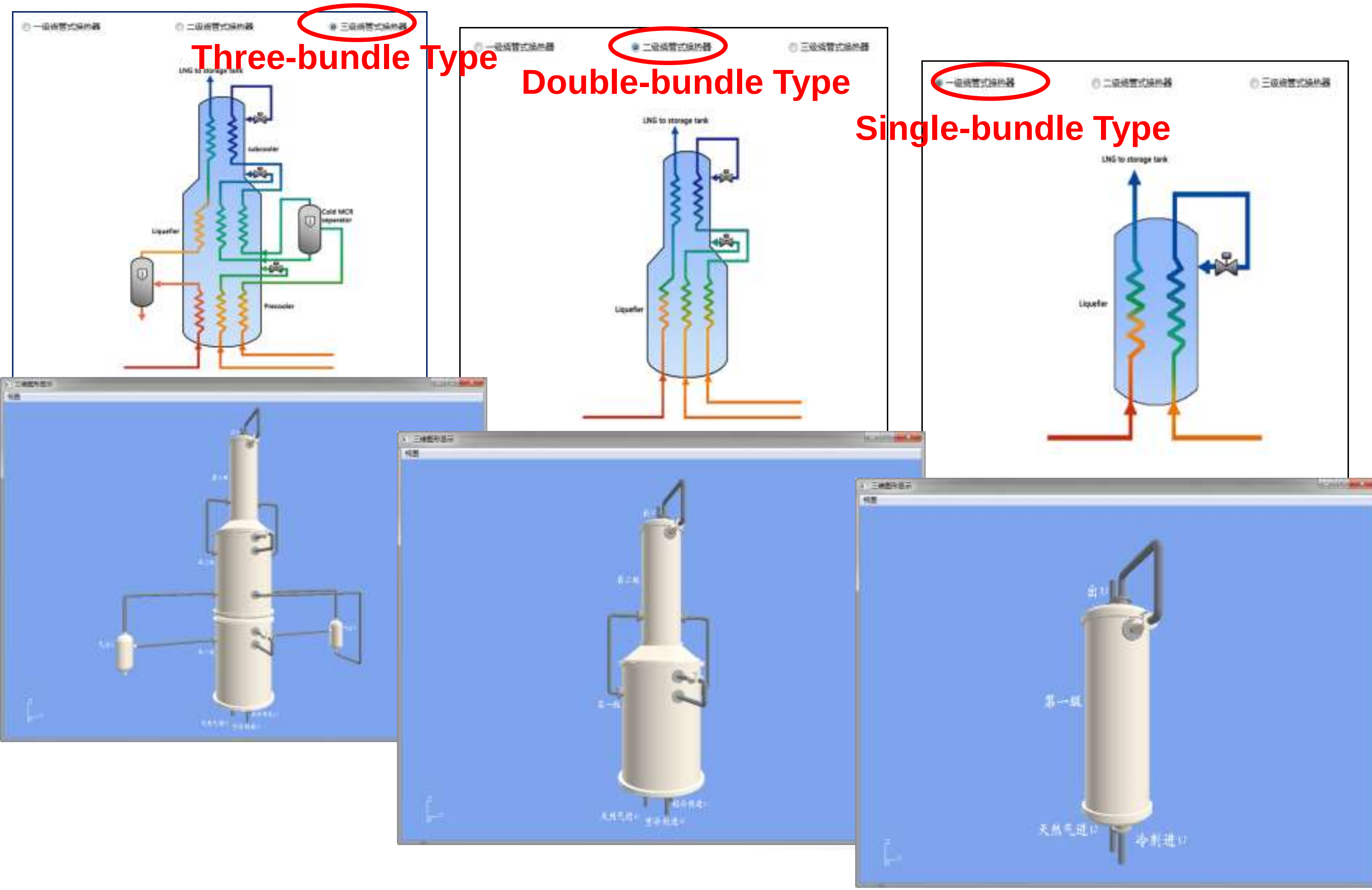


Simulation tool

Main interface of Simulation tool



Simulation tool



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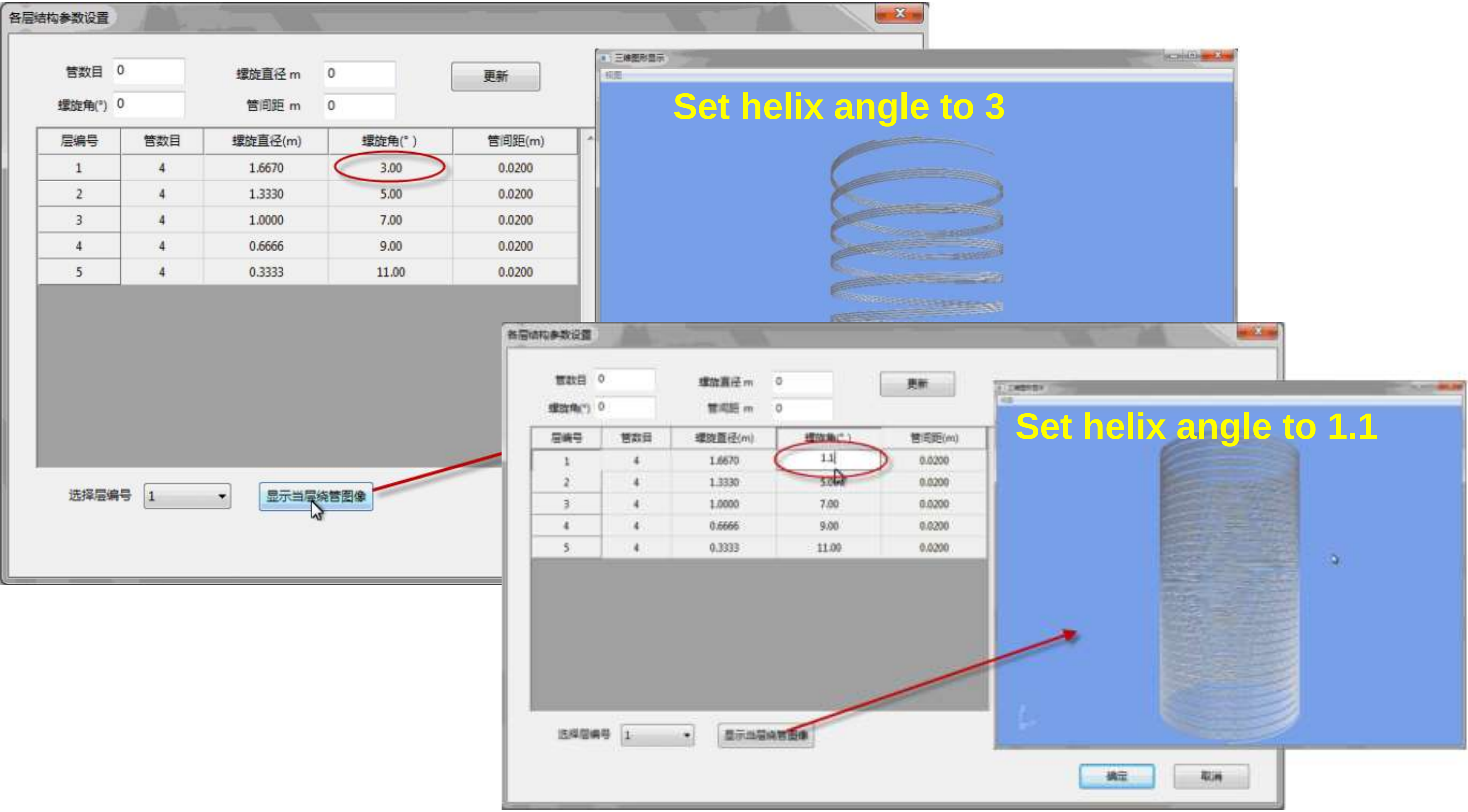
Simulation tool

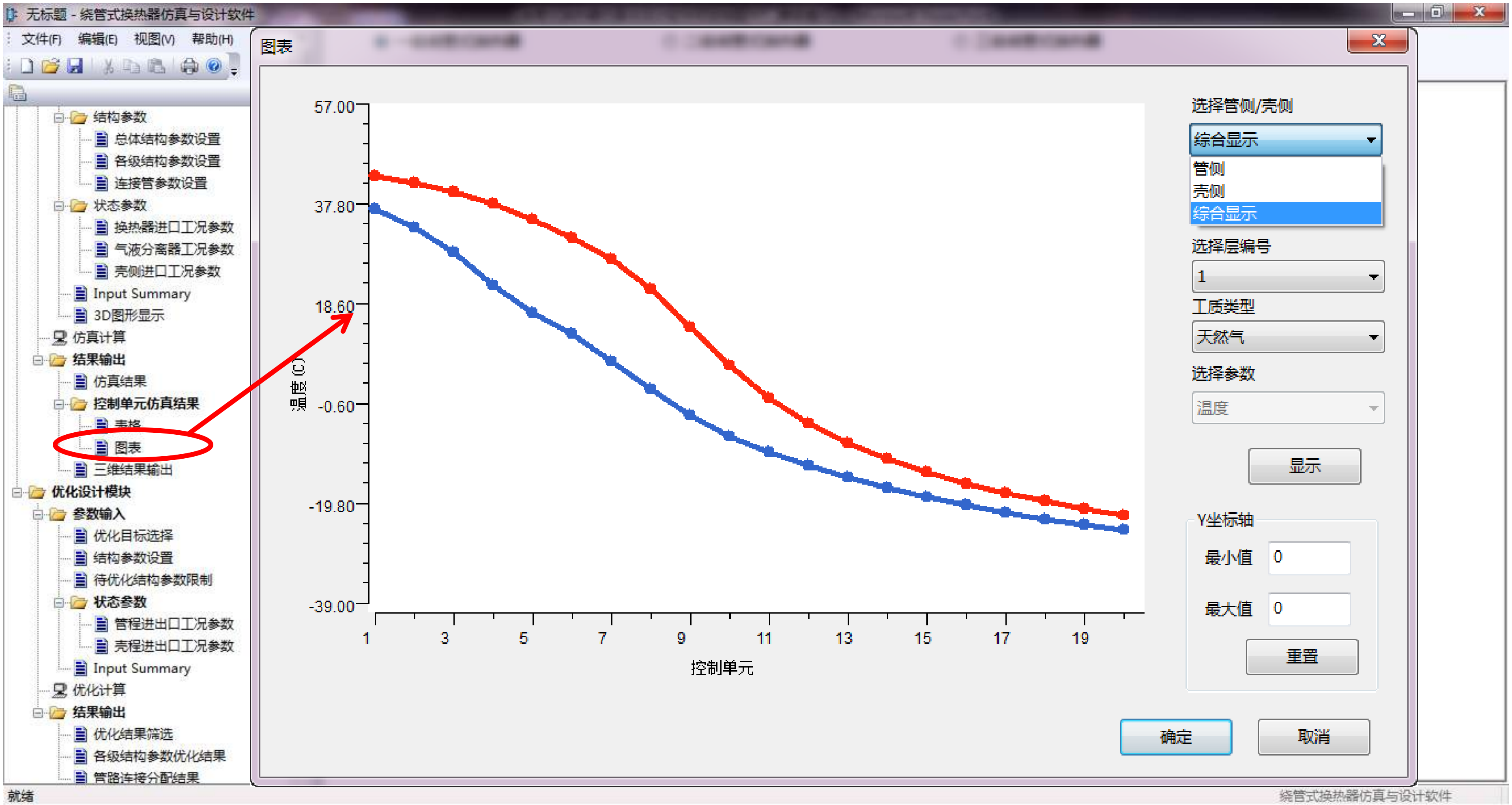
Three-dimensional graphics aided design



Simulation tool

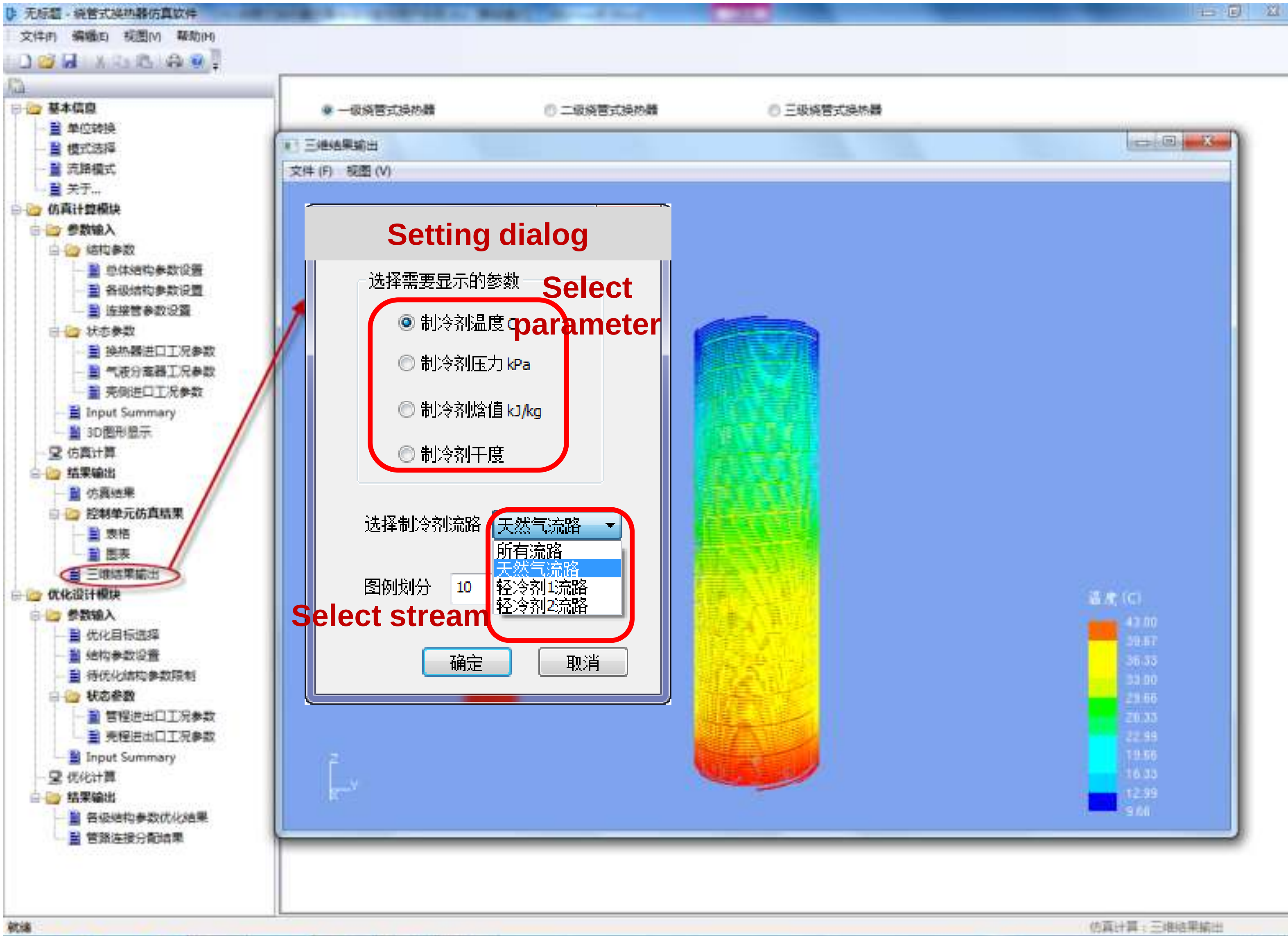
Results in coordinate chart

- Show the temperature, pressure, enthalpy and quality variation along the tube



Simulation tool

Results in 3D colored graph



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Conclusions

1. A layer evolution model is built, which could take the flow maldistribution effect and the tube arrangement effect into account .

2. A directed graph and corresponding adjacent matrix is introduced to describe arbitrary tube.

3. Specific algorithms are designed to consider the pressure drop effects on heat transfer and tube-side mass flow rate distribution.

4. A general framework of the simulation tool is established and a friendly GUI with OpenGL display technique is developed.

5. This simulation tool can be applied to study the above-mentioned effects on CWHE performance and guide for CWHE

Thank you!