



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

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- ④ **Background**
 - ④ **CWHE Model and Algorithm**
 - ④ **Simulation Tool**
 - ④ **Conclusions**
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Coil-Wound Heat Exchanger(CWHE)——main cryogenic HE in LNG process

Advantages:

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



Global distribution of LNG plant

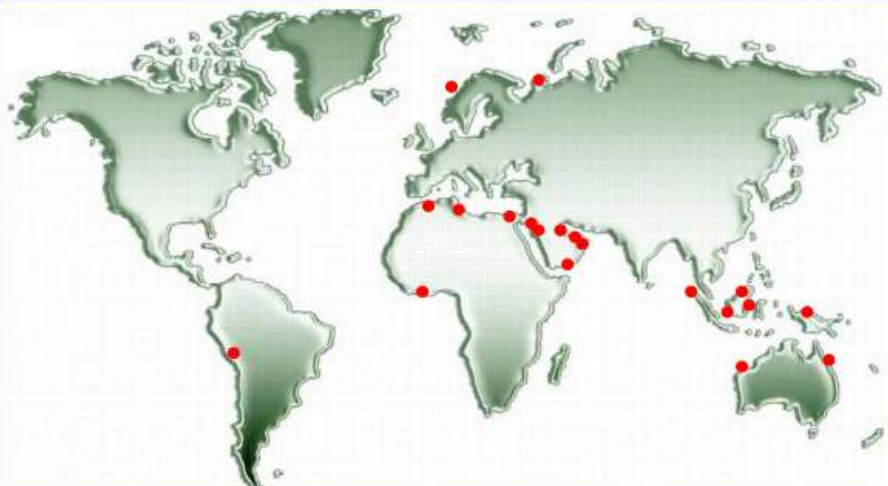
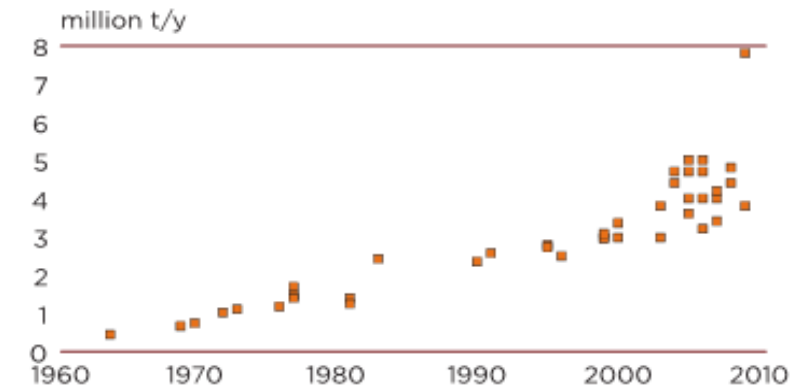


Figure 1: LNG train-size growth



Source: Air Products and Chemicals

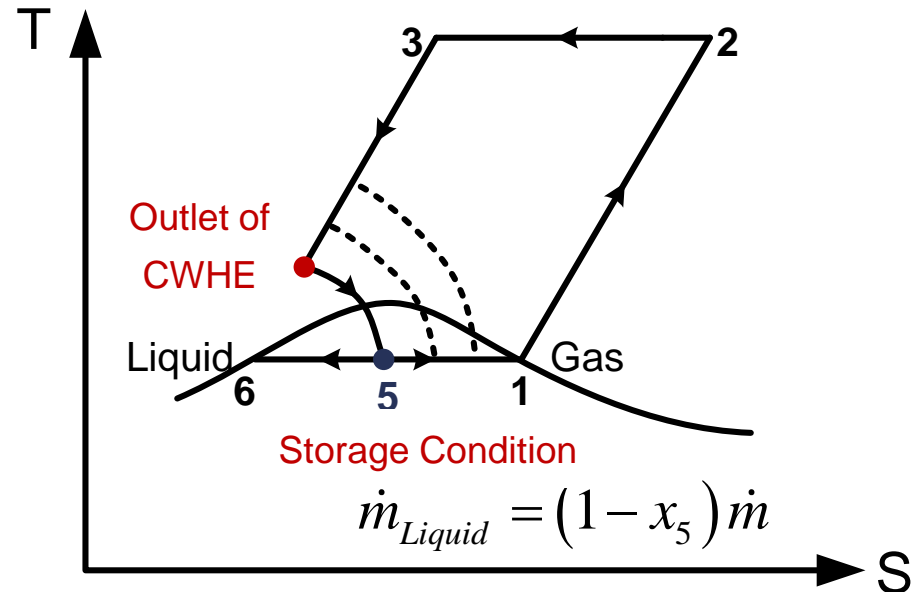
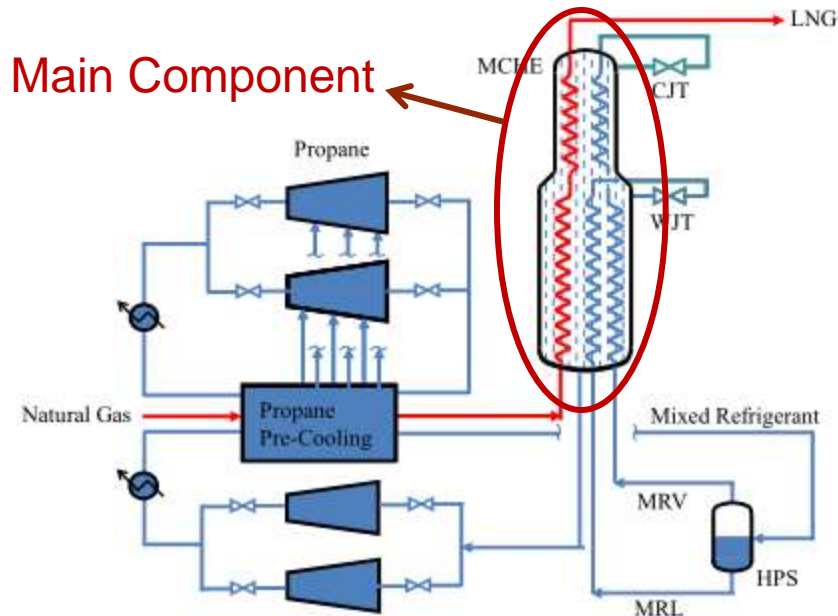
The performance of CWHE is critically important

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.



Existed models for CWHE heat exchanger

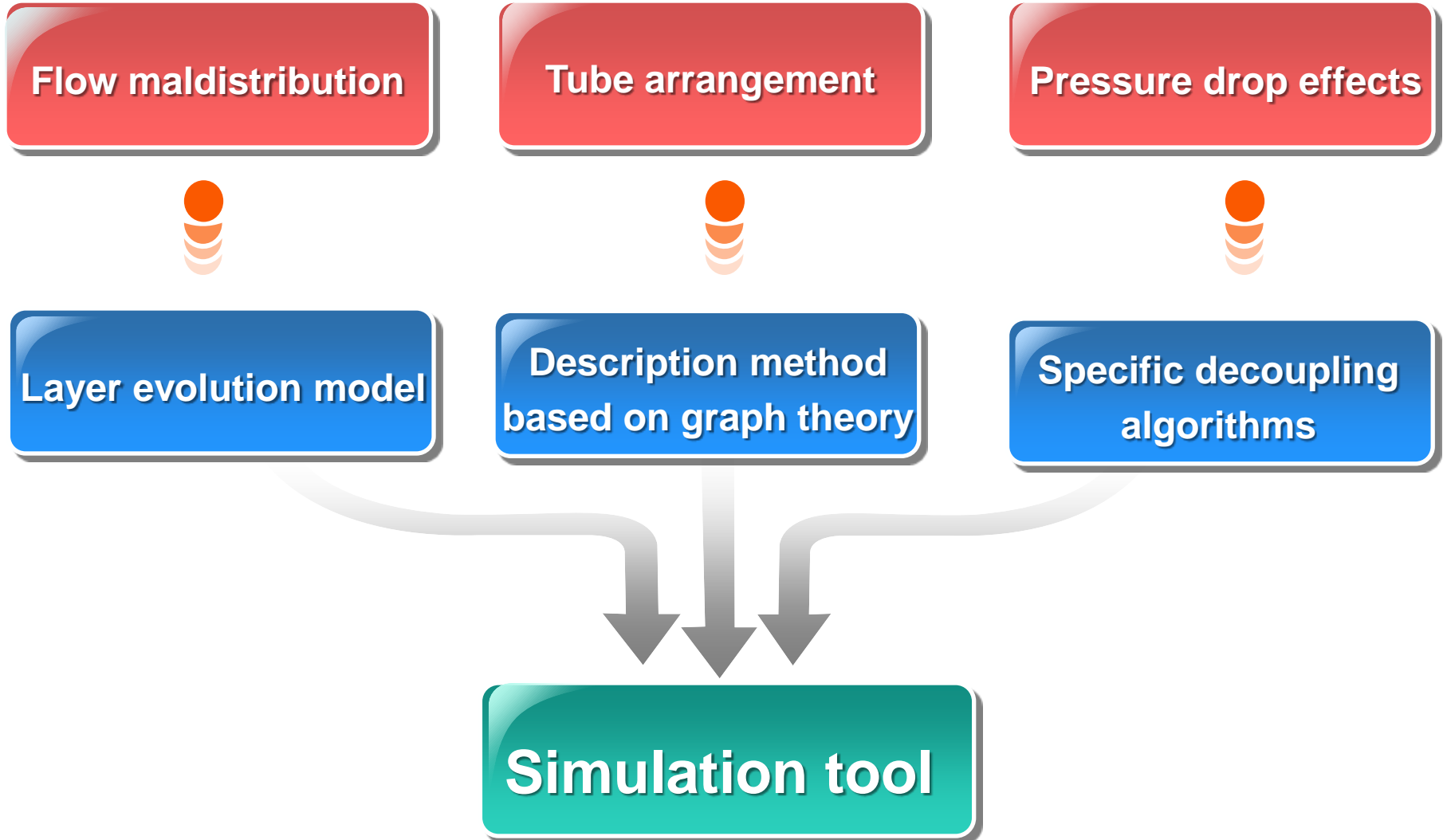
- Effect considered by model
- Effect not considered by model

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	○	○	○	○

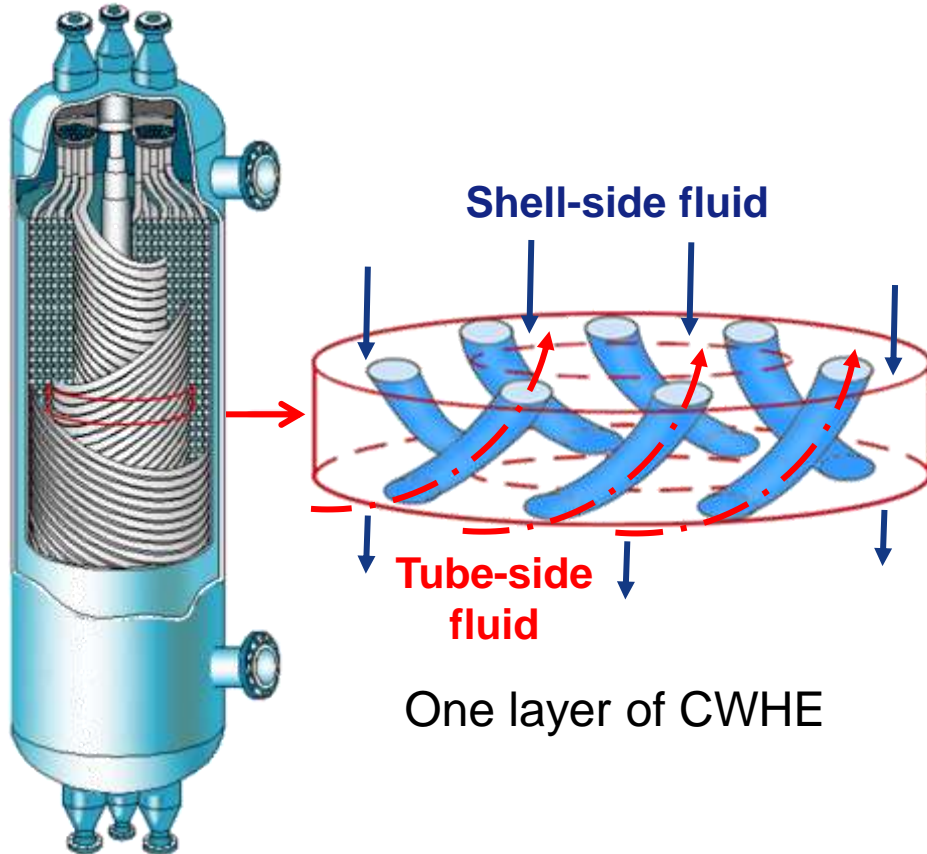


Need to be considered for high-effectiveness CWHE design!

Approach



Layer evolution model



Model characteristic

1. CV is divided layer-by-layer

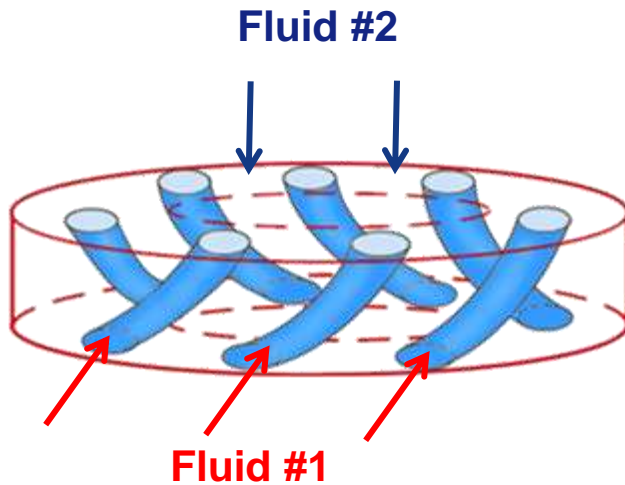
- Model can evaluate the thermal hydraulic performance of each layer

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

Governing equations



Tube-side fluid

Mass equation:

$$\nabla \cdot (\rho \mathbf{v}) = 0$$

Momentum equation:

$$\rho \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla p + \nabla \cdot \boldsymbol{\tau}$$

Shell-side fluid

Mass equation:

$$\nabla \cdot (\rho_s \mathbf{v}_s) = 0$$

Momentum equation:

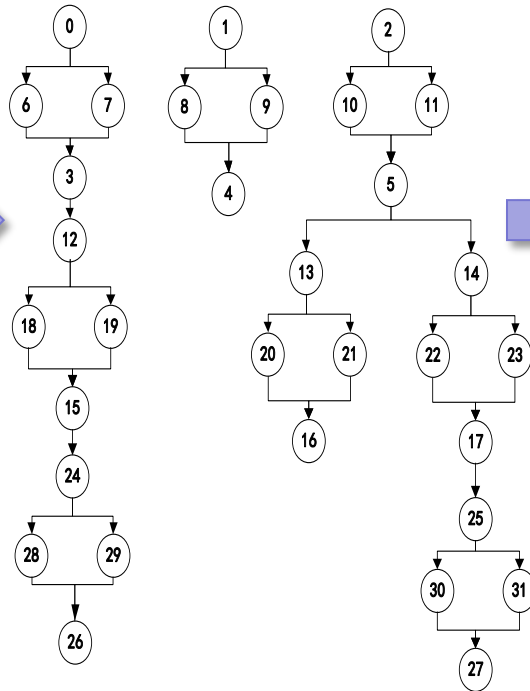
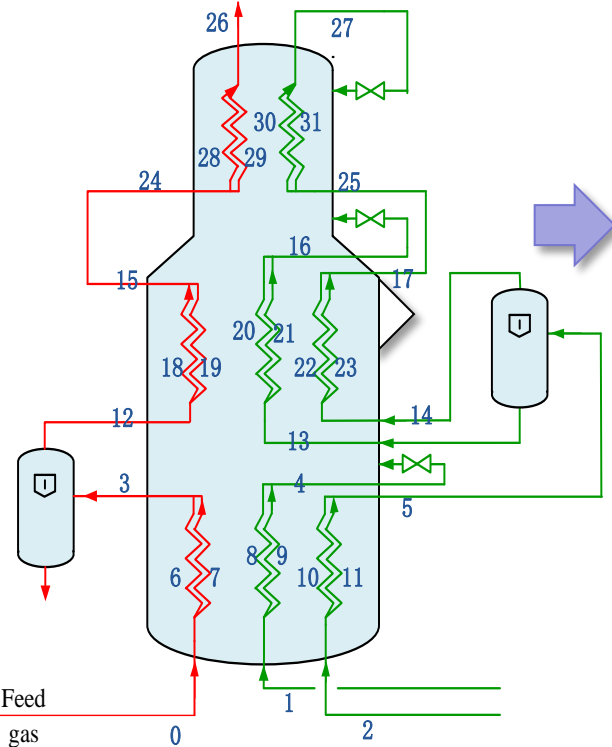
$$\rho_s \mathbf{v}_s \cdot \nabla \mathbf{v}_s = -\nabla p_s + \nabla \cdot \boldsymbol{\tau}_s$$

Energy conservation

$$\rho \mathbf{v} \cdot \nabla T = \nabla \cdot (\mathbf{k} \cdot \nabla T) + \dot{q}$$

Tube arrangement description method

LNG to storage tank



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

$$M = \begin{matrix} & \begin{matrix} 1 & 2 & 3 & 4 & & 27 & 28 & 29 & 30 & 31 & 32 \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ \vdots \\ 27 \\ 28 \\ 29 \\ 30 \\ 31 \\ 32 \end{matrix} & \begin{bmatrix} 0 & 0 & 0 & 0 & & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & & 0 & 0 & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \dots & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \dots & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \end{matrix}$$

Arbitrary tube arrangement

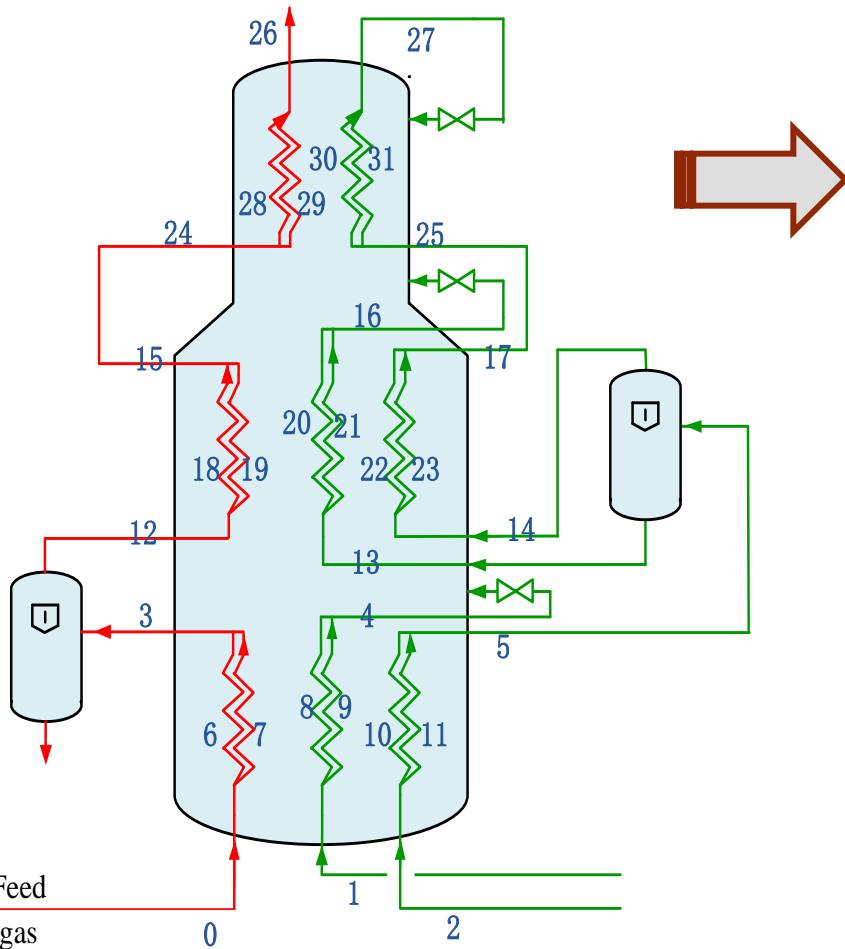
The directed graph

The adjacent matrix

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

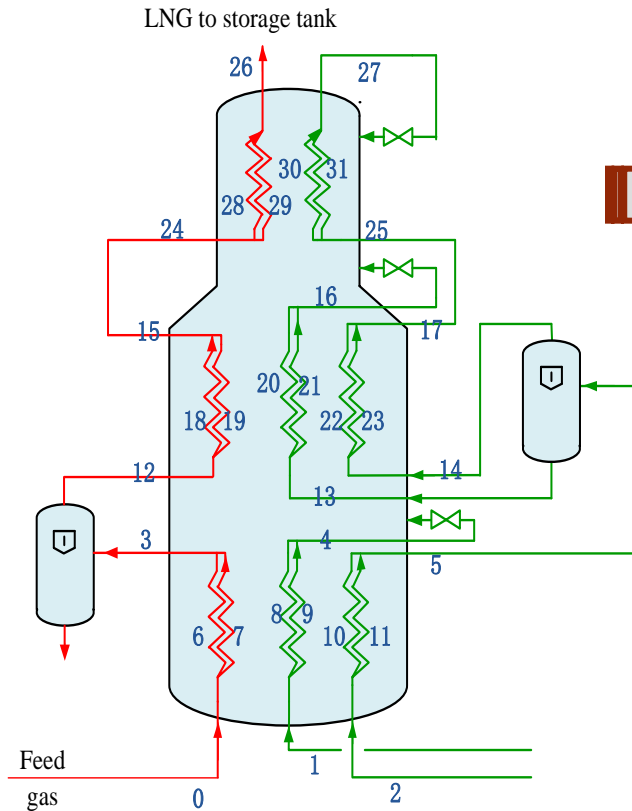
LNG to storage tank



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

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

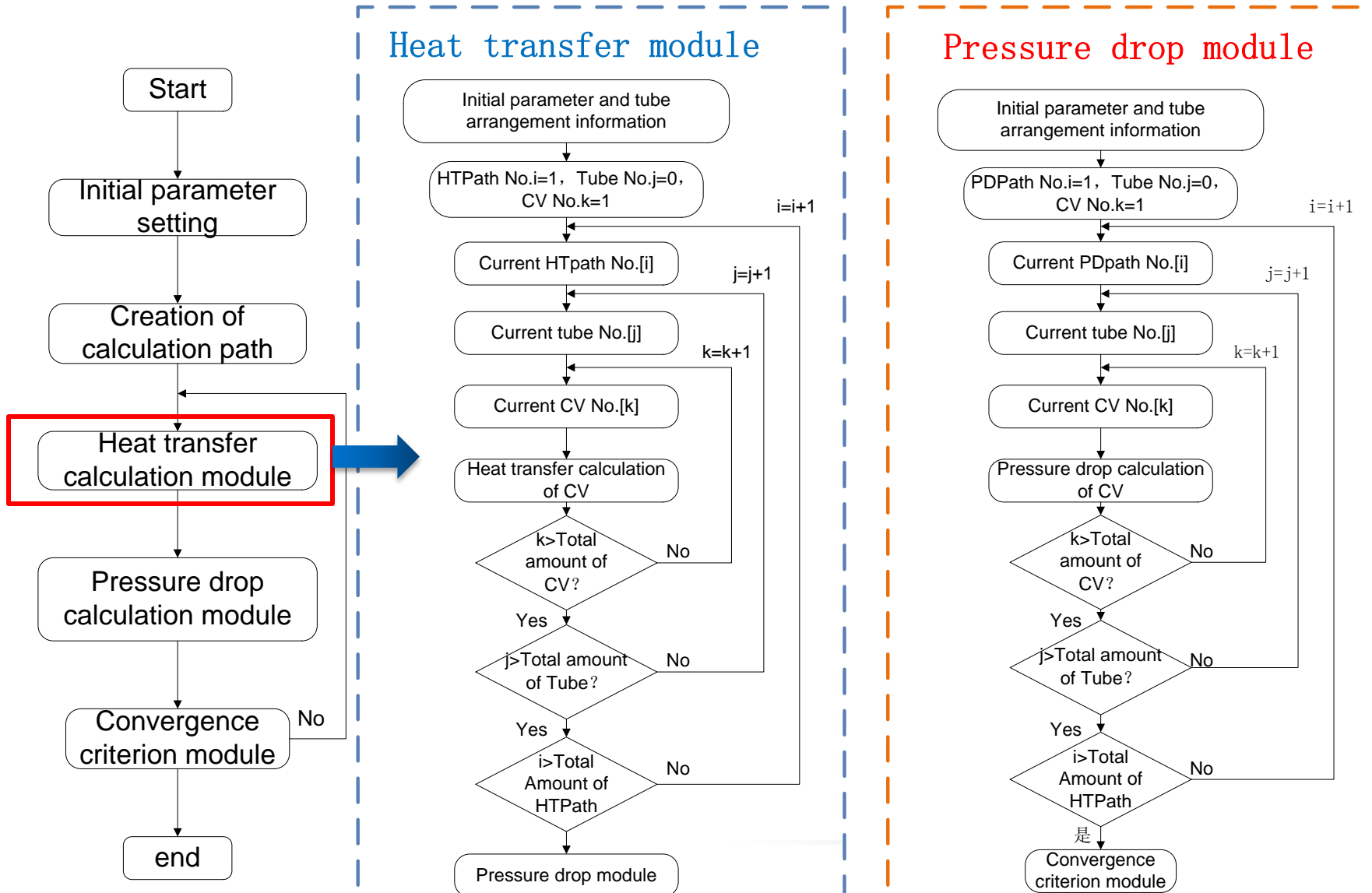
Inlet 1

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

Heat transfer and pressure drop alternative iteration algorithm



Mass flow rate distribution principle

- The value of S (equivalent flow resistance) and Δp 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

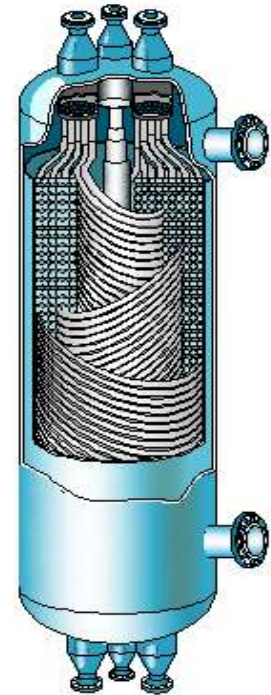
$$\Delta p = S_1 G_1^2 \quad \Delta p = S_2 G_2^2 \quad \dots \quad \Delta p = S_n G_n^2$$

Mass flow rate of each path

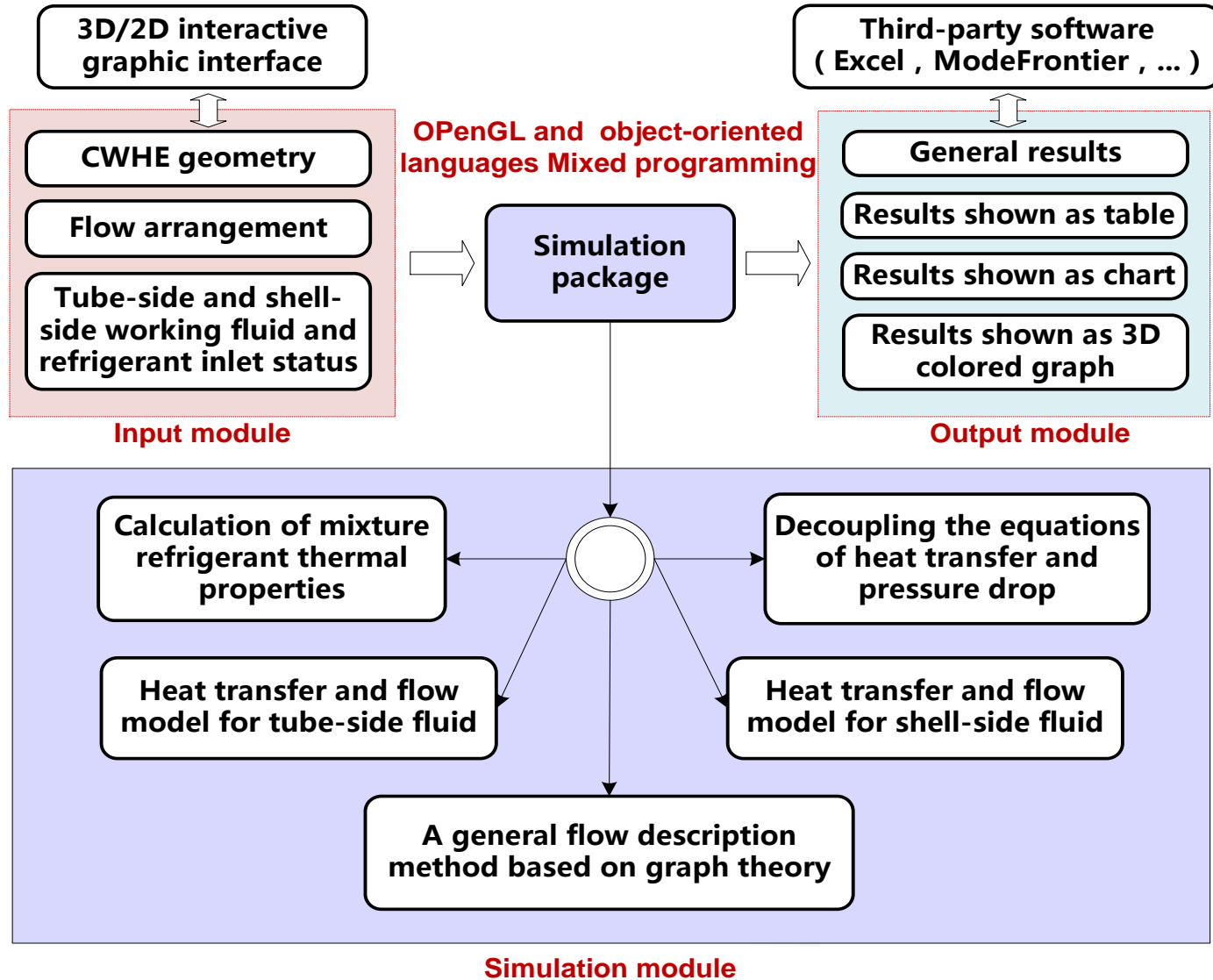
$$G_1 : G_2 : \dots : G_n = \frac{1}{\sqrt{S_1}} : \frac{1}{\sqrt{S_2}} : \dots : \frac{1}{\sqrt{S_n}}$$

Normalization of mass flow rate:

$$G'_1 : G'_2 : \dots : G'_n = \frac{1/\sqrt{S_1}}{\sum_{i=1}^n 1/\sqrt{S_i}} : \frac{1/\sqrt{S_2}}{\sum_{i=1}^n 1/\sqrt{S_i}} : \dots : \frac{1/\sqrt{S_n}}{\sum_{i=1}^n 1/\sqrt{S_i}}$$



Framework of Simulation tool



Main interface of Simulation tool

The screenshot displays the main interface of the Simulation tool. At the top, there is a menu bar with options: 文件(F), 编辑(E), 视图(V), 帮助(H). Below the menu bar is a toolbar with icons for file operations. On the left side, there is a tree menu with the following structure:

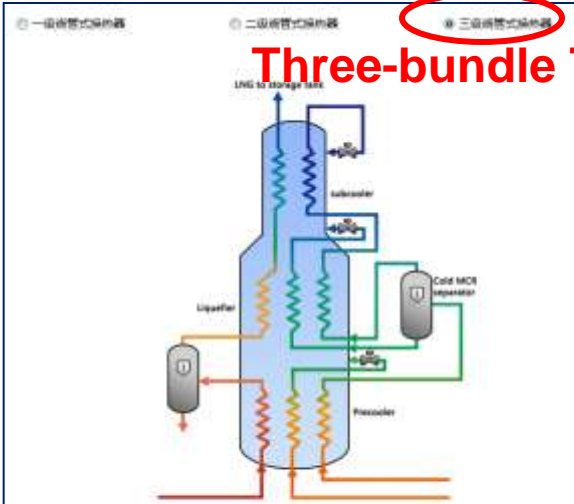
- 基本信息
 - 单位转换
 - 模式选择
 - 流路模式
 - 关于...
- 仿真计算模块
 - 参数输入
 - 结构参数
 - 总体结构参数设置
 - 各级结构参数设置
 - 连接管参数设置
 - 状态参数
 - 换热器进口工况参数
 - 气液分离器工况参数
 - 壳侧进口工况参数
 - Input Summary
 - 3D图形显示
 - 仿真计算
 - 结果输出
 - 仿真结果
 - 控制单元仿真结果
 - 表格
 - 图表
 - 三维结果输出
 - 优化设计模块
 - 参数输入
 - 优化目标选择
 - 结构参数设置
 - 待优化结构参数限制
 - 状态参数
 - 管程进出口工况参数

On the right side, there is a schematic diagram of a three-stage coiled tube heat exchanger. The diagram shows a central vertical vessel with three stages of coiled tubes. The top stage is labeled "LNG to storage tank". The middle stage is labeled "subcooler". The bottom stage is labeled "Precooler". A "Liquefier" is connected to the top stage, and a "Cold MCR separator" is connected to the middle stage. The diagram also shows various pipes, valves, and flow directions.

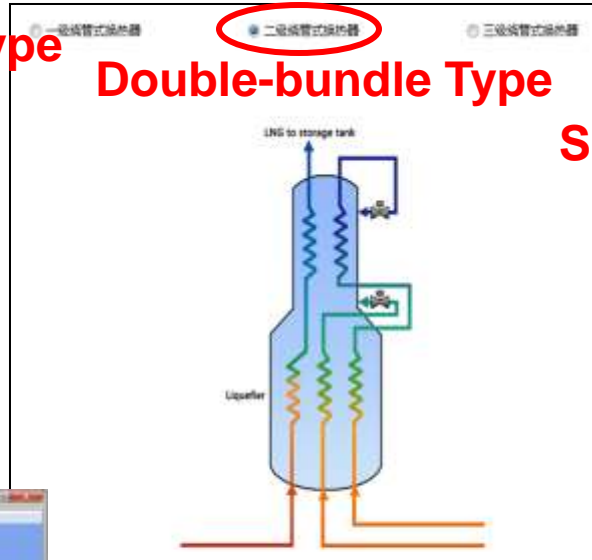
Labels in the diagram include: 一级绕管式换热器, 二级绕管式换热器, 三级绕管式换热器, LNG to storage tank, subcooler, Liquefier, Cold MCR separator, Precooler.

Simulation tool

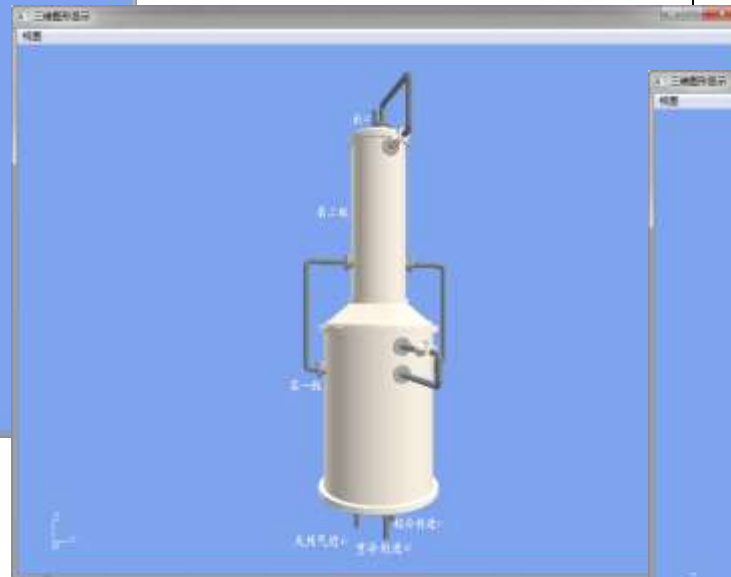
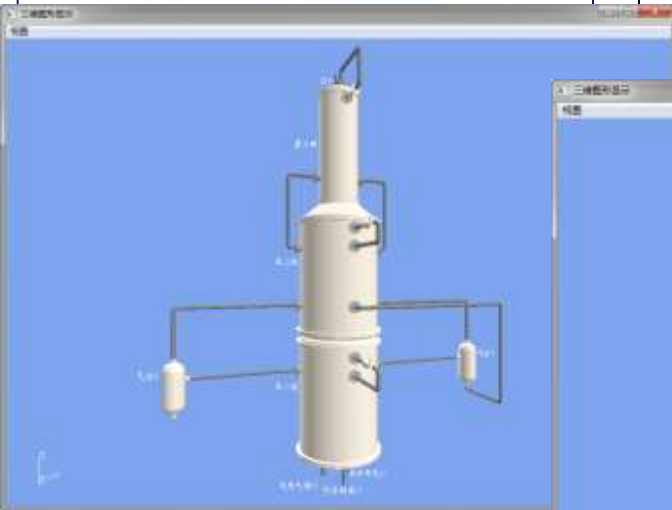
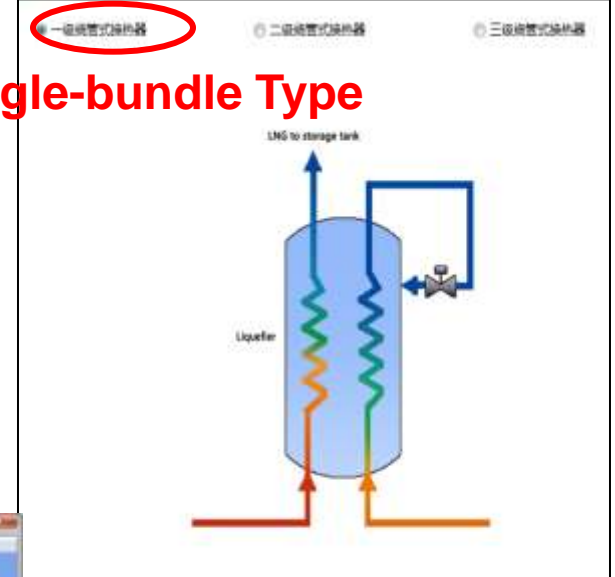
Three-bundle Type



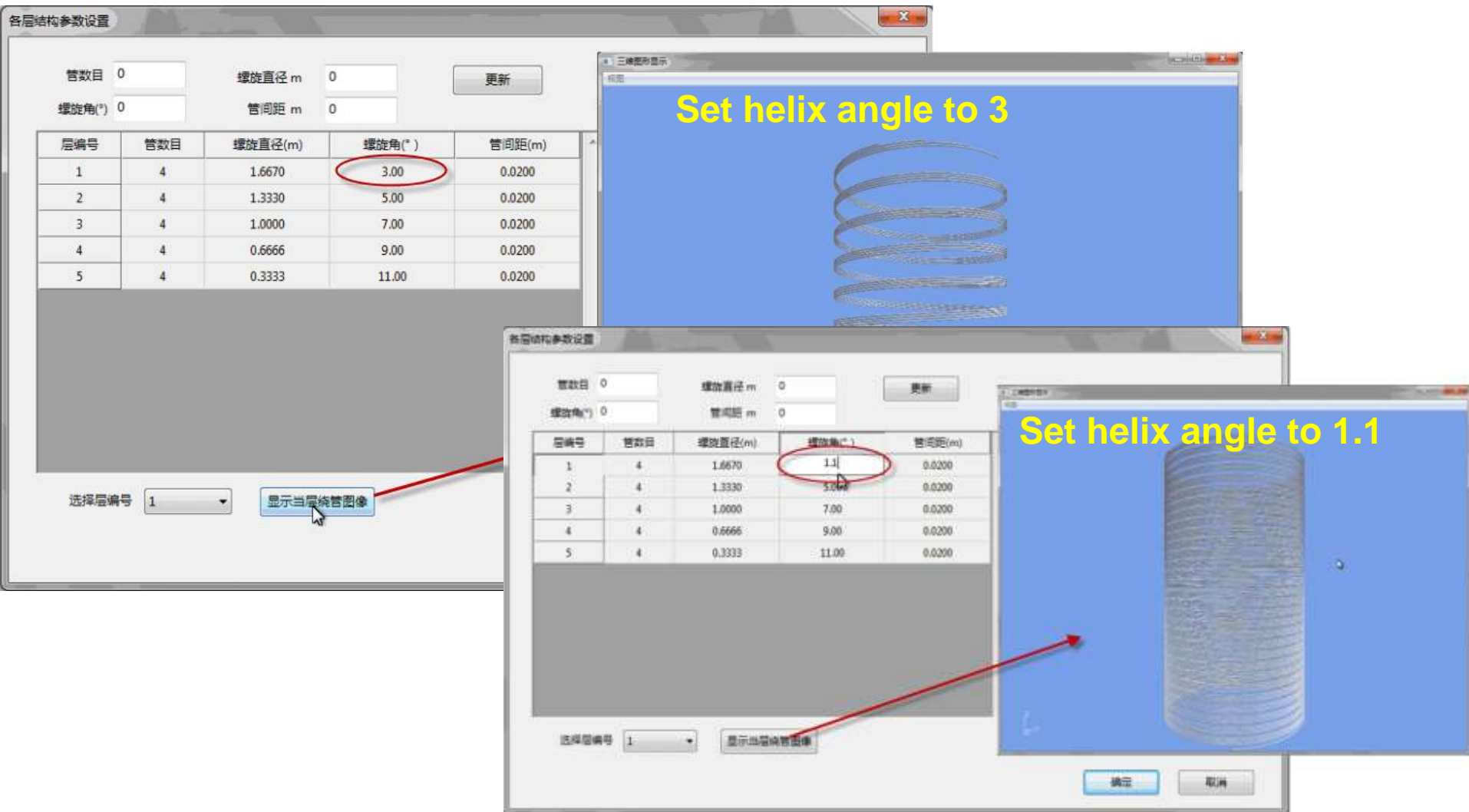
Double-bundle Type



Single-bundle Type



Three-dimensional graphics aided design



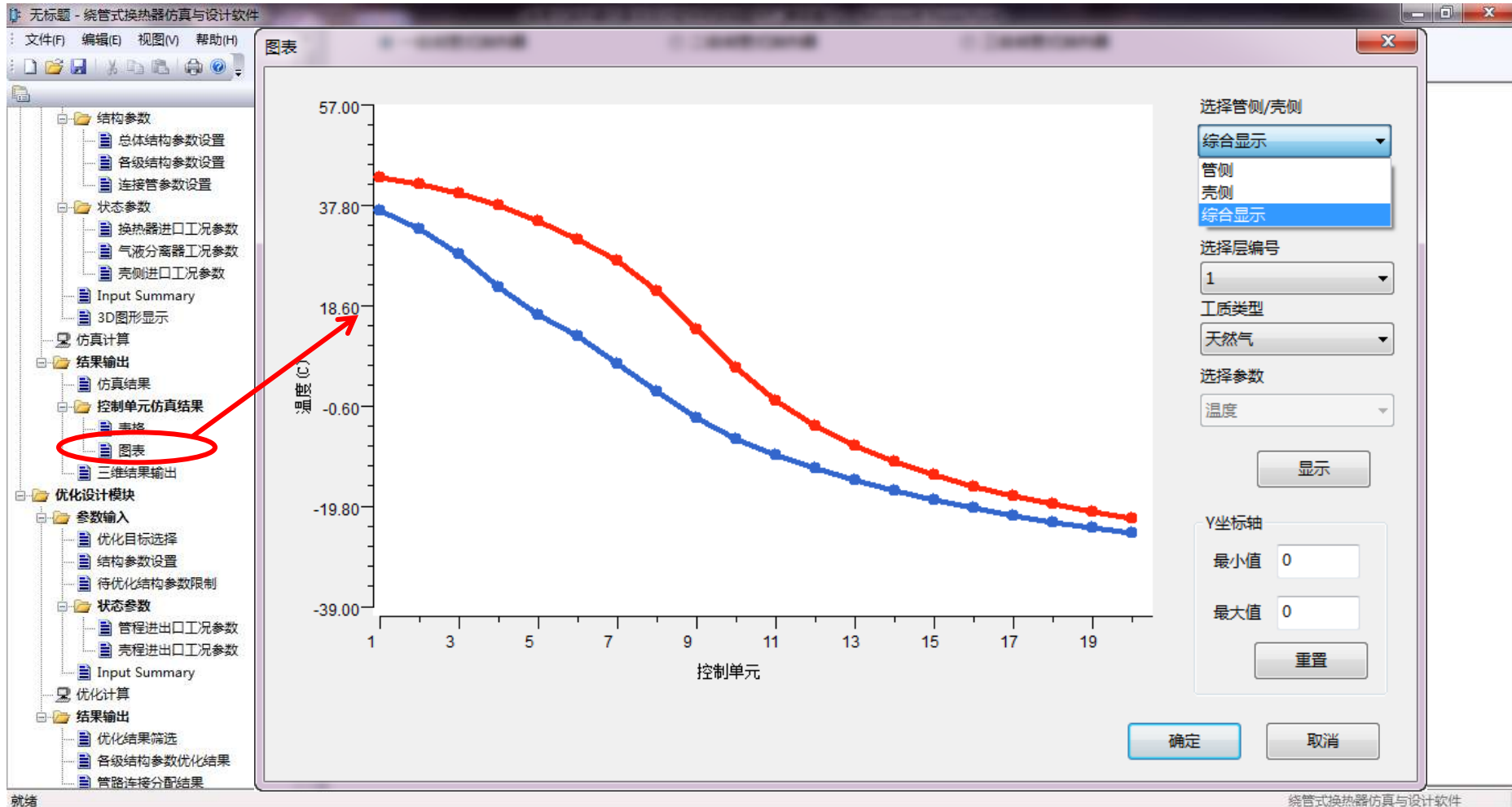
The image displays a software interface for configuring and visualizing helical structures. It consists of several overlapping windows:

- Parameter Settings Window (Top Left):** Titled "各层结构参数设置" (Layer Structure Parameter Settings). It contains input fields for "管数目" (Number of pipes), "螺旋直径 m" (Helix diameter m), "螺旋角(°)" (Helix angle °), and "管间距 m" (Pipe spacing m). A "更新" (Update) button is present.
- Table (Top Left):** A table listing parameters for five layers. The "螺旋角(°)" column for Layer 1 is circled in red.

层编号	管数目	螺旋直径(m)	螺旋角(°)	管间距(m)
1	4	1.6670	3.00	0.0200
2	4	1.3330	5.00	0.0200
3	4	1.0000	7.00	0.0200
4	4	0.6666	9.00	0.0200
5	4	0.3333	11.00	0.0200
- 3D Visualization Window (Top Right):** Titled "三维图形显示" (3D Graphics Display). It shows a 3D wireframe model of a helical structure. A yellow text overlay reads "Set helix angle to 3".
- Parameter Settings Window (Bottom Middle):** A second instance of the parameter settings window. The "螺旋角(°)" field for Layer 1 is set to 1.1 and is circled in red. A red arrow points from the "显示当前层管图像" (Display current layer pipe image) button in this window to the 3D visualization window.
- 3D Visualization Window (Bottom Right):** Shows a 3D wireframe model of a helical structure. A yellow text overlay reads "Set helix angle to 1.1". A red arrow points from the "显示当前层管图像" button in the parameter settings window above to this 3D view.

Results in coordinate chart

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



Results in 3D colored graph

The screenshot displays a simulation software interface for a heat exchanger. The main window shows a 3D colored graph of a cylindrical heat exchanger with a temperature distribution. A 'Setting dialog' window is open, allowing users to select parameters and streams. The dialog includes the following options:

- Setting dialog**
- 选择需要显示的参数 **Select parameter**
 - 制冷剂温度
 - 制冷剂压力 kPa
 - 制冷剂焓值 kJ/kg
 - 制冷剂干度
- 选择制冷剂流路 **Select stream**
 - 天然气流路
 - 所有流路
 - 天然气流路
 - 轻制冷剂流路
 - 轻制冷剂流路
- 图例划分 10
- 确定 取消

The 3D graph shows a temperature distribution with a color scale on the right ranging from 9.66 to 43.00 °C. The software interface includes a menu bar (文件(F), 编辑(E), 视图(V), 帮助(H)), a toolbar, and a tree view on the left with categories like '基本信息', '仿真计算模块', '结果输出', and '优化设计模块'. The '三維結果輸出' option is highlighted in the tree view.



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



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Thank you!

