应用小管径的高效制冷空调装置开发技术

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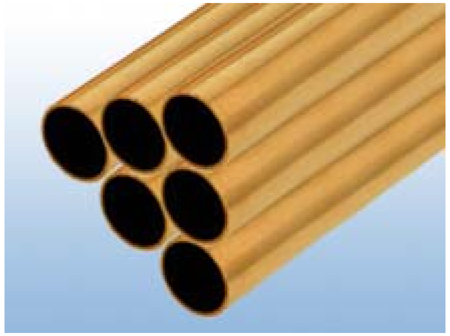
2016-05-26

提纲

1. 小管径问题概述
2. 管内制冷剂传热与流动特性
3. 翅片侧传热流动模拟与翅片设计
4. 换热器热力性能模拟与优化设计
5. 整机热力性能模拟与优化设计
6. 降噪与长效
7. 结论

小管径思路的提出

- "铜管-铝翅片"的翅片管式换热器是最常用的制冷剂-空气热交换器
- 小管径提出的直接原因- 减少铜材料的消耗，降低成本



空调器

Air Conditioner

翅片管换热器

Heat Exchanger

铜管

Copper Tubes

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小管径的好处

- 降低生产成本 – 管子细了，还可以更薄
- 提高传热效率 – 制冷剂可以更好与管子换热
- 减小空调器的体积
- 降低制冷剂充注量

管径： 9.52mm 7.0mm → 改进 → **管径：**5.0mm → 改进 → **管径更小**

Previous **Now** **Future**

对于**7 mm → 5 mm**：

同样长度管节省铜材料约30%，降低充注量50%

应用小管径需要解决的主要问题

制造技术问题：

- 细径薄壁管子的制造
- 防止胀管收缩
- 薄壁细管的胀接焊

设计技术问题：

- 如何选管子 － 没有管内传热与压降特性的关联式了
- 如何设计翅片 － 没有为细管配套的翅片，没有计算翅片侧空气传热与压降特性的成果
- 如何设计换热器 － 5mm管直接替代7mm管产生4倍压降
- 如何设计整机 － 同时考虑管子、翅片、流路的变动

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管内制冷剂换热与流动工作概述

目标：

- 了解小管径内实际制冷剂-油混合物的换热与流动特性
- 建立相应关联式

蒸发工况：

- 建立制冷剂-油混合物蒸发换热与流动实验台
- 进行不同工况参数下的蒸发实验：管子尺寸、制冷剂－油混合物质流密度、油浓度、热流密度
- 开发关联式

冷凝工况：

- 建立制冷剂-油混合物冷凝换热与流动实验台
- 进行不同工况参数下的蒸发实验：管子尺寸、制冷剂－油混合物质流密度、油浓度、热流密度
- 开发关联式

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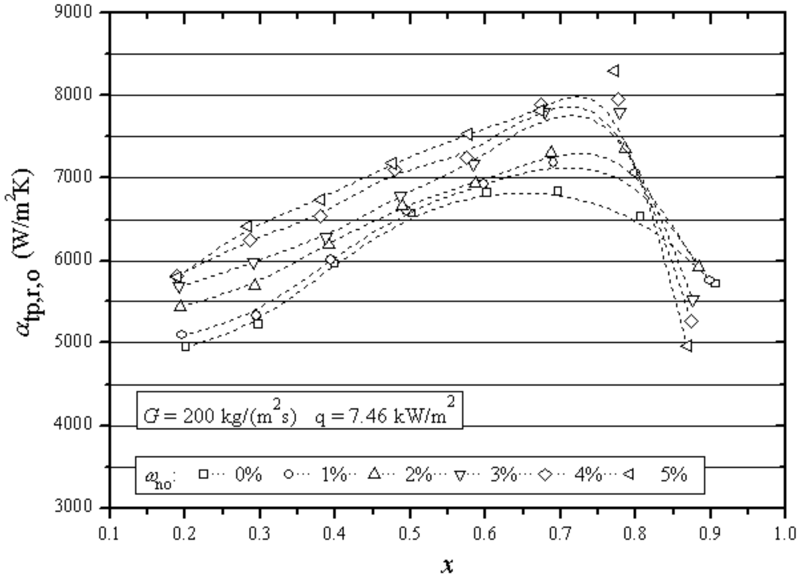
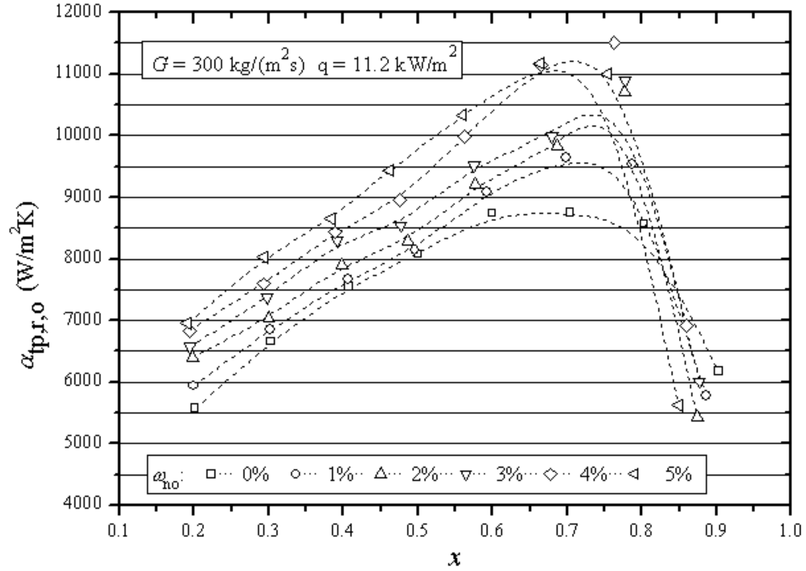
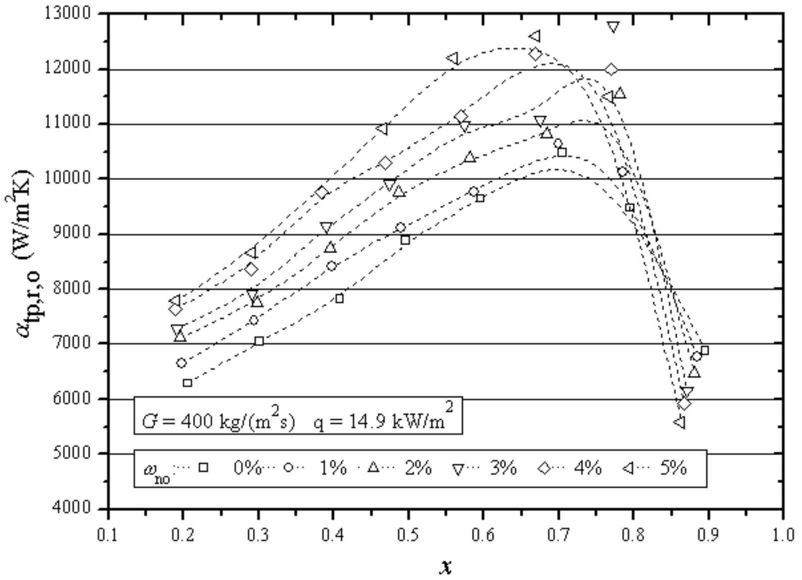
蒸发换热实验台

5 mm强化管内的蒸发换热-干度与油浓度





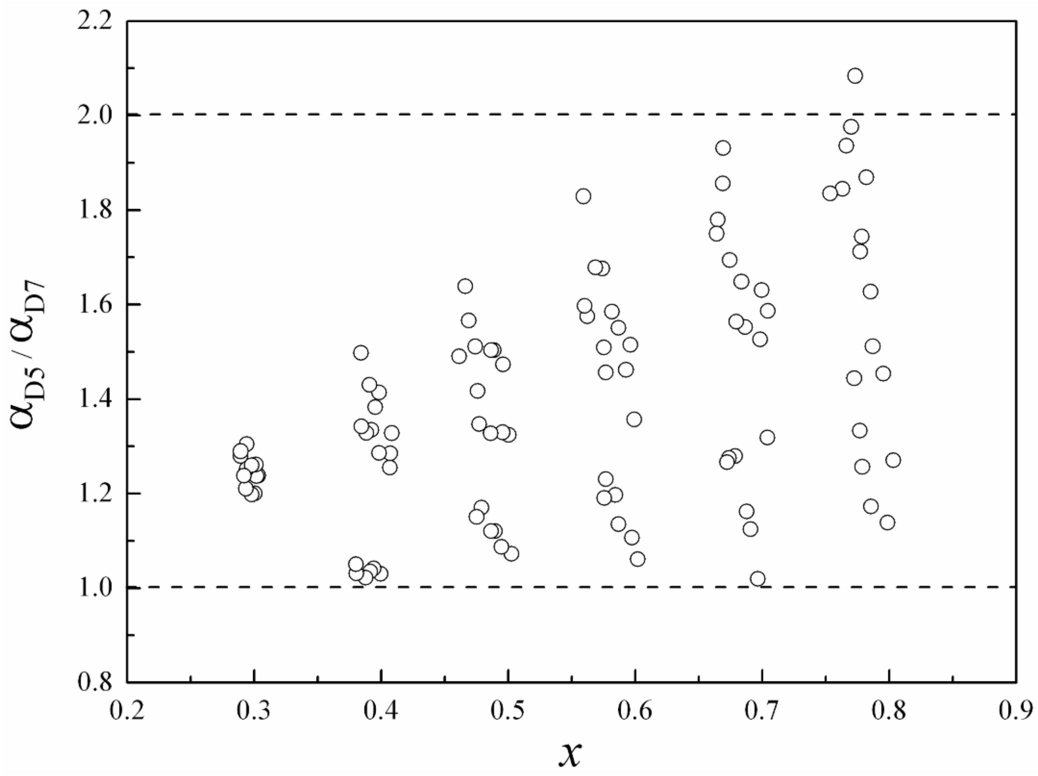


- 对于纯R410A：
  换热系数随干度的增大先增大，再下降。

- 对于R410A-油混合物：
  在干度小于0.6时，润滑油的存在对换热起增强作用；干度大于0.8时，换热系数随着油浓度和干度的增大迅速降低。

5 mm强化管内的蒸发换热-对比7mm管

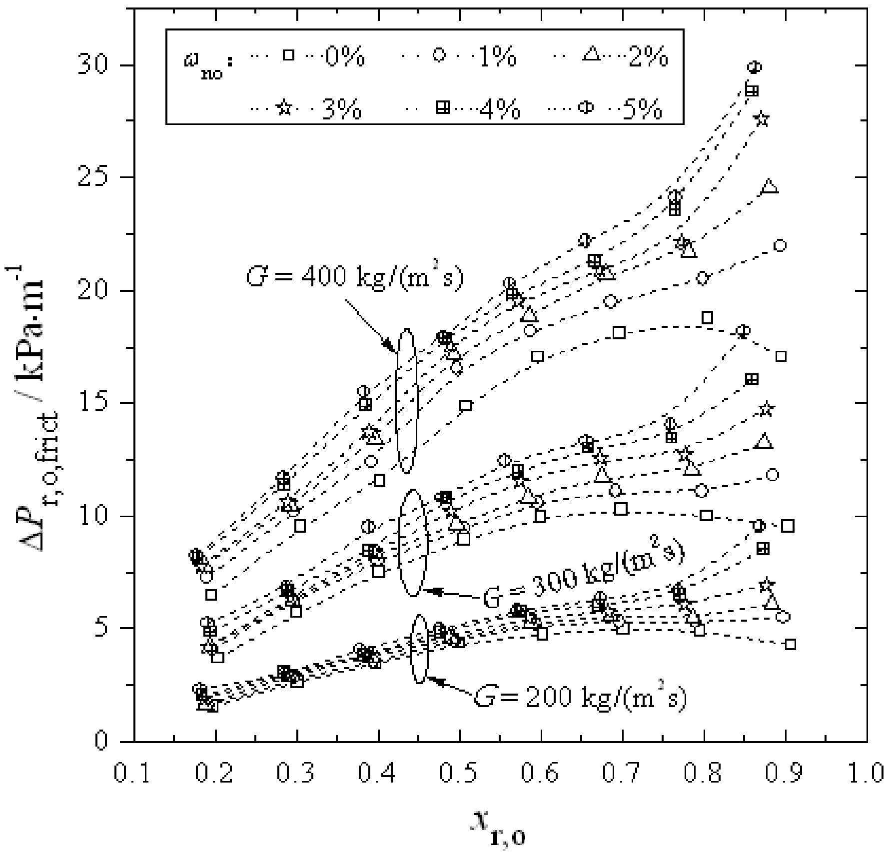
5mm管和7mm管的换热系数的比值



结论：

5mm强化管内的换热系数比7mm强化管的换热增大0%~100%

5 mm强化管内的蒸发压降-干度与油浓度

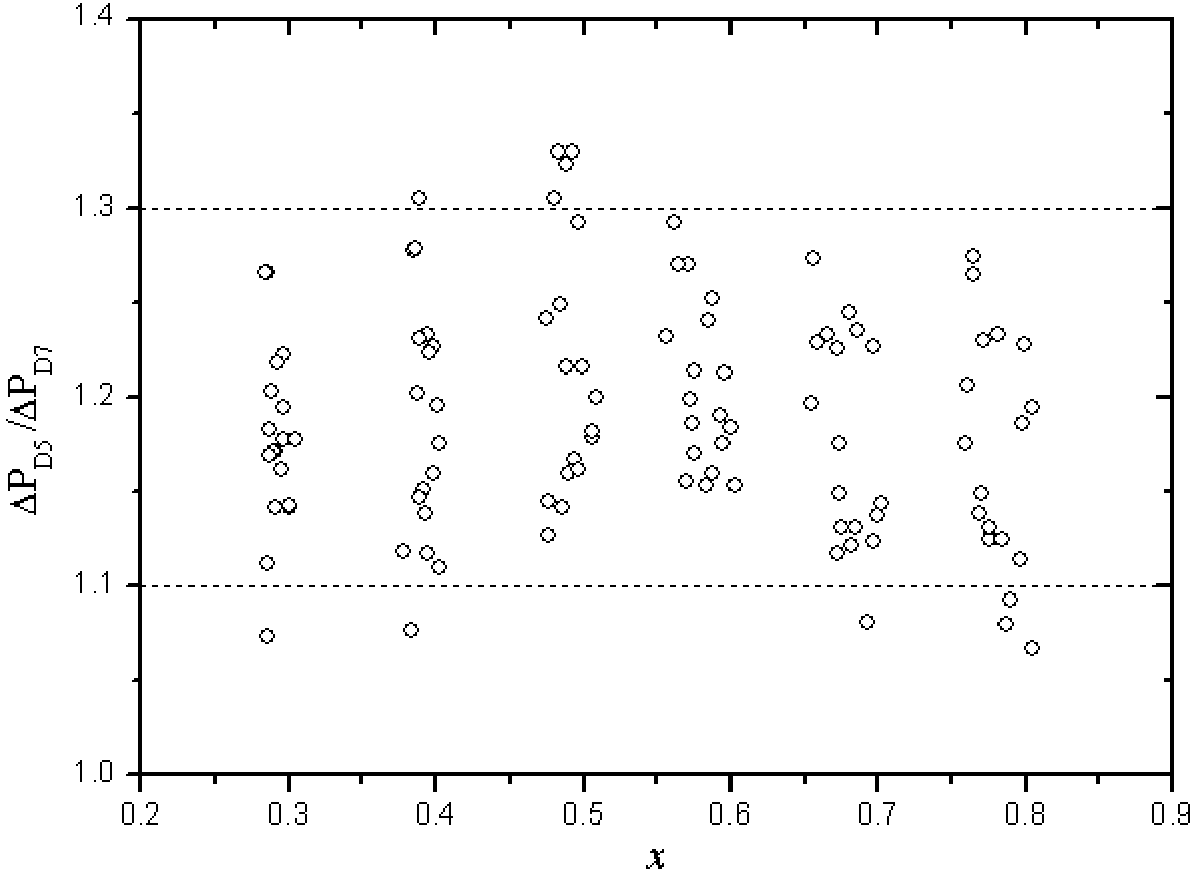


1）R410A-油混合物的摩擦压降随平均油浓度、质流密度和干度的增大而增大

2）纯制冷剂R410A，摩擦压降随着干度的增大先增大后减小，峰值出现在干度为0.7～0.8左右

5 mm强化管内的蒸发压降-对比7mm管

5mm管和7mm管的摩擦压降的比值



结论:

5mm强化管内的摩擦压降比7mm强化管的摩擦压降增大10%~30%

冷凝换热实验台

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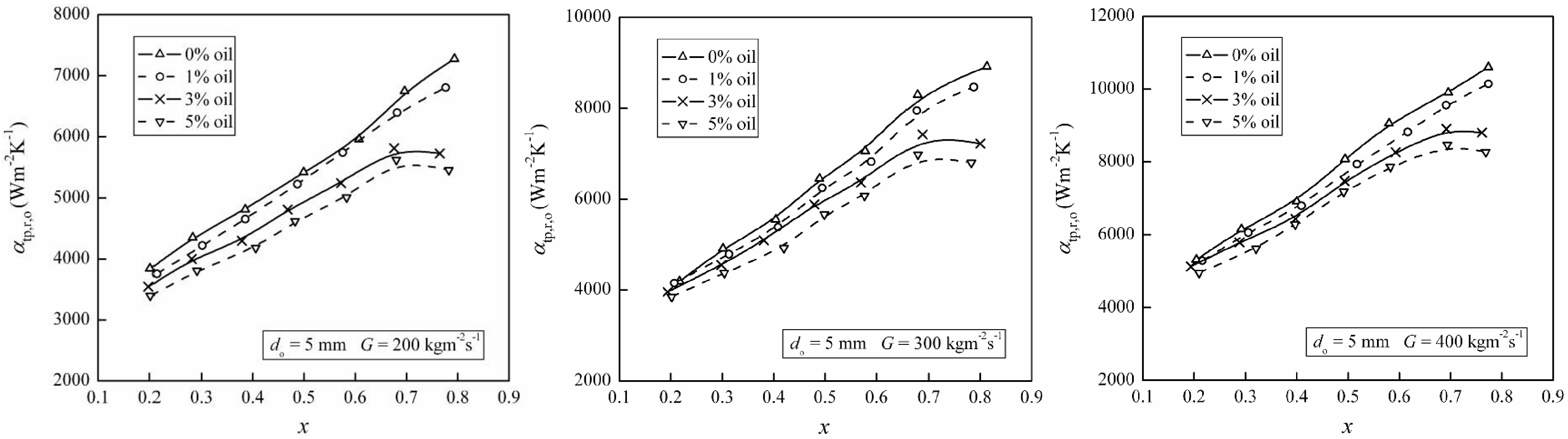
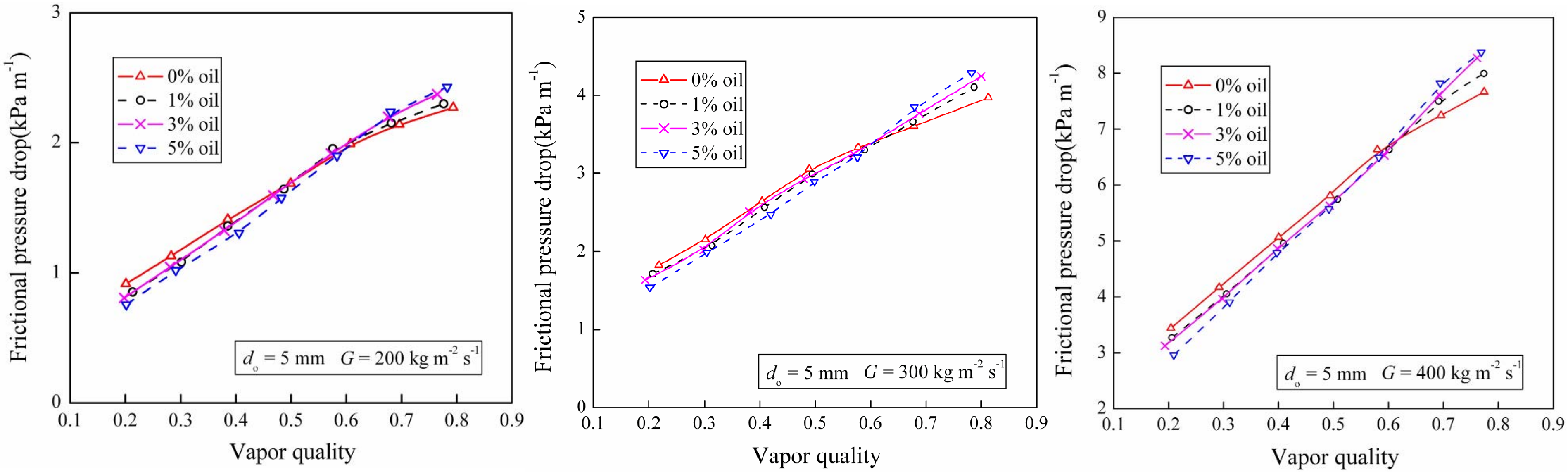
5 mm强化管内的冷凝换热



干度对换热系数的影响：

- 纯制冷剂R410A和1%油浓度，R410A-油混合物的换热系数随干度的减小而减小
- 3%和5%油浓度，换热系数随着干度的下降先增大，在干度0.7左右达到峰值，然后随着干度的下降而下降

5 mm强化管内的冷凝压降



x < 0.6：$\Delta P_{r,o,frict} < \Delta P_{r,frict}$　　　x > 0.6：$\Delta P_{r,o,frict} > \Delta P_{r,frict}$

油对压降的影响：

中低干度：油的存在 → 降低摩擦压降

高干度：油的存在 → 增加摩擦压降

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适应小管径的翅片开发问题概述

直接的问题：

- 翅片间距必须小到一定程度 – 强化结构风阻加大
- 不能照搬国外产品 – 几乎没有现成产品，不想多开翅片模，想用现成的大部分产品模具

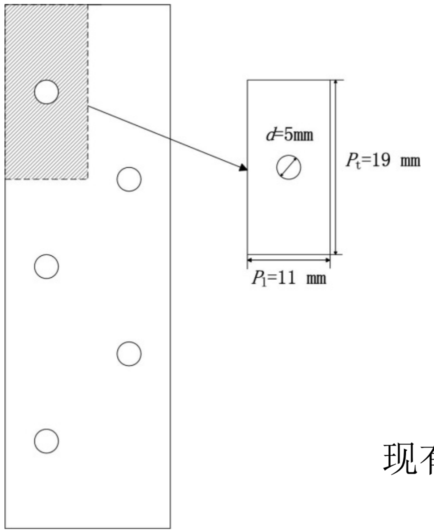
技术上的短缺：

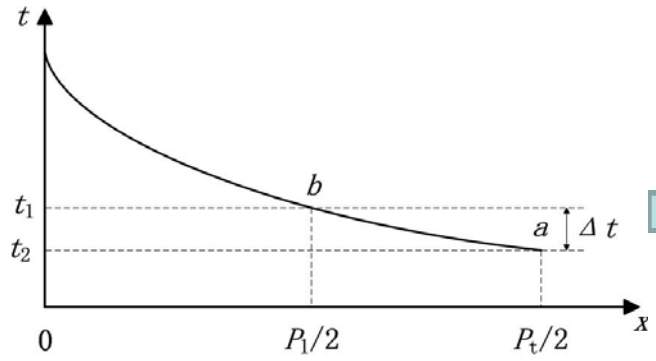
- 缺针对小管径翅片的设计方法
- 缺可以针对翅片析湿过程模拟的CFD软件
- 缺少小管径翅片的实验测试与关联式

开展的工作：

- 提出小管径翅片设计的一般原则
- 开发可以模拟复杂结构翅片析湿过程的模拟软件
- 进行小管径翅片的实验测试与关联式开发

一些现有翅片的问题分析





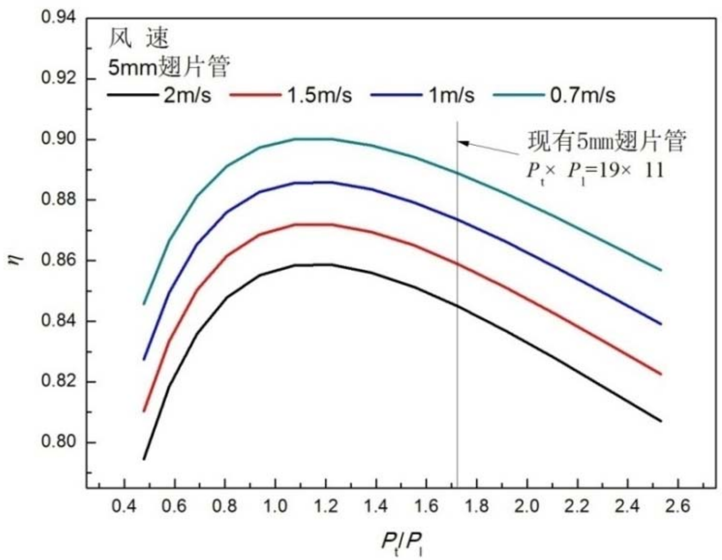
现有5 mm 换热器翅片P_t、P_l方向的温度分布图

理想翅片：

$T_{P_t/2}=T_{P_l/2}$

现有翅片：

$T_{P_t/2} < T_{P_l/2}$



现有翅片的效率不是最大值

翅片开缝结构的选择

➢ 开缝类型选取目标：

- 换热好
- 空气侧压降小

➢百叶窗式开缝特点：

•切断散热带上空气侧边界层的发展、提高换热性能，缺点是空气侧压降较大；

➢桥式开缝特点：

•相比窗片，其换热性能略低，但是空气侧压降较小。

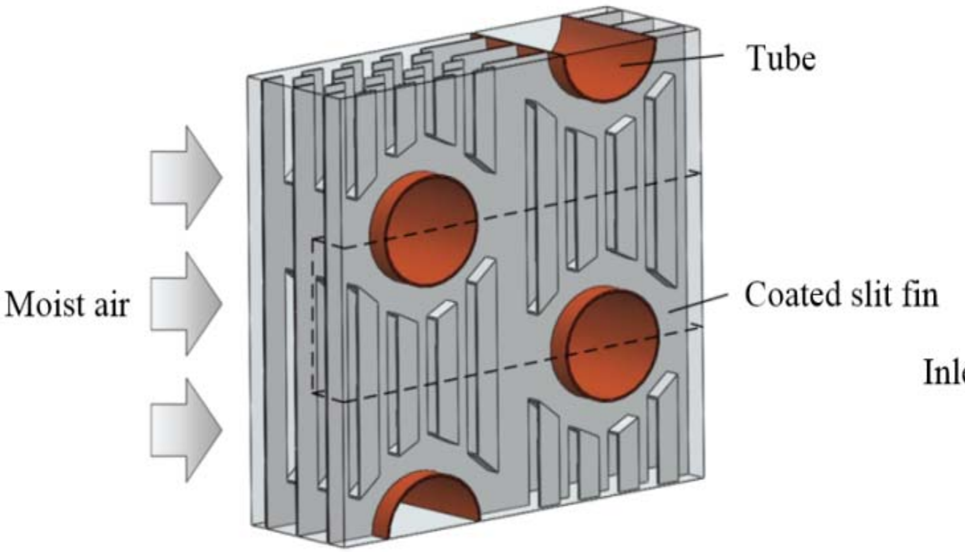
➢确定开缝尺寸：

•采用**CFD**模拟

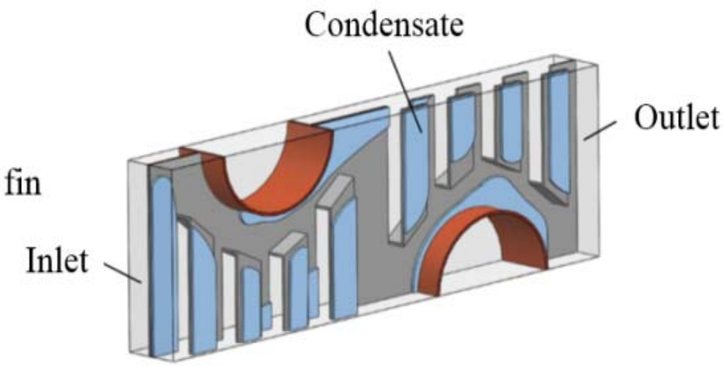
•干工况可以用商业软件；湿工况得二次开发

翅片表面析湿过程的模拟

❑ 空调器析湿过程的物理模型



a) 翅片管式换热器



b) 翅片上析湿产生的冷凝水

湿空气流经翅片表面，由于翅片表面温度低于露点温度，翅片表面有冷凝水产生

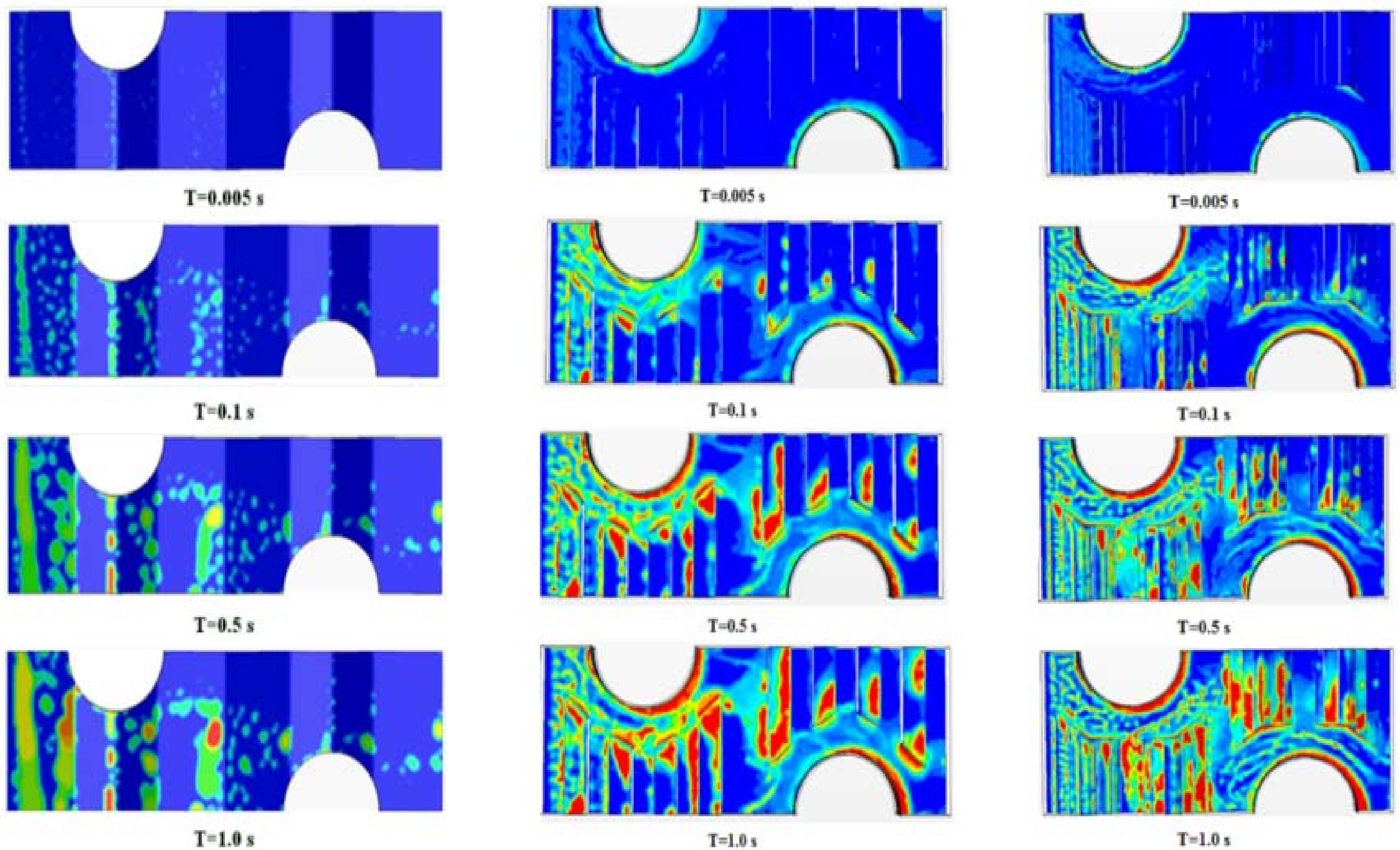
→

随着时间推移，翅片表面的冷凝水越来越多并开始发生流动

翅片表面析湿过程的模拟

❑ 模型计算结果-亲水强化翅片

波纹片 | 条缝片 | 百叶窗片

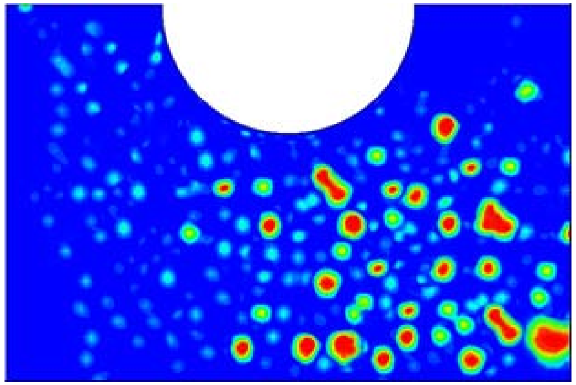


- 对于亲水强化翅片，冷凝水形成过程与平翅片不同。冷凝水更容易在强化结构处（例如波纹、开缝和百叶窗）形成，并沿重力方向流出翅片表面。

翅片表面析湿模型的实验验证

❑可视化验证结果

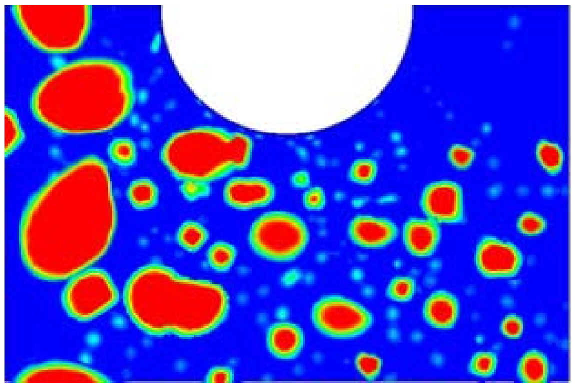
翅片表面
液滴形成过程



模拟结果

实验结果

翅片表面
液滴生长过程



模拟结果

实验结果

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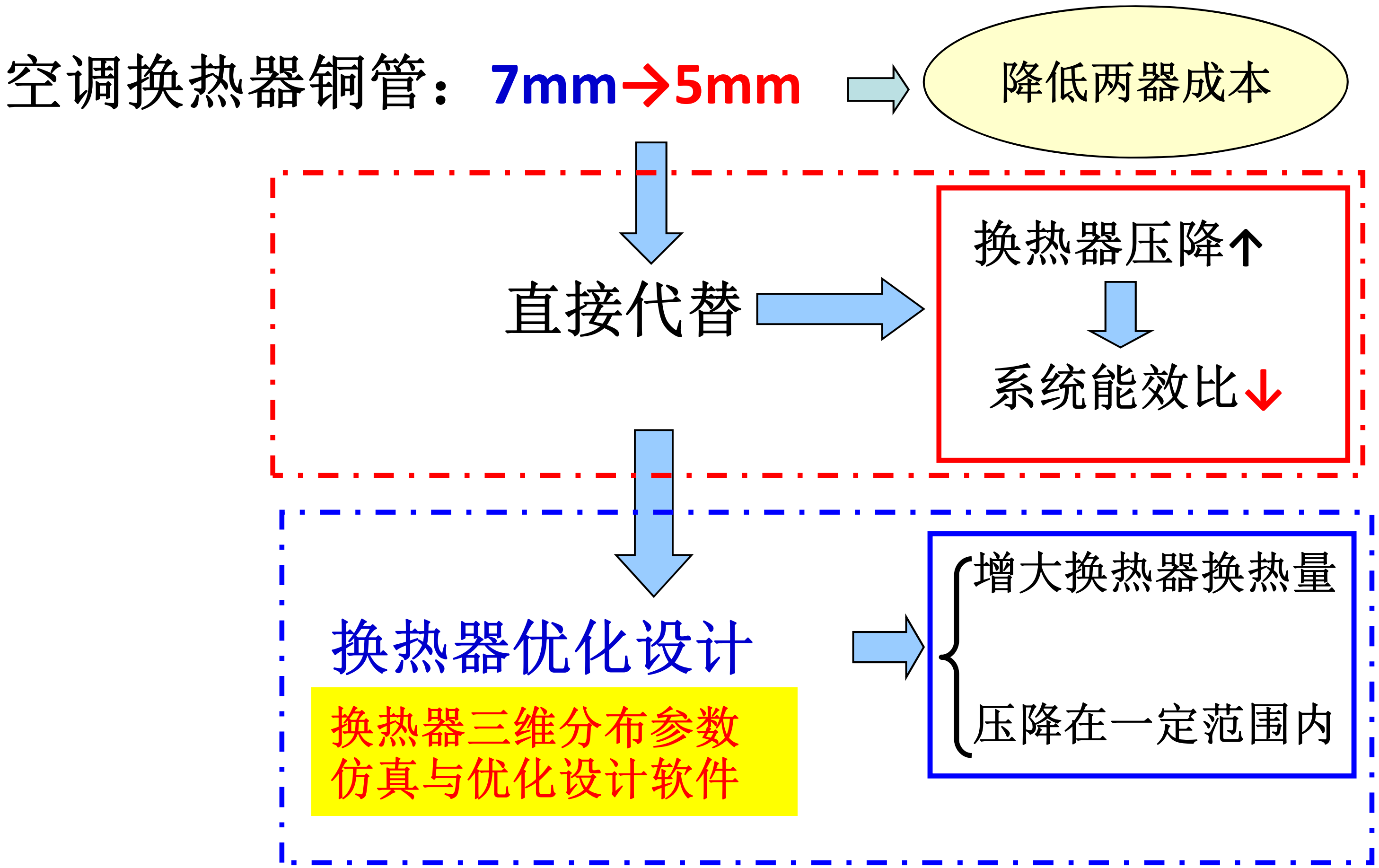
换热器优化设计思路


空调换热器铜管：7mm→5mm
降低两器成本
直接代替
换热器压降↑
系统能效比↓
换热器优化设计
换热器三维分布参数
仿真与优化设计软件
增大换热器换热量
压降在一定范围内

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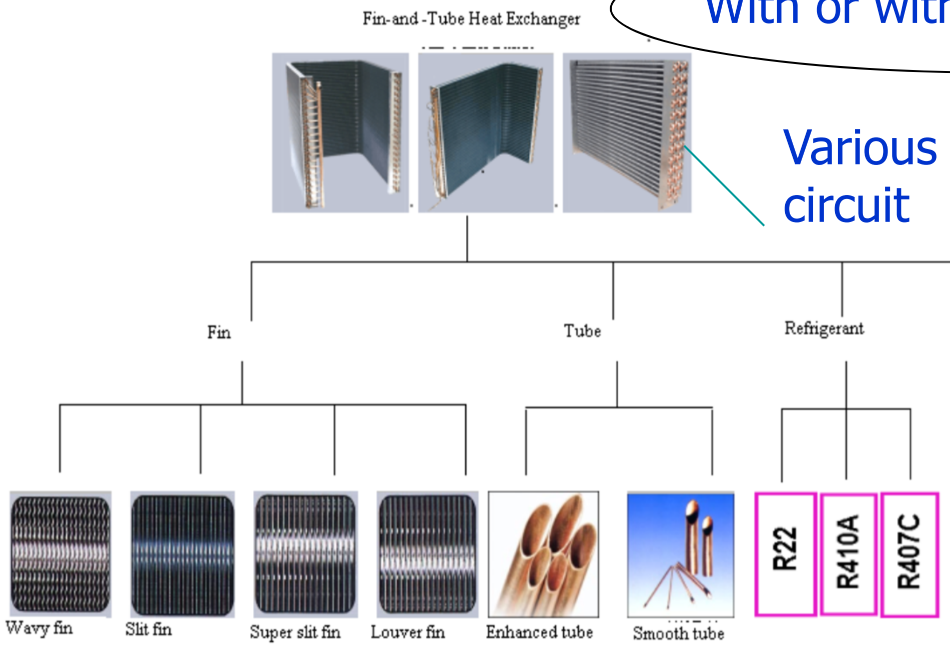
翅片管式换热器的类型

With or without inner capillary

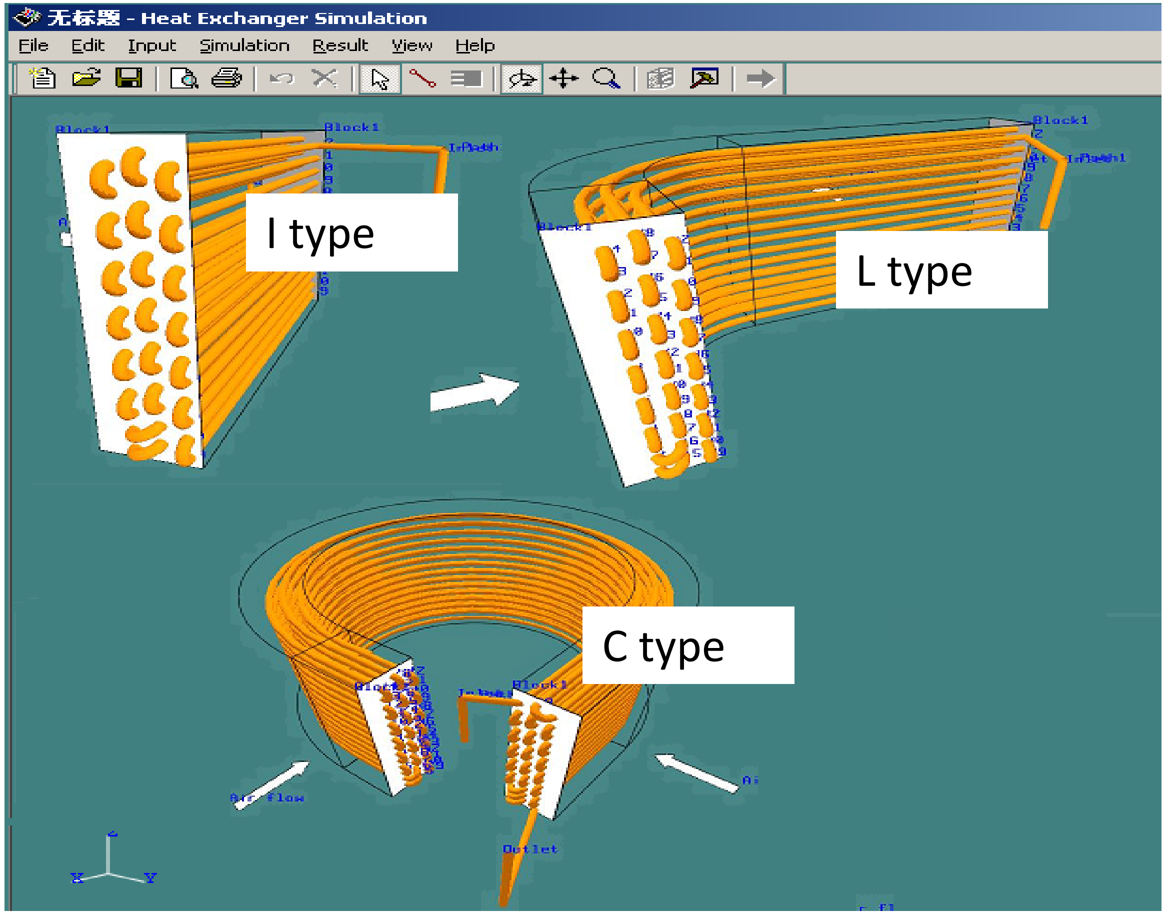
Various block number and refrigerant circuit



Two dimension non uniform air distribution

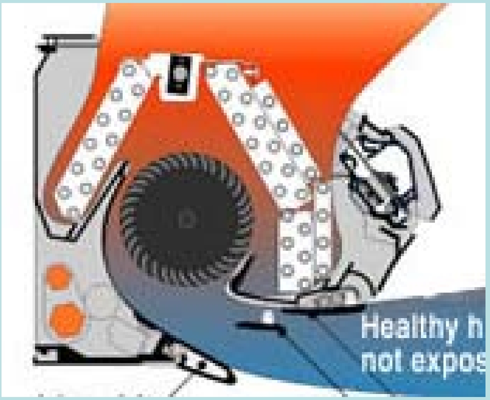
Various fin and tube structure and 3 kinds refrigerants

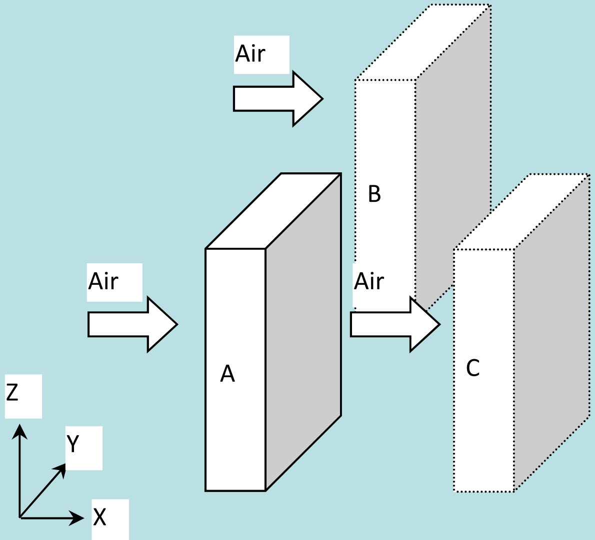
要可以描述不同的换热器形状态

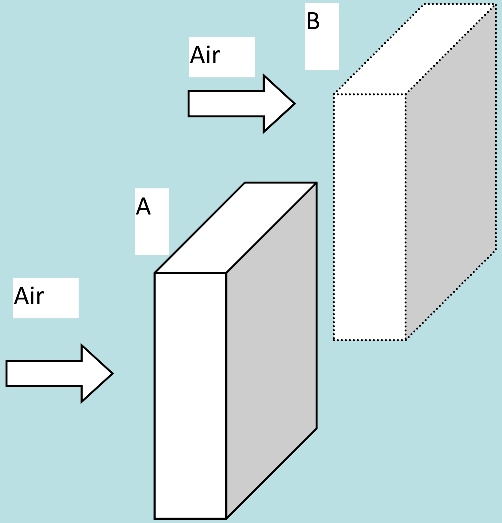


三种基本的形式，可组成其余的形式

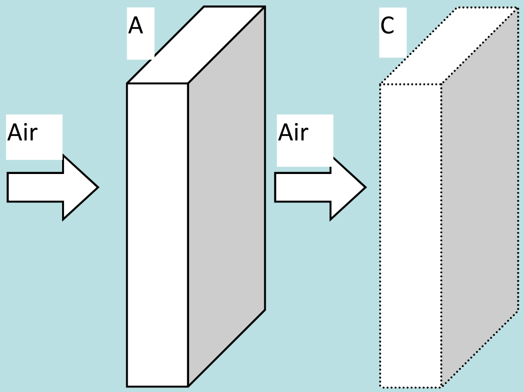
适用于多个换热块的位置排列







Parallel



Serial

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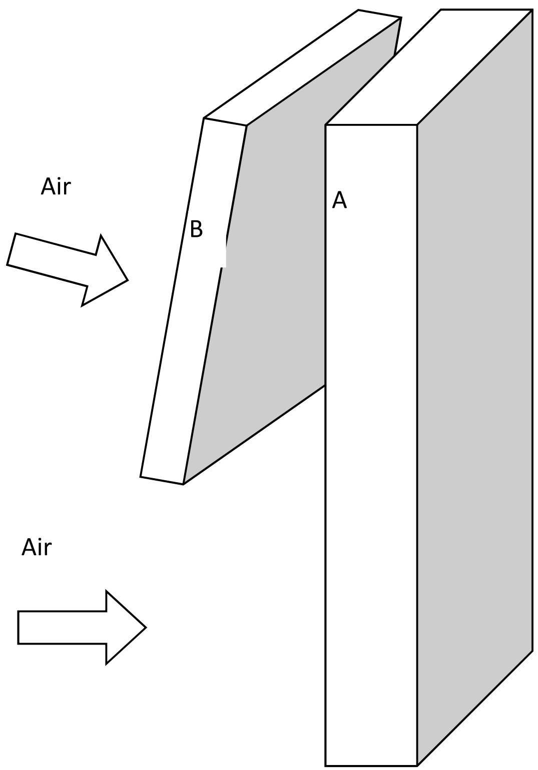
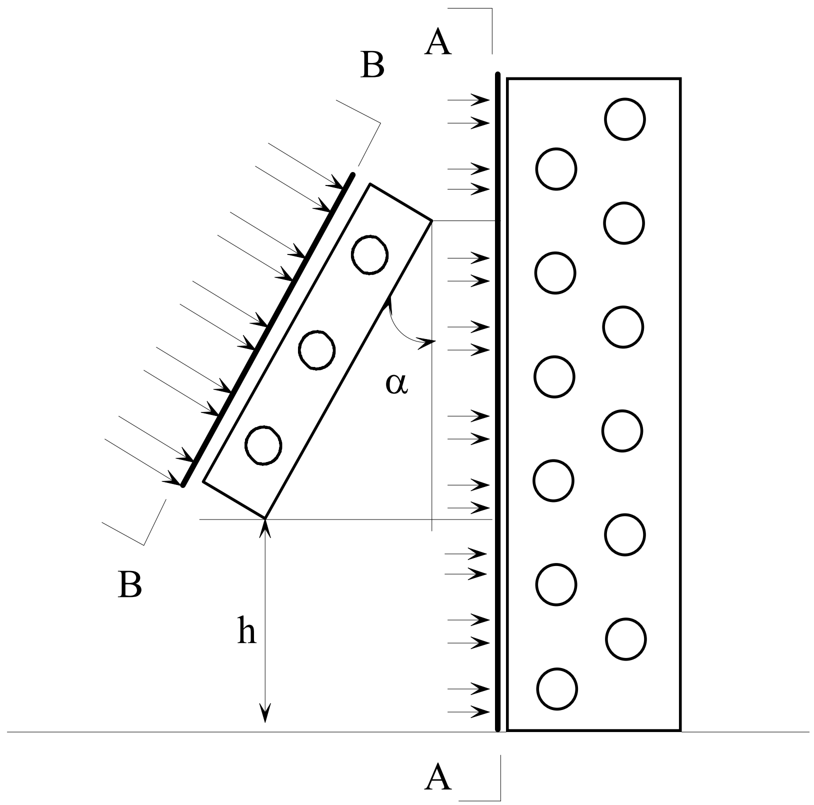
“一主一从”换热块组合





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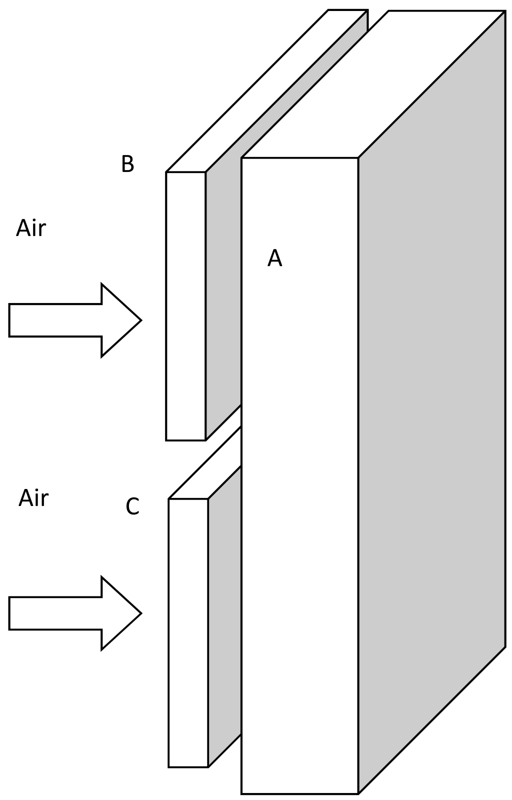
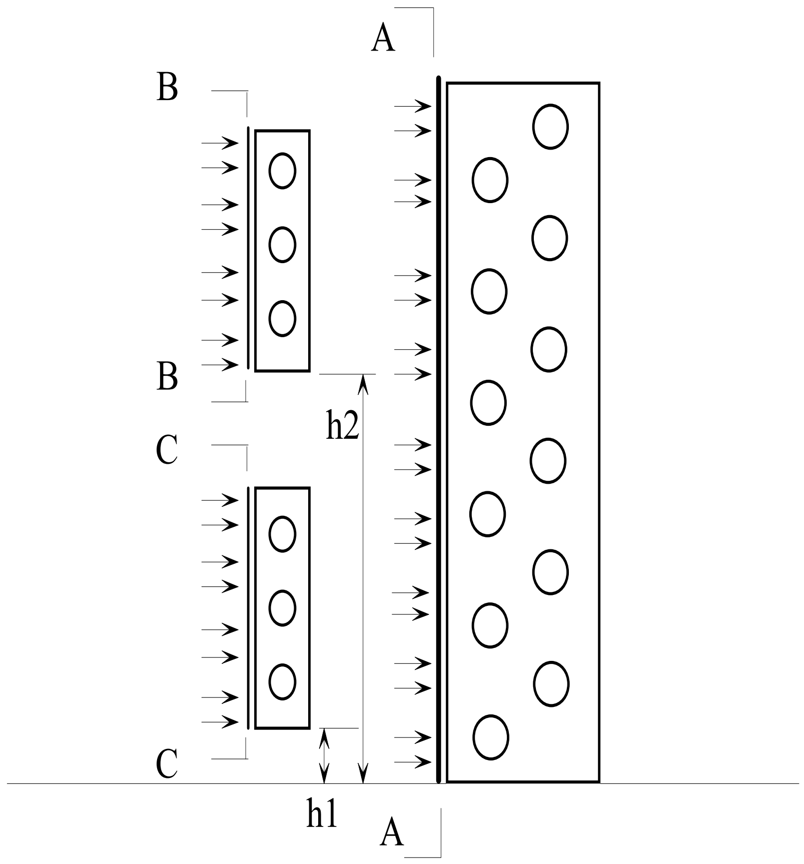
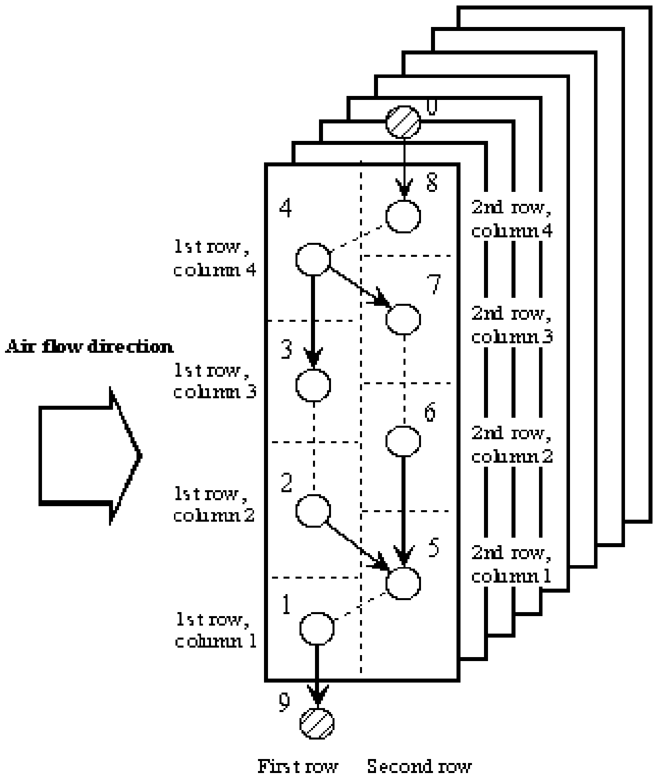
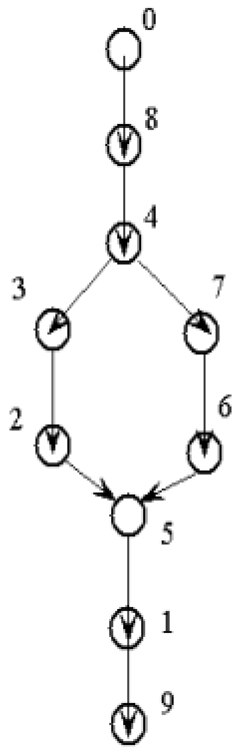
“一主二从”换热块组合





任意管子的连接





$$M=\begin{bmatrix}0&0&0&0&0&0&0&0&1&0\\0&0&0&0&0&0&0&0&0&1\\0&0&0&0&0&1&0&0&0&0\\0&0&1&0&0&0&0&0&0&0\\0&0&0&1&0&0&0&1&0&0\\0&1&0&0&0&0&0&0&0&0\\0&0&0&0&0&1&0&0&0&0\\0&0&0&0&0&0&1&0&0&0\\0&0&0&0&1&0&0&0&0&0\\0&0&0&0&0&0&0&0&0&0\end{bmatrix}$$

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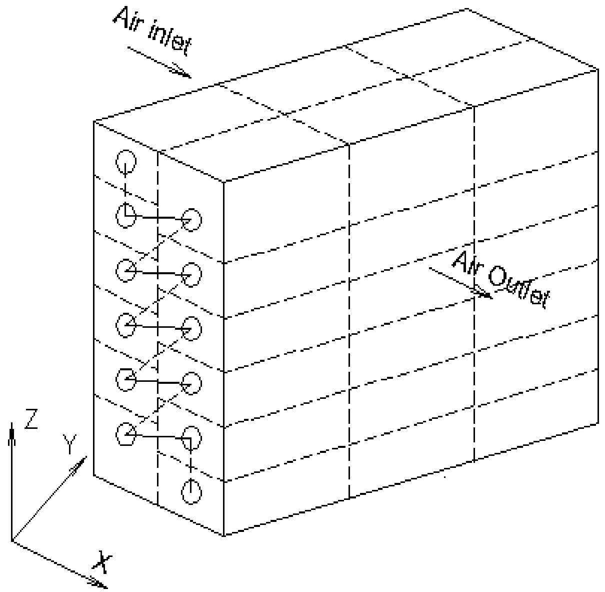
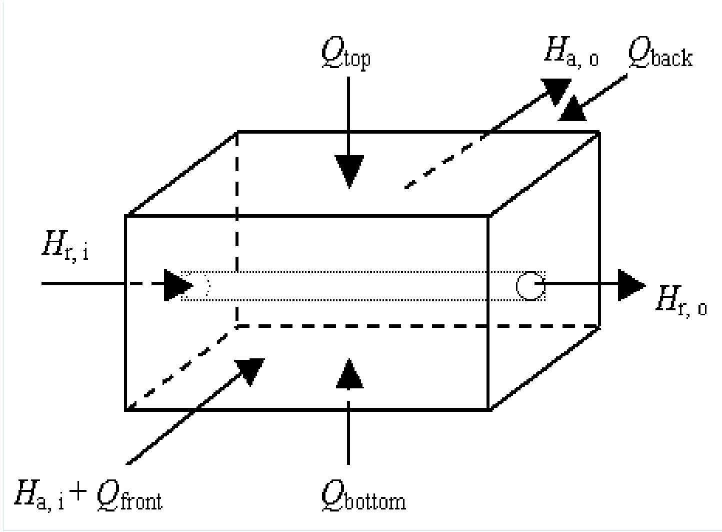
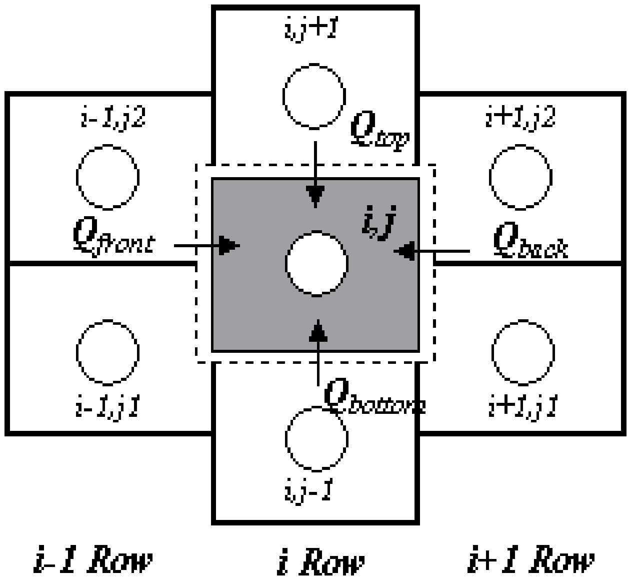
三维分布参数模型





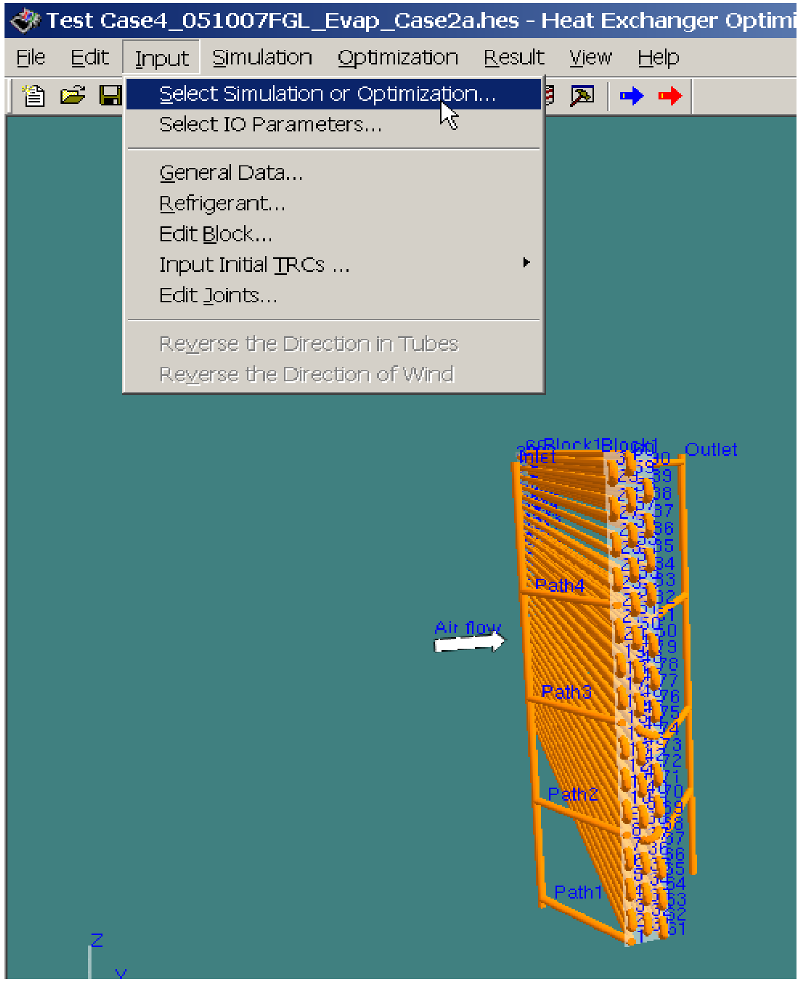
Schematic diagram of typical control volume

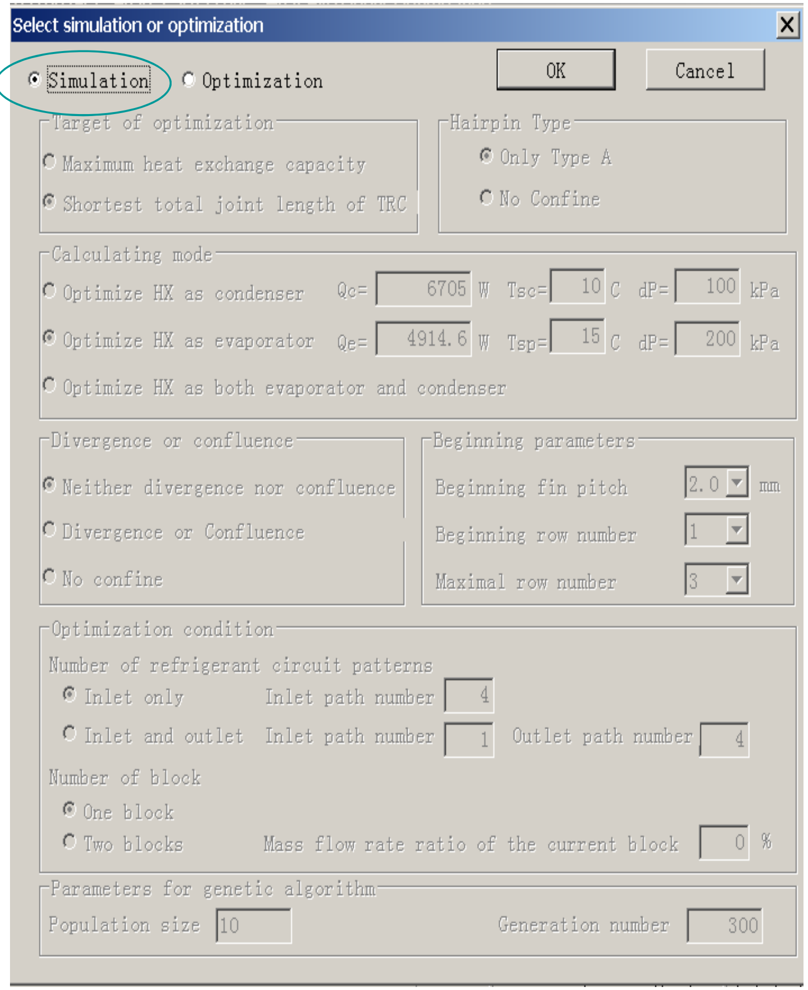
考虑相邻管子通过翅片的导热



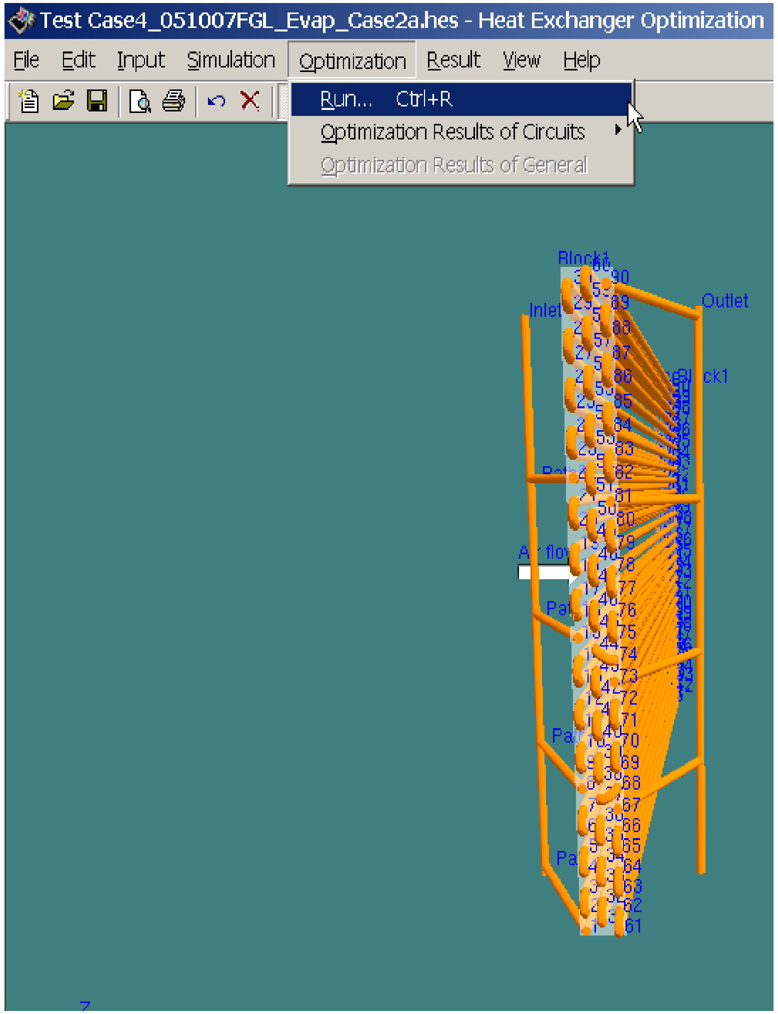
$$Q_r + Q_a + Q_{front} + Q_{back} + Q_{top} + Q_{bottom} = 0$$

可选择“仿真”或“优化”

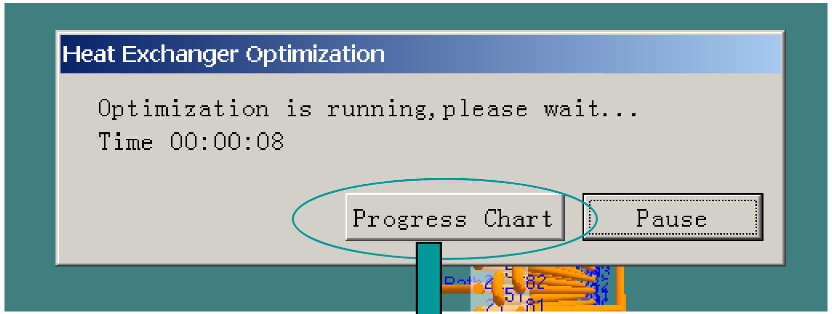

Test Case4_051007FGL_Evap_Case2a.hes - Heat Exchanger Optimi
File Edit Input Simulation Optimization Result View Help
Select Simulation or Optimization...
Select IO Parameters...
General Data...
Refrigerant...
Edit Block...
Input Initial TRCs ...
Edit Joints...
Reverse the Direction in Tubes
Reverse the Direction of Wind
Outlet
Inlet
Path4
Air flow
Path3
Path2
Path1


Select simulation or optimization
Simulation
Optimization
OK
Cancel
Target of optimization
Maximum heat exchange capacity
Shortest total joint length of TRC
Hairpin Type
Only Type A
No Confine
Calculating mode
Optimize HX as condenser Qc= 6705 W Tsc= 10 C dP= 100 kPa
Optimize HX as evaporator Qe= 4914.6 W Tsp= 15 C dP= 200 kPa
Optimize HX as both evaporator and condenser
Divergence or confluence
Neither divergence nor confluence
Divergence or Confluence
No confine
Beginning parameters
Beginning fin pitch 2.0 mm
Beginning row number 1
Maximal row number 3
Optimization condition
Number of refrigerant circuit patterns
Inlet only Inlet path number 4
Inlet and outlet Inlet path number 1 Outlet path number 4
Number of block
One block
Two blocks Mass flow rate ratio of the current block 0 %
Parameters for genetic algorithm
Population size 10
Generation number 300

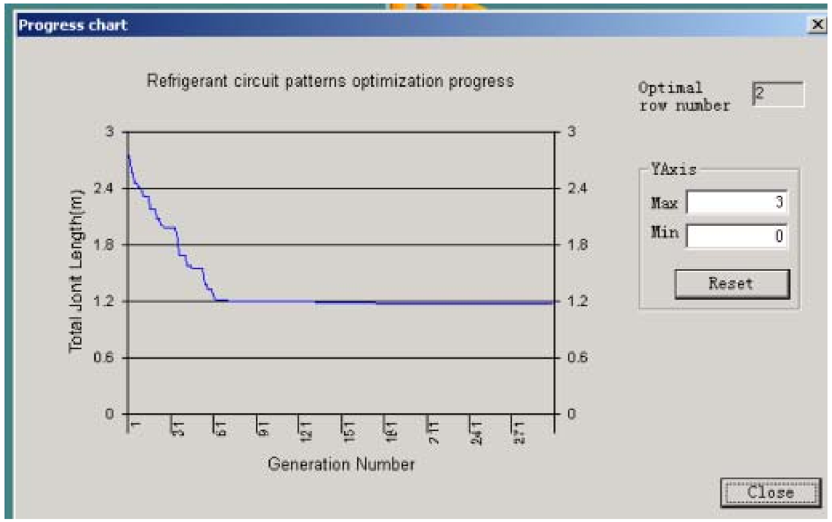
优化时的进程显示



Test Case4_051007FGL_Evap_Case2a.hes - Heat Exchanger Optimization
File Edit Input Simulation Optimization Result View Help
Run... Ctrl+R
Optimization Results of Circuits
Optimization Results of General
Inlet
Outlet

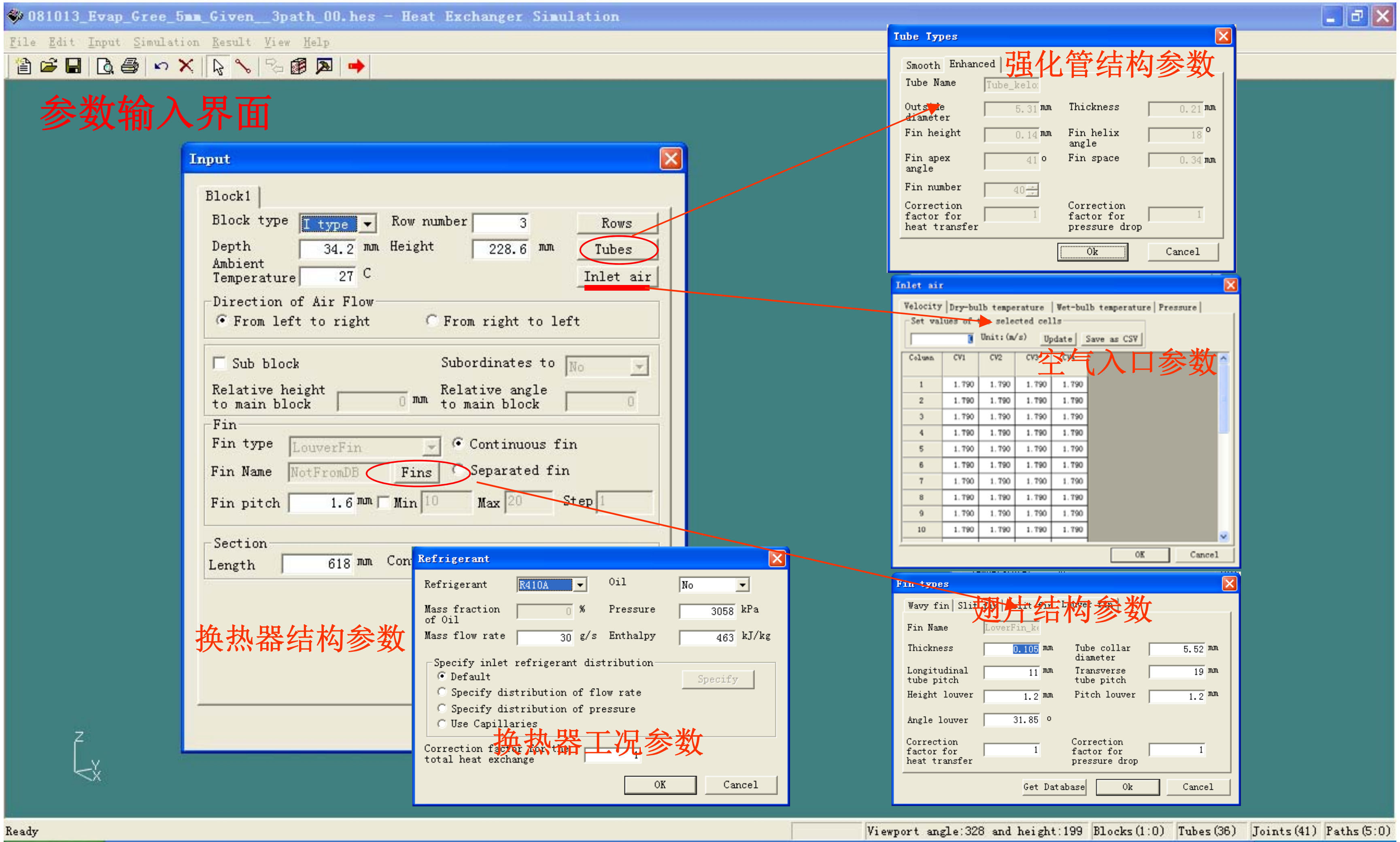


Heat Exchanger Optimization
Optimization is running,please wait...
Time 00:00:08
Progress Chart
Pause



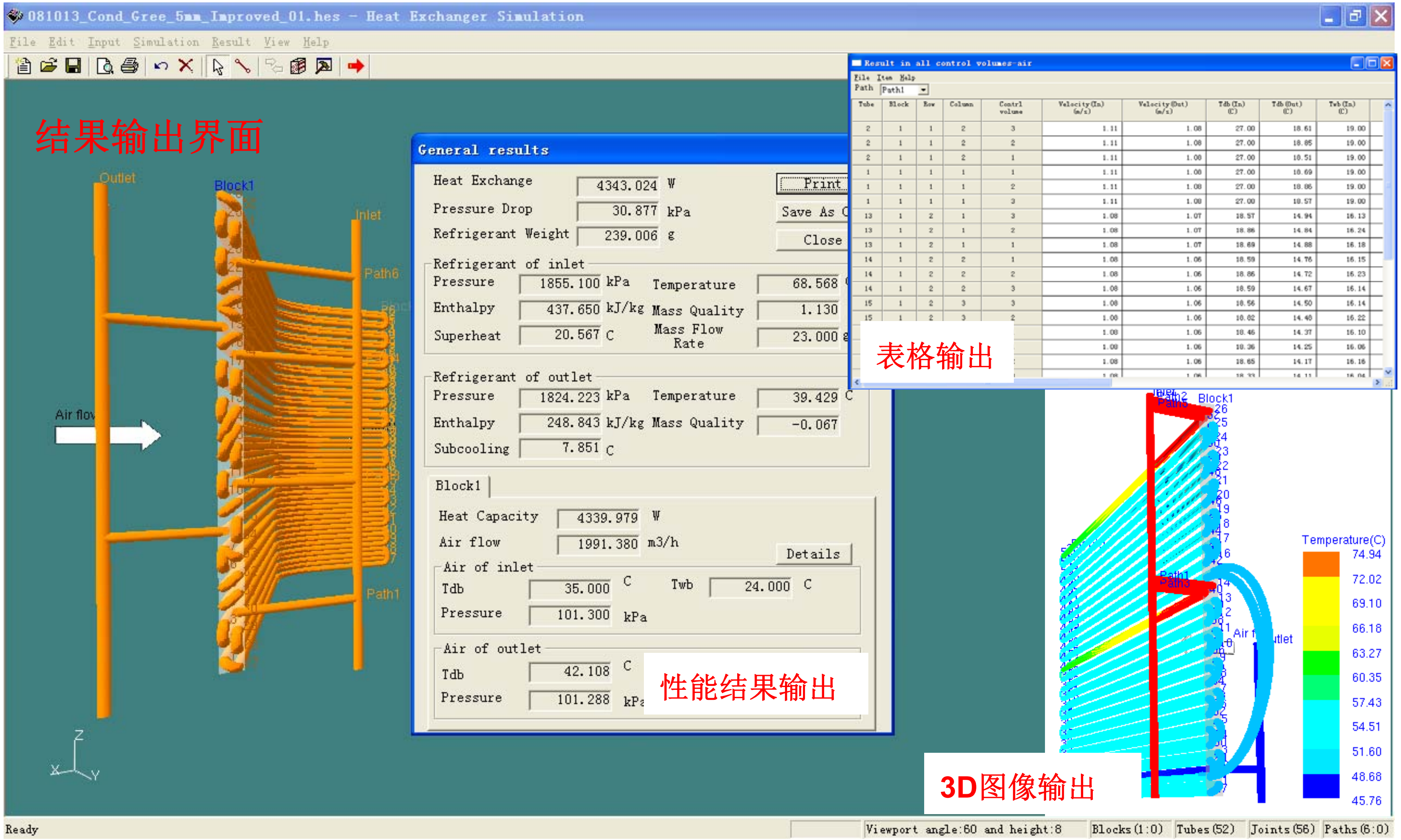
Progress chart
Refrigerant circuit patterns optimization progress
Optimal row number
YAxis
Max
Min
Reset
Total Jont Length(m)
Generation Number
Close

参数输入界面



081013_Evap_Gree_5mm_Given__3path_00.hes - Heat Exchanger Simulation
参数输入界面
强化管结构参数
空气入口参数
翅片结构参数
换热器结构参数
换热器工况参数
Input
Block type
Row number
Depth
Height
Ambient Temperature
Rows
Tubes
Inlet air
Direction of Air Flow
From left to right
From right to left
Fin type
Fin Name
Fins
Fin pitch
Continuous fin
Separated fin
Tube Types
Inlet air
Refrigerant
R410A
Fin types
Ready

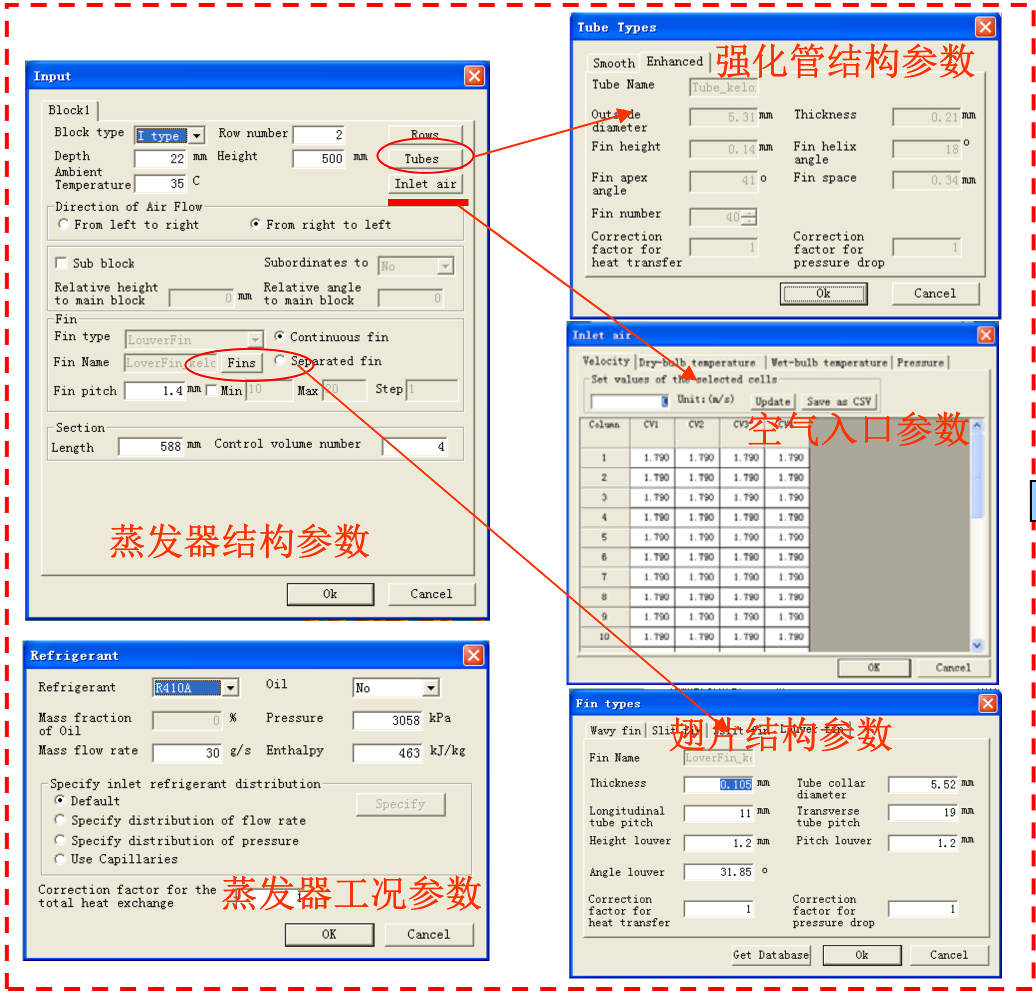
参数输出界面

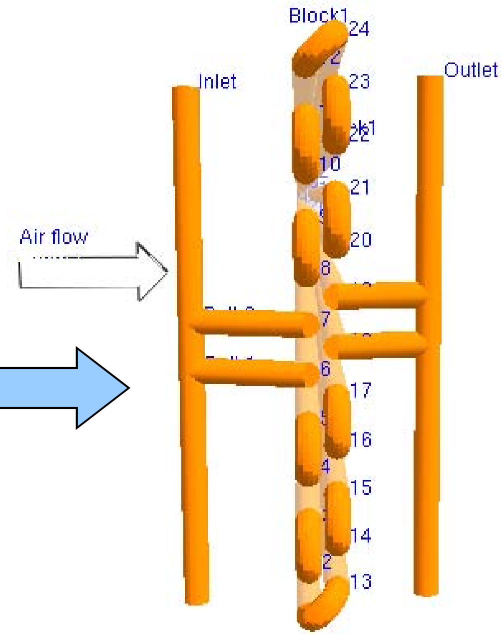


081013_Cond_Gree_5mm_Improved_01.hes - Heat Exchanger Simulation
File Edit Input Simulation Result View Help
结果输出界面
Outlet
Block1
Inlet
Path6
Air flow
Path1
General results
Heat Exchange 4343.024 W
Pressure Drop 30.877 kPa
Refrigerant Weight 239.006 g
Print
Close
Refrigerant of inlet
Pressure 1855.100 kPa
Temperature 68.568
Enthalpy 437.650 kJ/kg
Mass Quality 1.130
Superheat 20.567 C
Mass Flow Rate 23.000
Refrigerant of outlet
Pressure 1824.223 kPa
Temperature 39.429 C
Enthalpy 248.843 kJ/kg
Mass Quality -0.067
Subcooling 7.851 C
Block1
Heat Capacity 4339.979 W
Air flow 1991.380 m3/h
Details
Air of inlet
Tdb 35.000 C
Twb 24.000 C
Pressure 101.300 kPa
Air of outlet
Tdb 42.108 C
Pressure 101.288
性能结果输出
Result in all control volumes-air
表格输出
Temperature(C)
74.94
72.02
69.10
66.18
63.27
60.35
57.43
54.51
51.60
48.68
45.76
3D图像输出
Ready
Viewport angle:60 and height:8
Blocks(1:0)
Tubes(52)
Joints(56)
Paths(6:0)

实例：某R410A蒸发器7 mm ➔ 5 mm优化设计

——蒸发器结构和工况参数输入





仿真软件生成的蒸发器3D模型

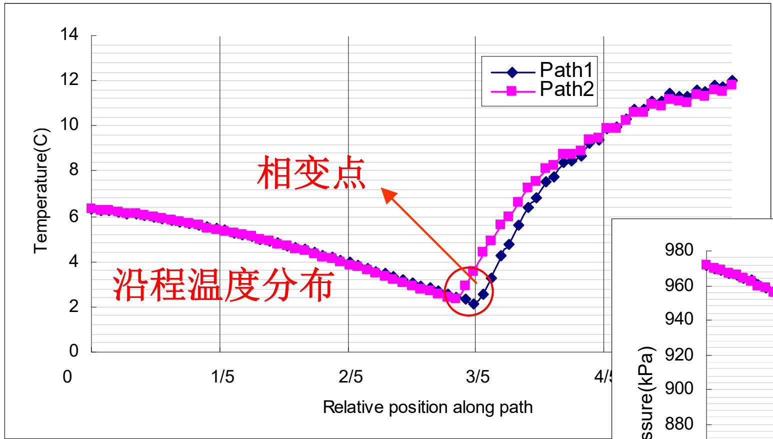
实例：某R410A蒸发器7 mm ➔ 5 mm优化设计

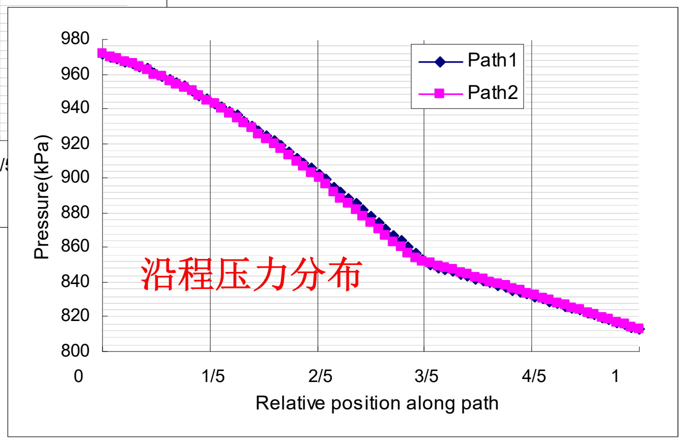
——5 mm管直接代替

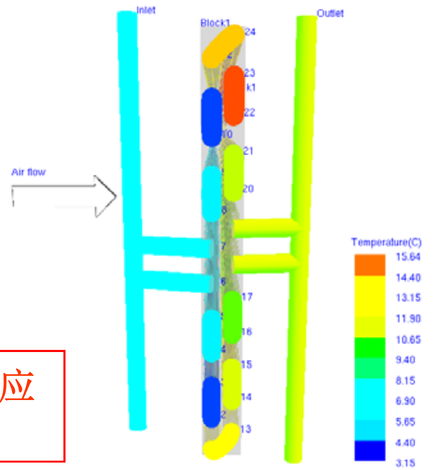
使用5mm管直接代替的仿真结果

连接	换热量 (W)	换热量增加	压降 (kPa)	压降增加
5mm替代	3369.5	1.5%↑	145.2	251.6%↑
原蒸发器	3318.6	--	41.3	--

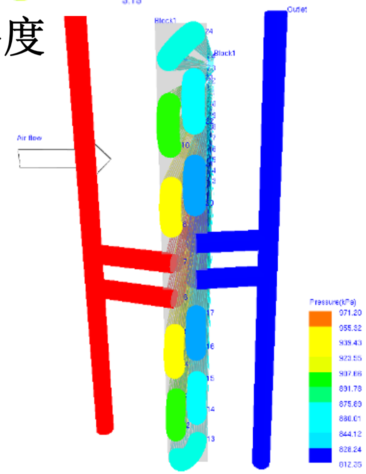
压降过大，应增加分路数







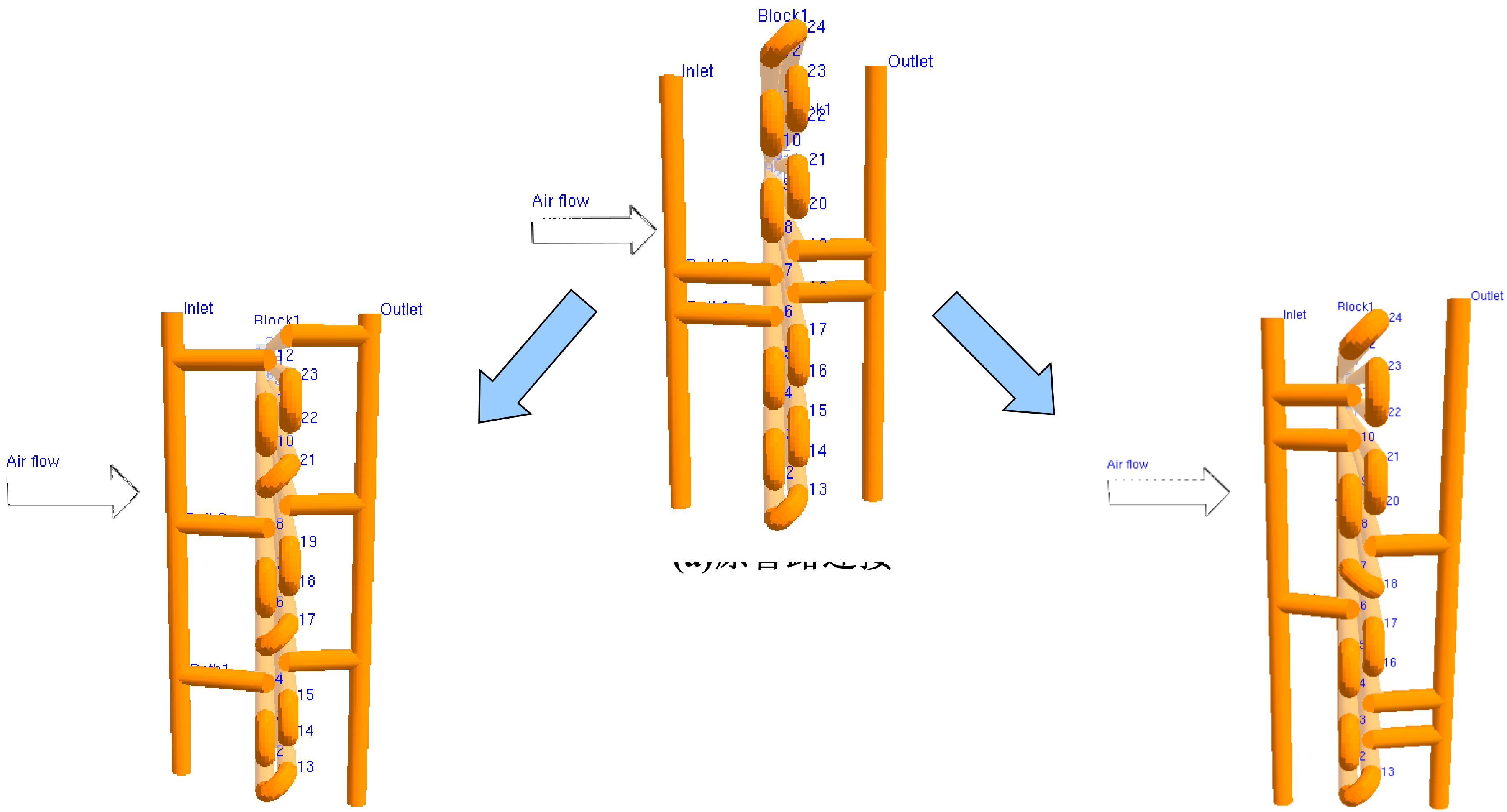
温度梯度



压力梯度

实例：某R410A蒸发器7 mm ➔ 5 mm优化设计

——3Path管路连接优化



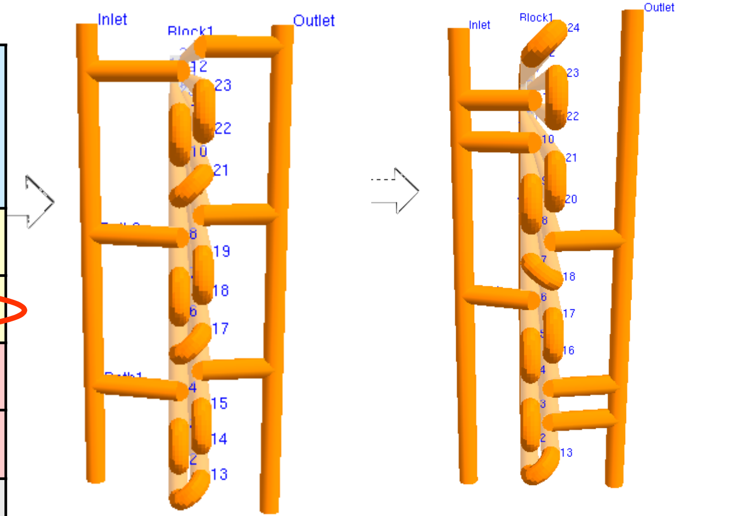
(b)3Path 均匀布管

(c)3Path 非均匀布管

实例：某R410A蒸发器7 mm ➔ 5 mm优化设计
——3Path管路连接小结

3Path优化结果

连接	图示	片距	换热量 (W)	同7mm管比较换热量增加	压降 (kPa)	同7mm比较压降增加
均匀	(a)	19FPI	3321.6	0.1%↑	54.8	32.7%↑
均匀	(a)	20FPI	3336.0	0.5%↑	55.6	34.6%↑
非均匀	(b)	19FPI	3326.0	0.2%↑	54.7	32.4%↑
非均匀	(b)	20FPI	3336.2	0.5%↑	55.8	35.1%↑
5mm替代	--	19FPI	3369.5	1.5%↑	145.2	251.6%↑
原蒸发器	--	19FPI	3318.6	--	41.3	--



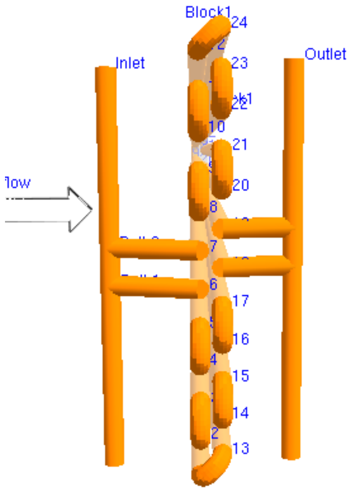
(a)3path均匀布置 (b)3path非均匀布置

优化后的3Path管路连接

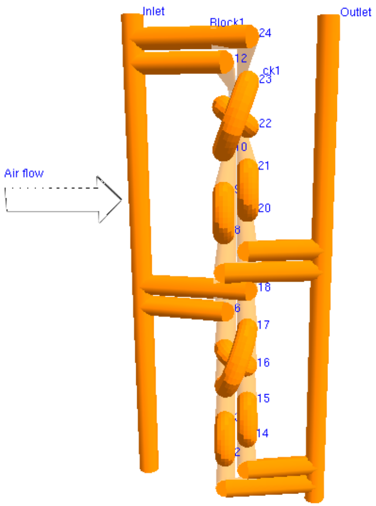
推荐采用的3Path优化方案

上海交通大学 Shanghai Jiao Tong University

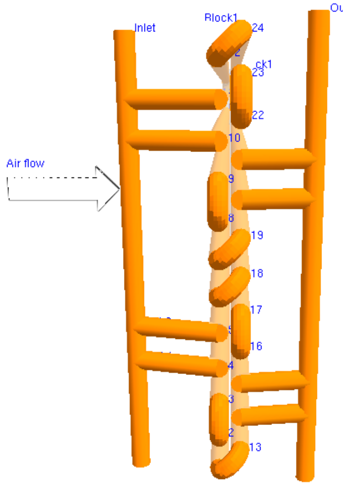
实例：某R410A蒸发器7 mm ➔ 5 mm优化设计
—4Path管路连接优化



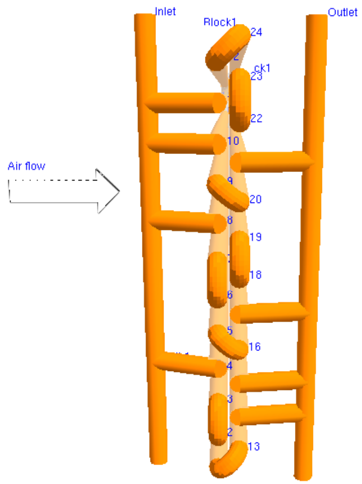
(a)原管路连接



(b) 4Path X型布管



(c)对称布管



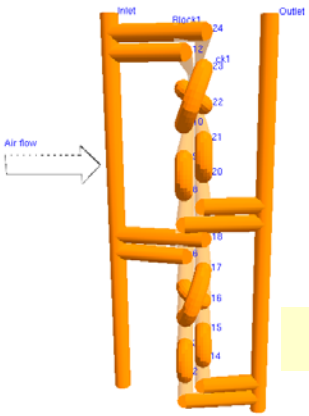
(d)非均匀布管

实例2：某R410A蒸发器7 mm ➔ 5 mm优化设计
—4Path管路连接小结

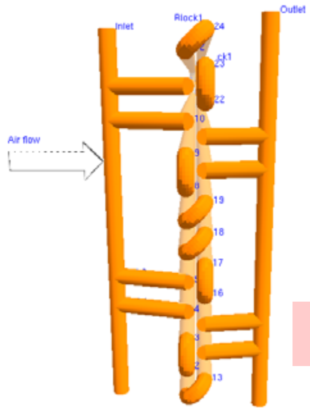
4Path优化结果

连接	图示	片距	换热量 (W)	同7mm管比较换热量增加	压降 (kPa)	同7mm管比较压降增加
X型	(a)	19FPI	3357.2	1.2% ↑	26.2	-36.6%↓
X型	(a)	20FPI	3374.2	1.7% ↑	26.6	-35.6%↓
对称	(b)	19FPI	3300.8	-0.5%↓	26.0	-37.0%↓
对称	(b)	20FPI	3303.4	-0.5%↓	26.2	-36.6%↓
非均匀	(c)	19FPI	3298.7	-0.6%↓	26.0	-37.0%↓
非均匀	(c)	20FPI	3304.0	-0.4%↓	26.2	-36.6%↓
原管路5mm	--	19FPI	3369.5	1.5% ↑	145.2	251%↑
原管路7mm	--	19FPI	3318.6	--	41.3	--

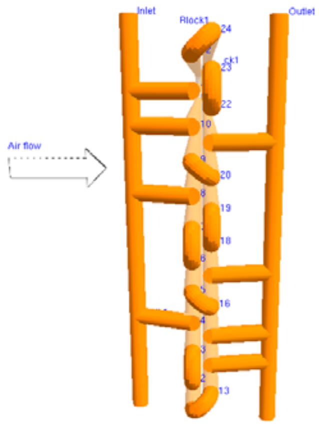
推荐采用的4Path优化方案



(a)4path X型布管



(b)4path 对称布管



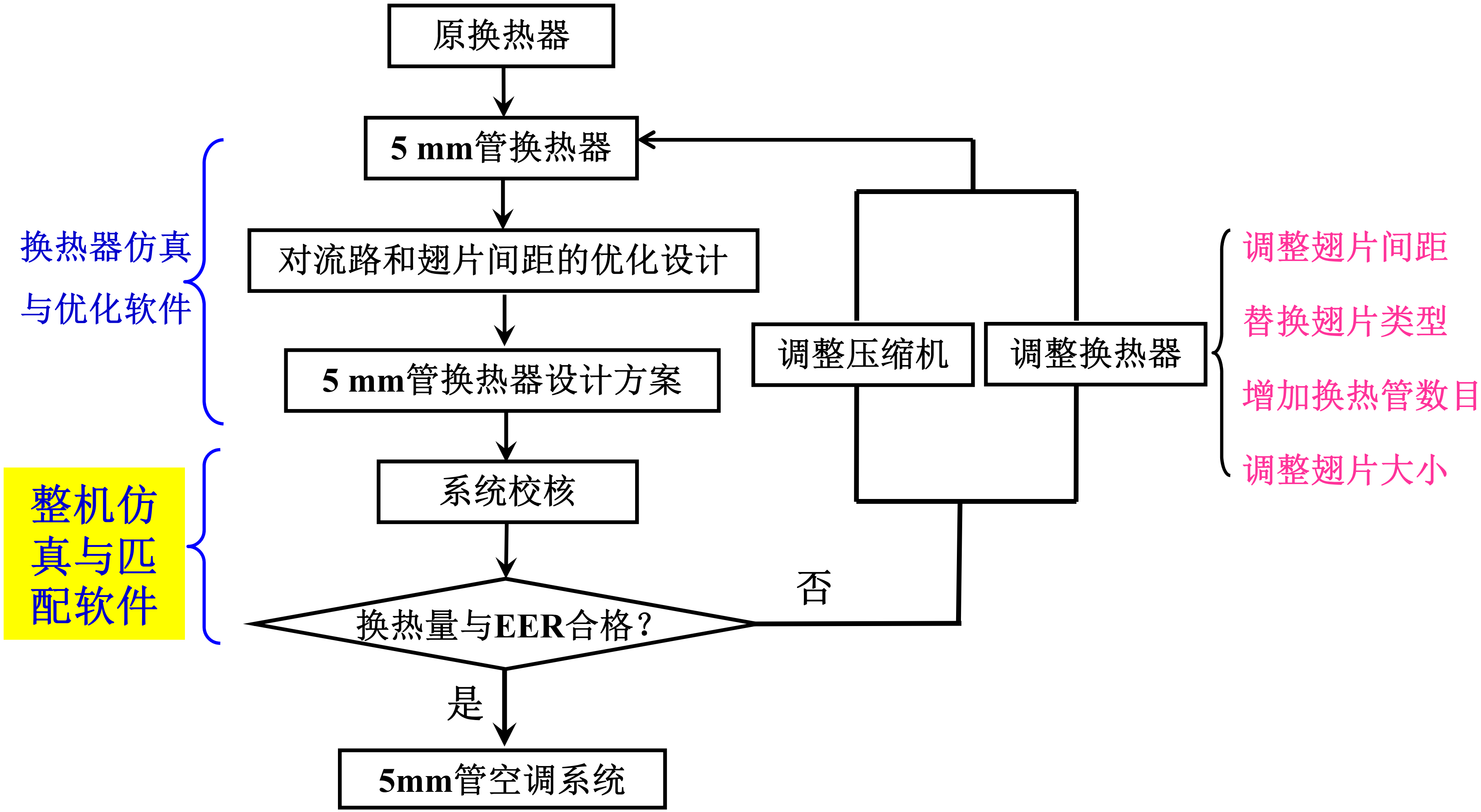
(c)4path 非均匀布管

Shanghai Jiao Tong University

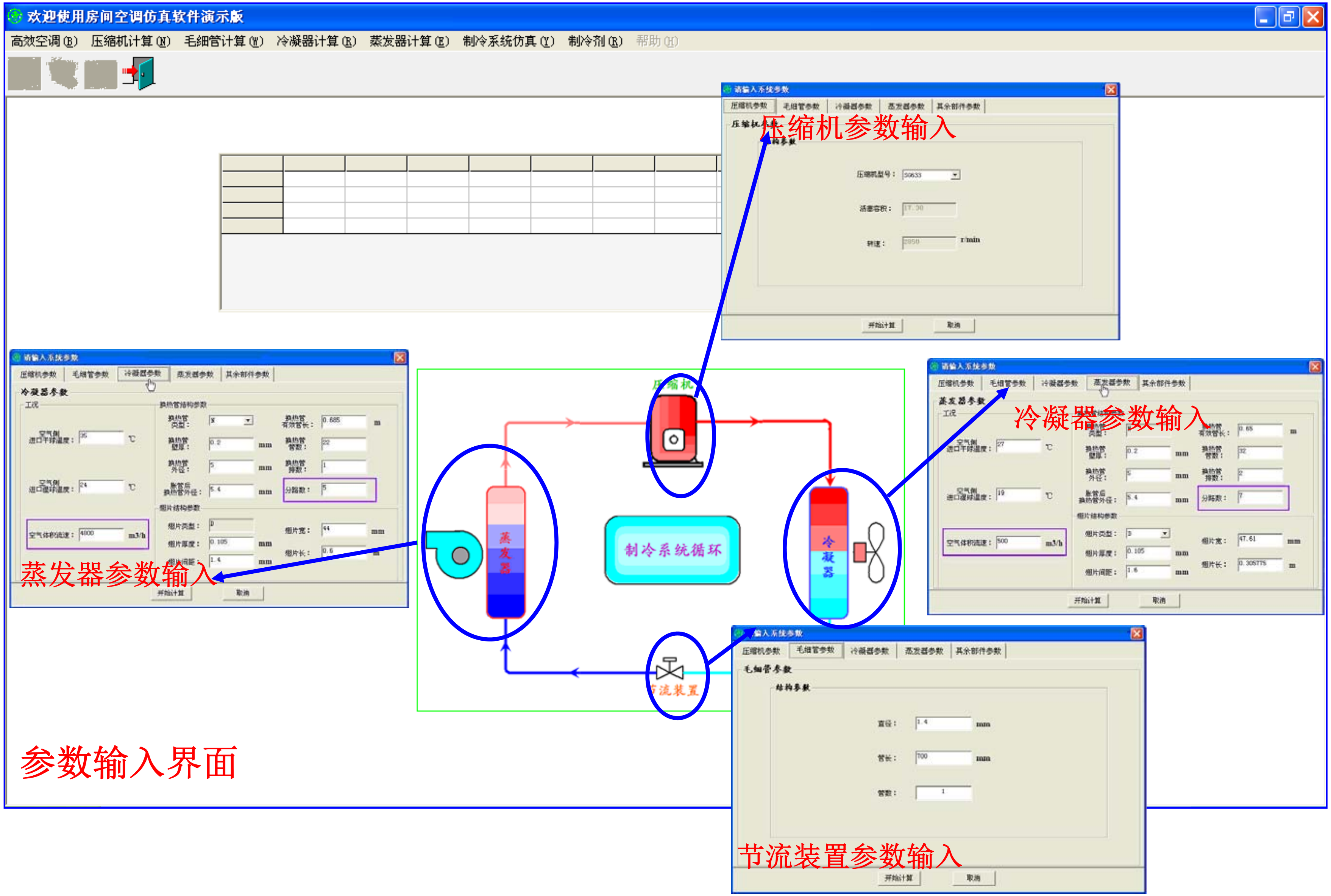
提 纲

1. 小管径问题概述
2. 管内制冷剂传热与流动特性
3. 翅片侧传热流动模拟与翅片设计
4. 换热器热力性能模拟与优化设计
5. 整机热力性能模拟与优化设计
6. 降噪与长效
7. 结论

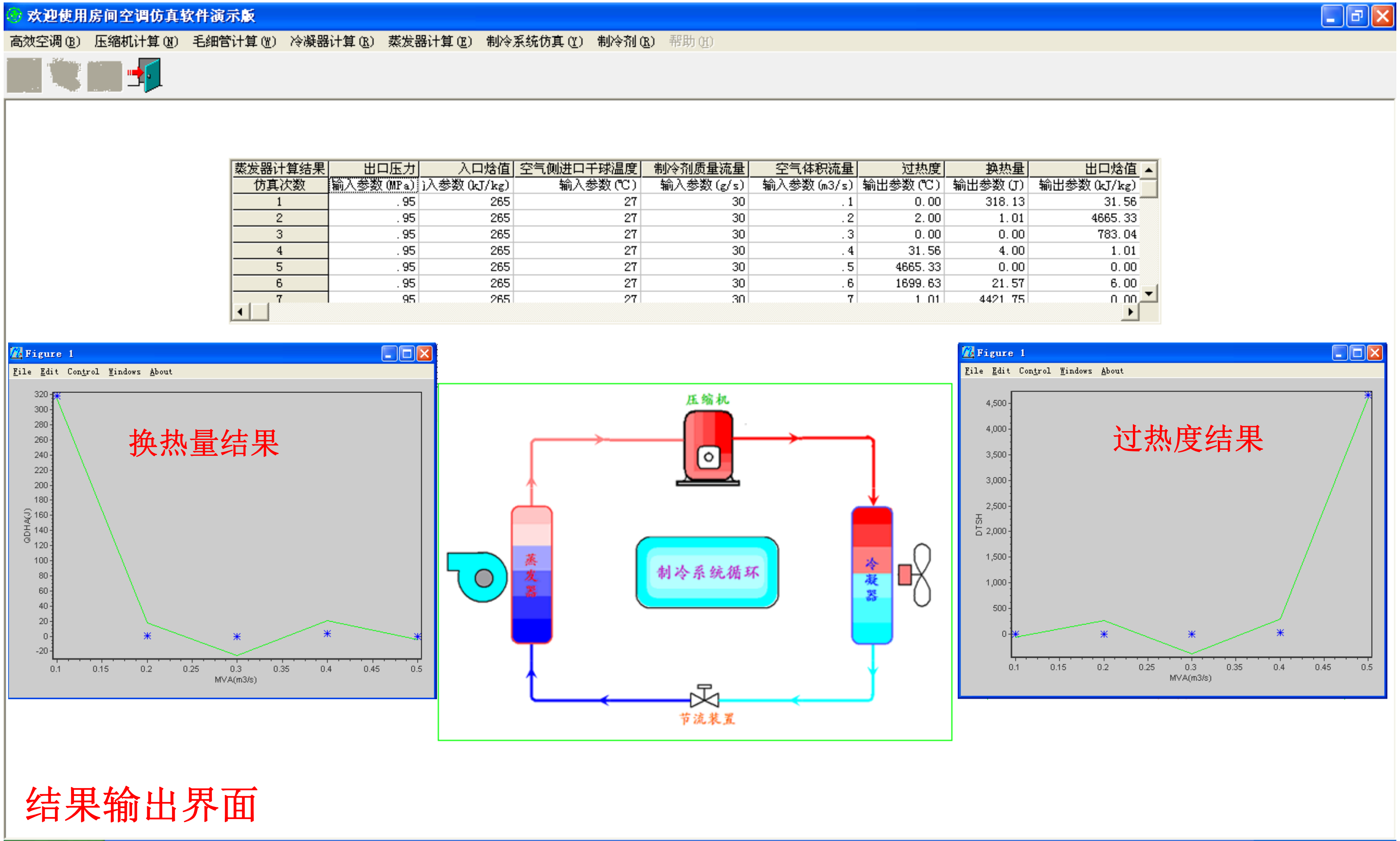
优化设计思路


原换热器
5 mm管换热器
对流路和翅片间距的优化设计
5 mm管换热器设计方案
系统校核
换热量与EER合格？
是
5mm管空调系统
否
调整压缩机
调整换热器
换热器仿真
与优化软件
整机仿
真与匹
配软件
调整翅片间距
替换翅片类型
增加换热管数目
调整翅片大小

一拖一的空调器仿真-输入界面

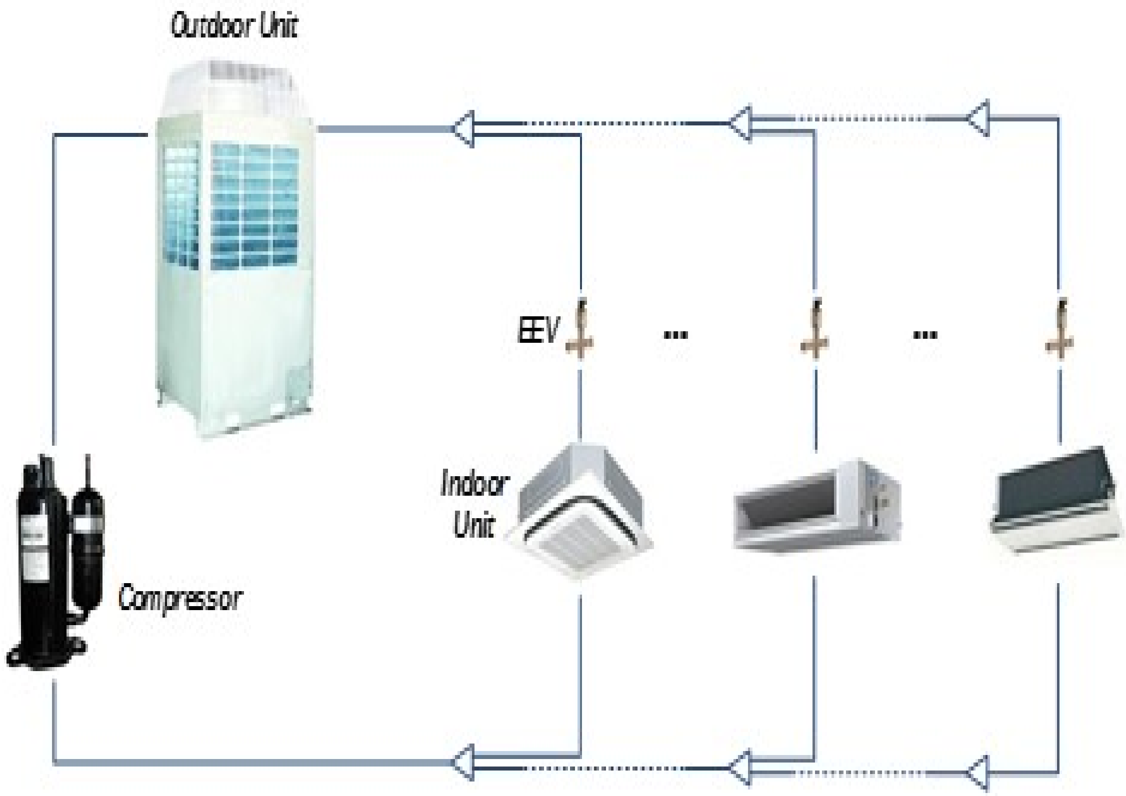


一拖一的空调器仿真-输出界面



蒸发器计算结果	出口压力	入口焓值	空气侧进口干球温度	制冷剂质量流量	空气体积流量	过热度	换热量	出口焓值
仿真次数	输入参数(MPa)	入参数(kJ/kg)	输入参数(℃)	输入参数(g/s)	输入参数(m3/s)	输出参数(℃)	输出参数(J)	输出参数(kJ/kg)
1	.95	265	27	30	.1	0.00	318.13	31.56
2	.95	265	27	30	.2	2.00	1.01	4665.33
3	.95	265	27	30	.3	0.00	0.00	783.04
4	.95	265	27	30	.4	31.56	4.00	1.01
5	.95	265	27	30	.5	4665.33	0.00	0.00
6	.95	265	27	30	.6	1699.63	21.57	6.00
7	95	265	27	30	7	1.01	4421.75	0.00

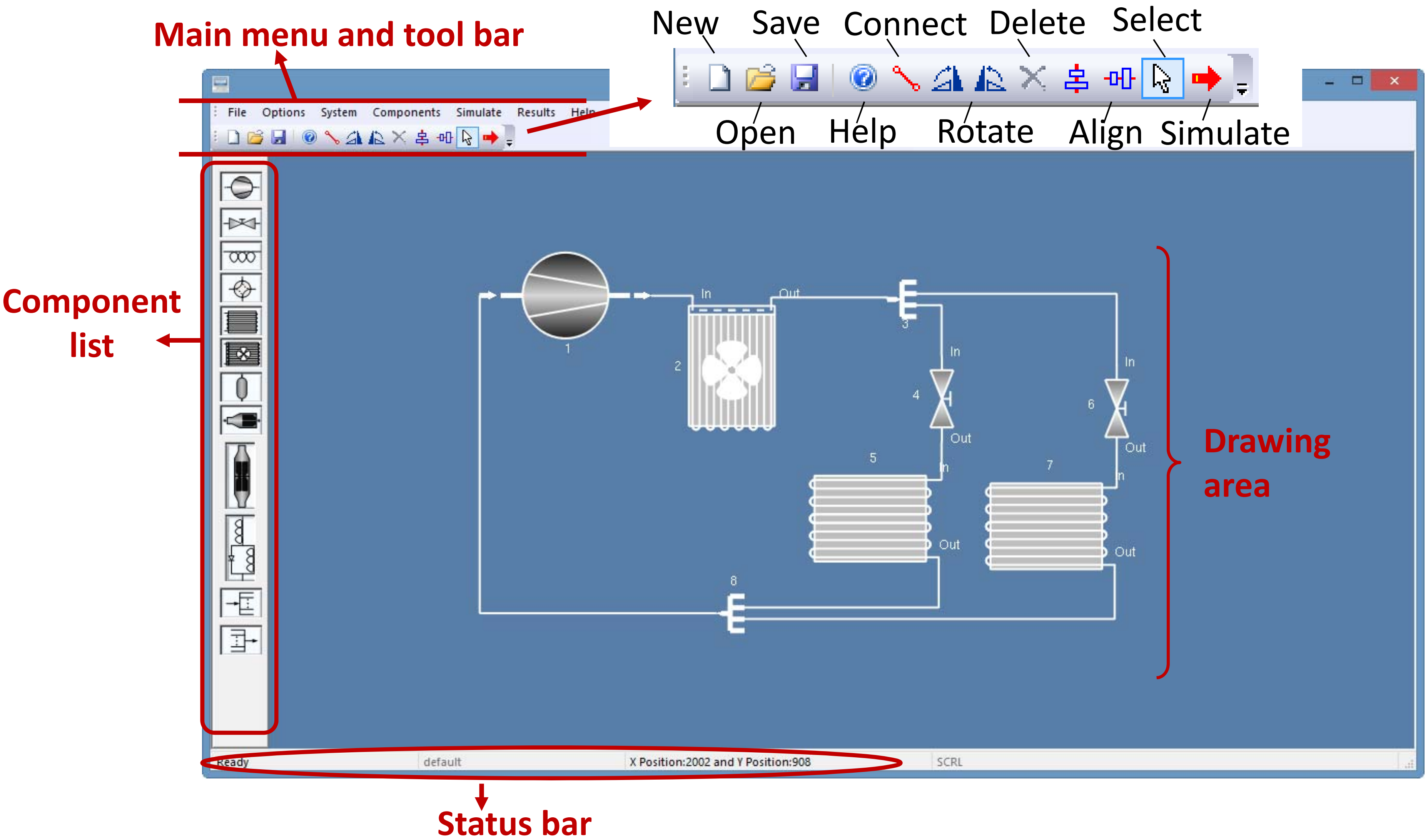
一拖多空调的仿真



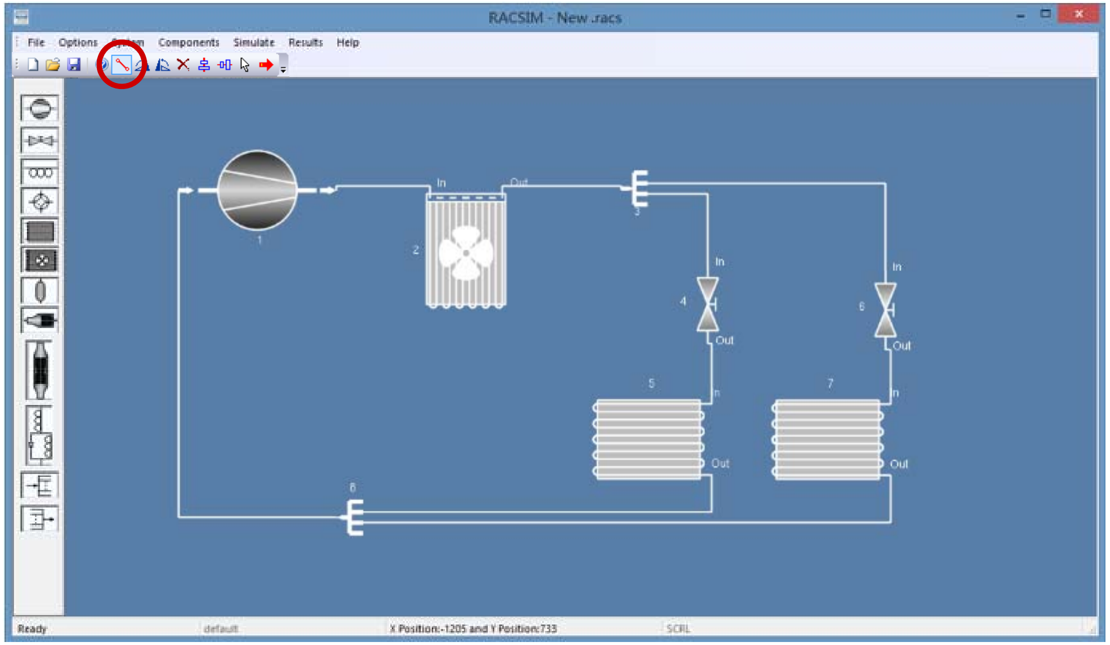
上海交通大學 Shanghai Jiao Tong University

软件实现

➢ 主界面



➢ 定义管子



Step 1: Select the component

Step 2: Click the blank drawing area

Step 3: Create all the components as step1 and step 2

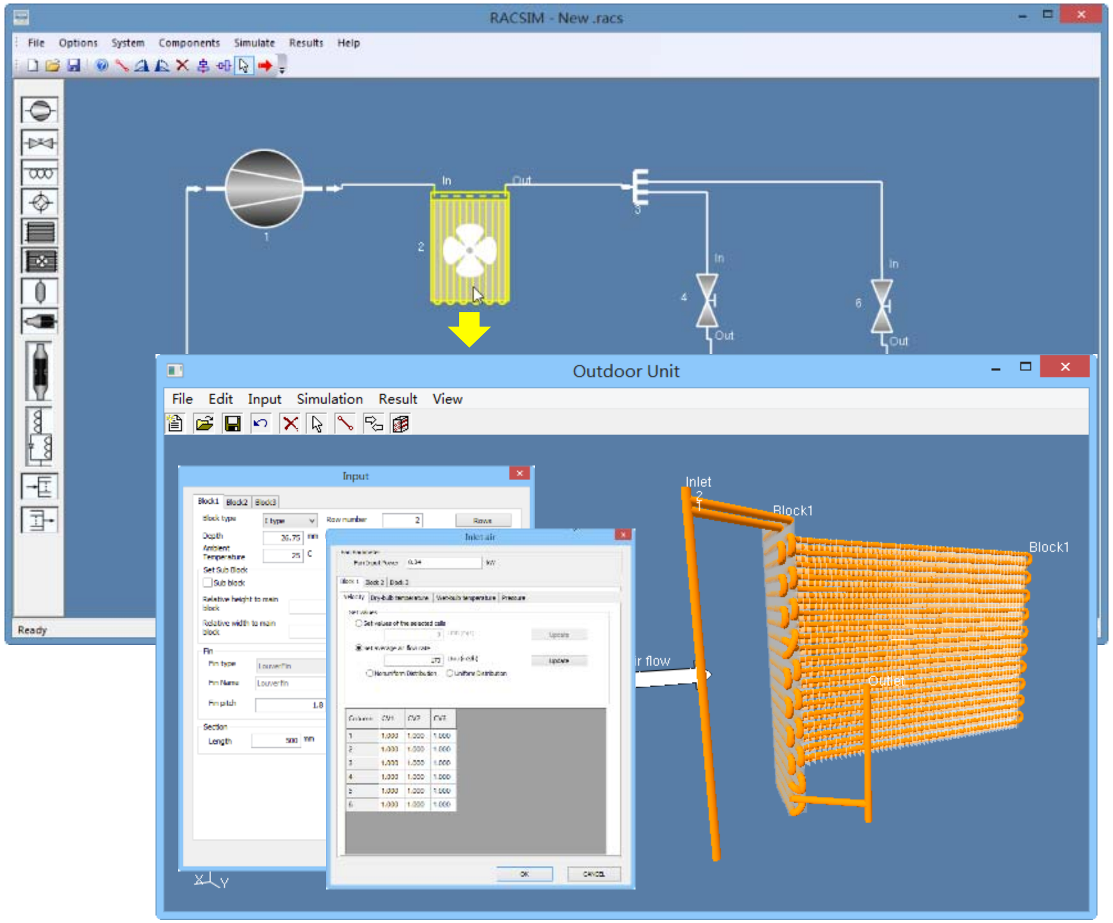
Step 4: Select connecting mode

Step 5: Click the components one by one

Step 6: Define all the pipelines as step 4 and step 5

软件实现

➢ 部件参数输入-室外机



Outdoor unit setting dialog

- Input block structure
- Input tube and fin structures
- Input inlet air status
- Define the flow circuitry

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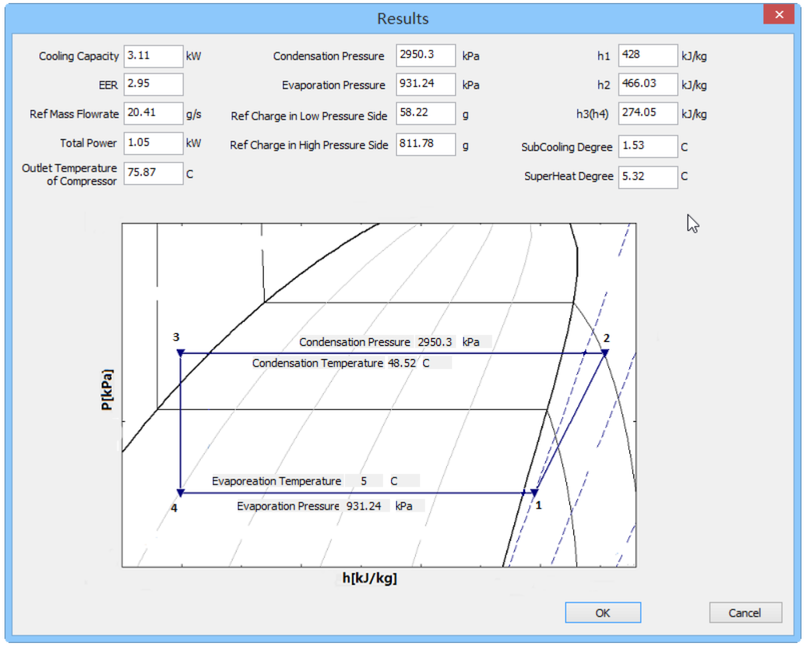
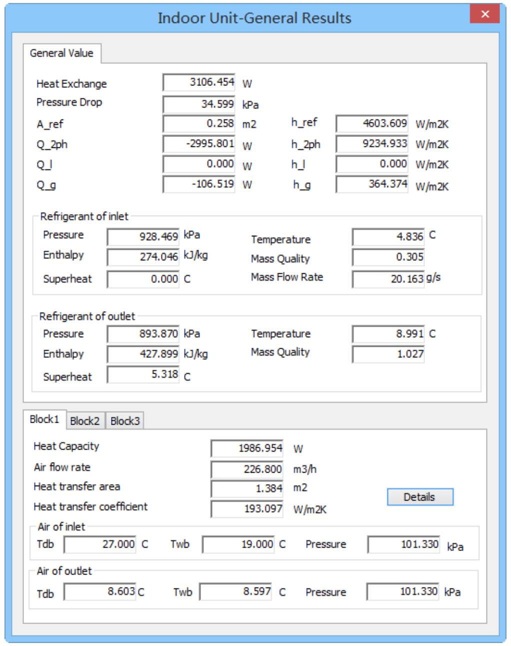
一拖多的空调器仿真输出-表格

- 系统性能结果



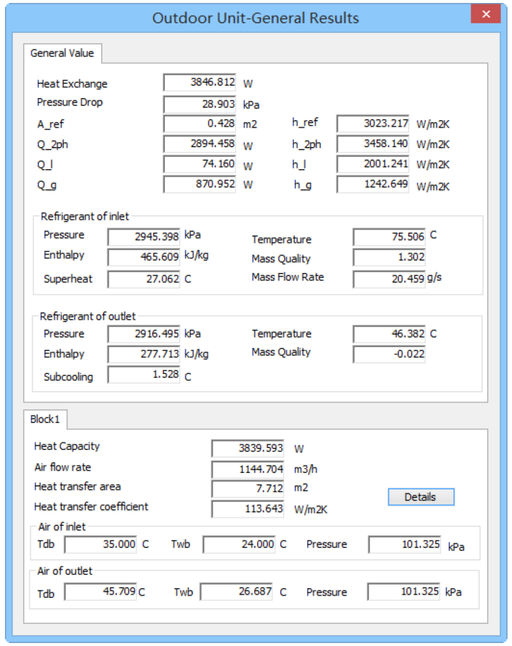
- 制冷量
- **EER**
- 冷凝温度/压力
- 蒸发温度/压力
- …

- 室内机结果



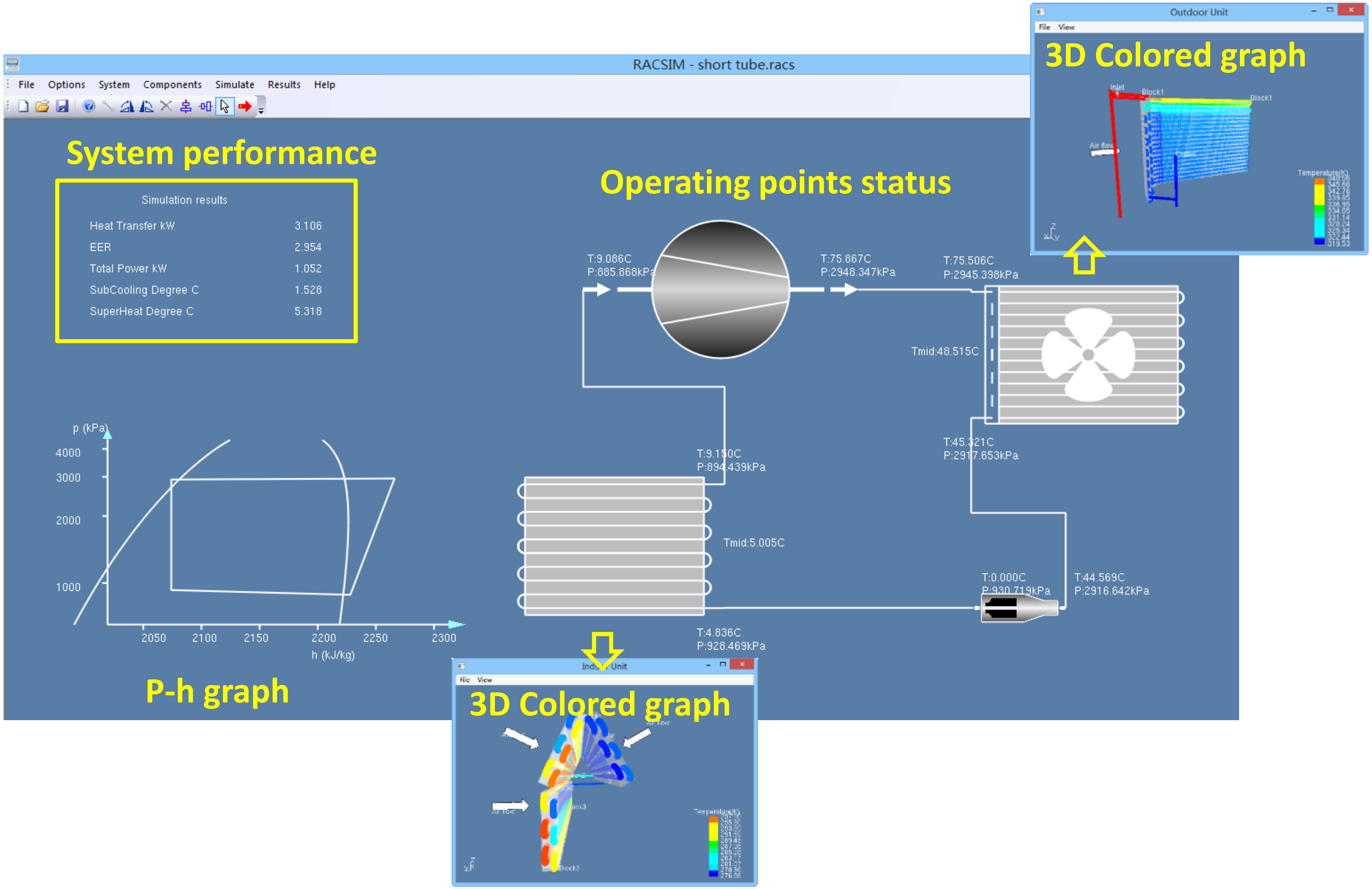
- 换热量
- 压降
- 过热度
- 空气侧出口温度
- …

- 室外机结果

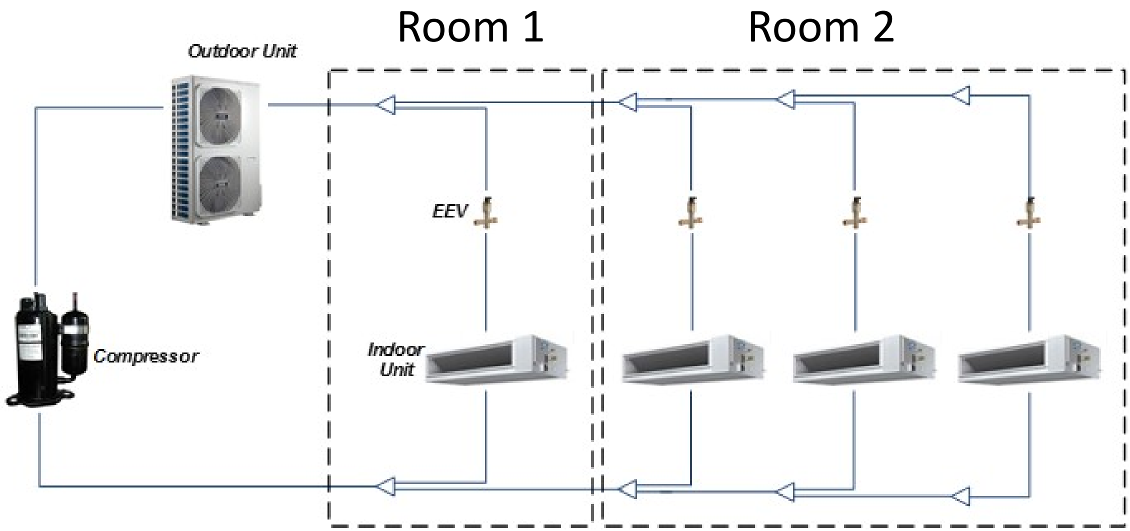


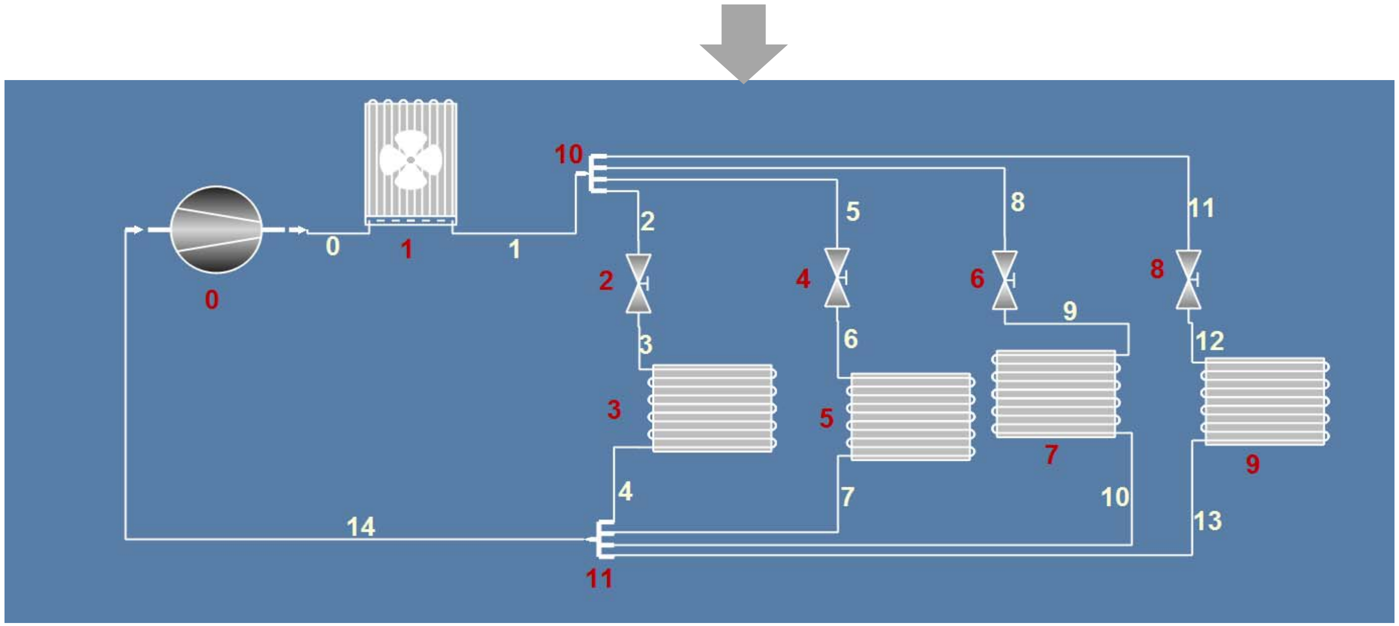
- 换热量
- 压降
- 过冷度
- 空气侧出口温度
- …

一拖多的空调器仿真输出-图形



应用实例


Room 1
Room 2
Outdoor Unit
EEV
Compressor
Indoor
Unit


10
0
1
1
0
2
2
3
3
4
5
4
6
5
7
8
6
9
7
10
11
8
12
9
13
14
11

应用实例

制冷工况

Item	Full load			Half load			Min load		
	Test Data	Simulation Results	Relative Error %	Test Data	Simulation Results	Relative Error %	Test Data	Simulation Results	Relative Error %
Capacity (W)	15.3	15.41	0.72	8.32	8.35	0.36	5.54	5.55	0.18
Power (W)	6.57	6.47	-1.52	2.14	2.09	-2.34	1.4	1.37	-2.14
EER/COP	2.33	2.38	2.15	3.89	4.00	2.83	3.96	4.05	2.27
P_{disc} (°C)	3083	3065	-0.58	2546	2512	-1.34	2609	2555	-2.07
P_{suc} (°C)	861	895.98	4.06	1246	1209	-2.97	1288	1245	-3.34

制热工况

Item	Full load			Half load			Min load		
	Test Data	Simulation Results	Relative Error %	Test Data	Simulation Results	Relative Error %	Test Data	Simulation Results	Relative Error %
Capacity (W)	18.12	18.3	0.99	9.37	9.41	0.43	4.87	4.88	0.21
Power (W)	6.47	6.45	-0.31	2.93	2.9	-1.02	1.65	1.68	1.82
EER/COP	2.80	2.84	1.43	3.20	3.24	1.25	2.95	2.90	-1.69
P_{disc} (°C)	3075	2967	-3.51	2802	2799	-0.11	2445	2462	0.70
P_{suc} (°C)	734	819	11.58	865	844	-2.43	898	896	-0.22

提 纲

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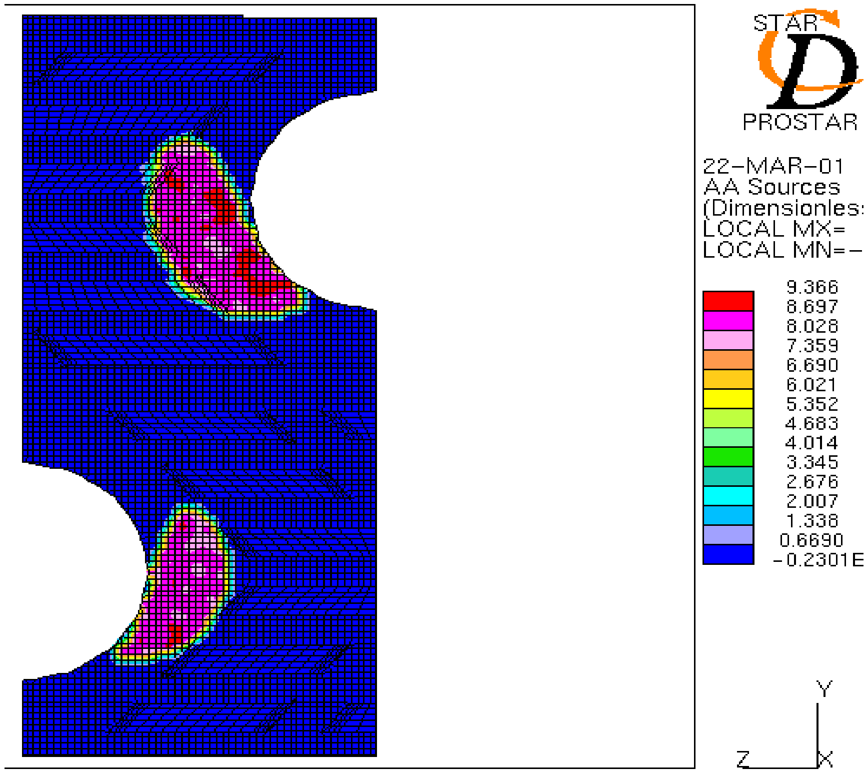
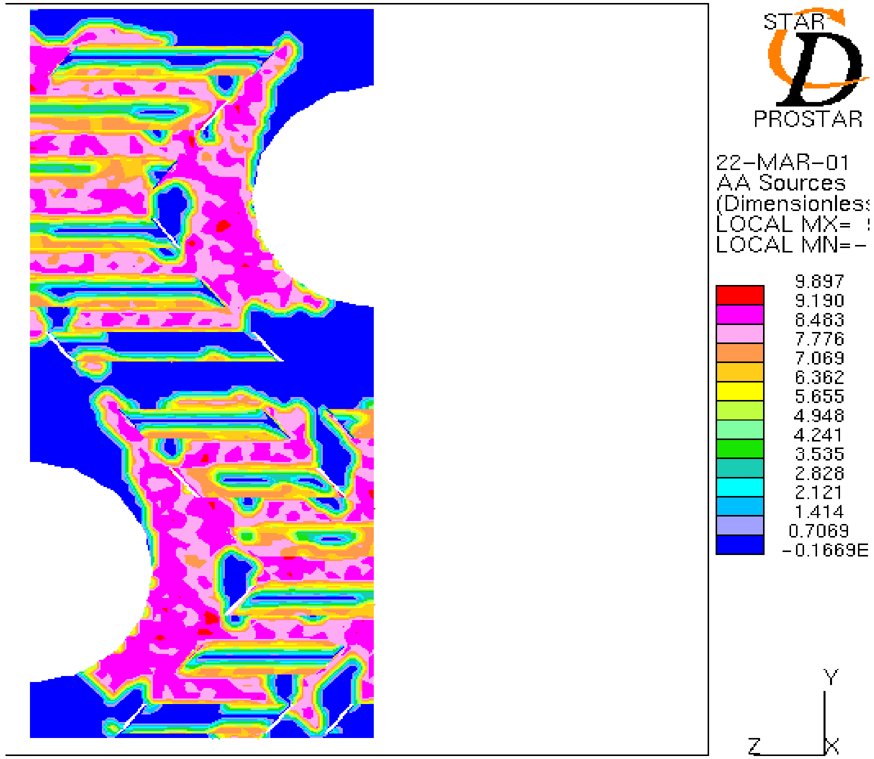
4. 换热器热力性能模拟与优化设计
5. 整机热力性能模拟与优化设计
6. 降噪与长效
7. 结论

翅片气动噪声-计算结果



Sound field of a plain fin



Sound field of a straight strip fin

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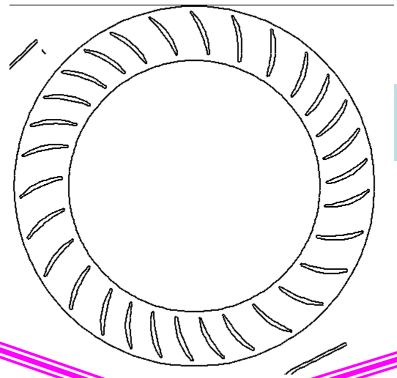
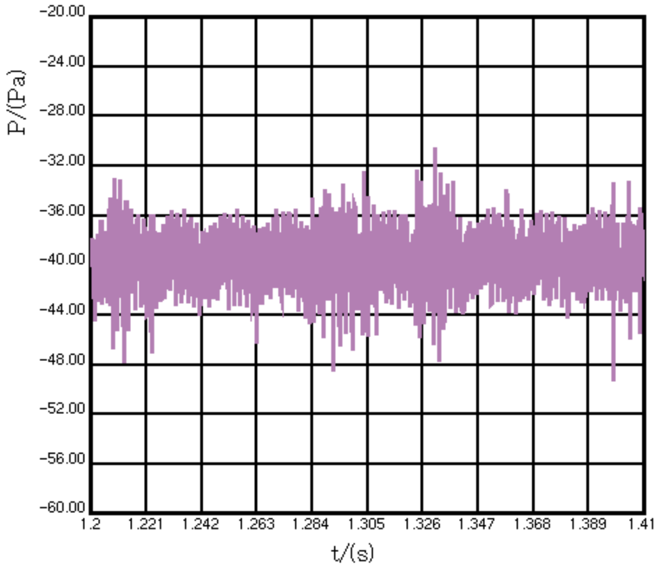
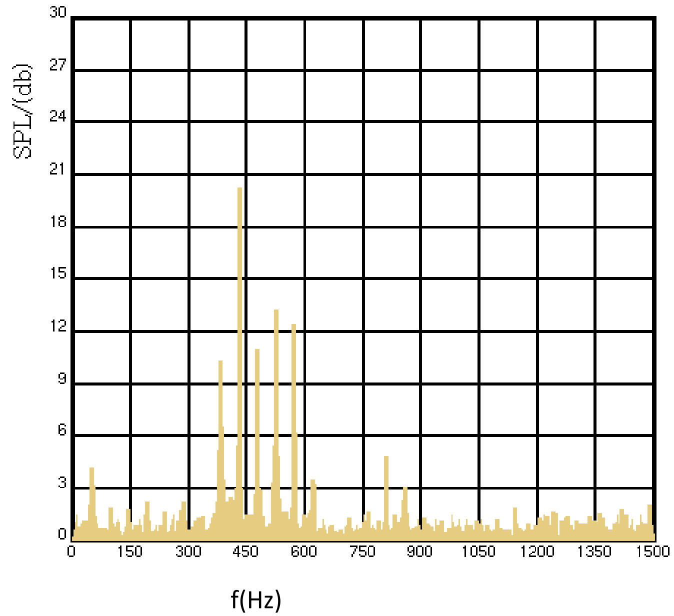
风机气动噪声



Random pitch blades

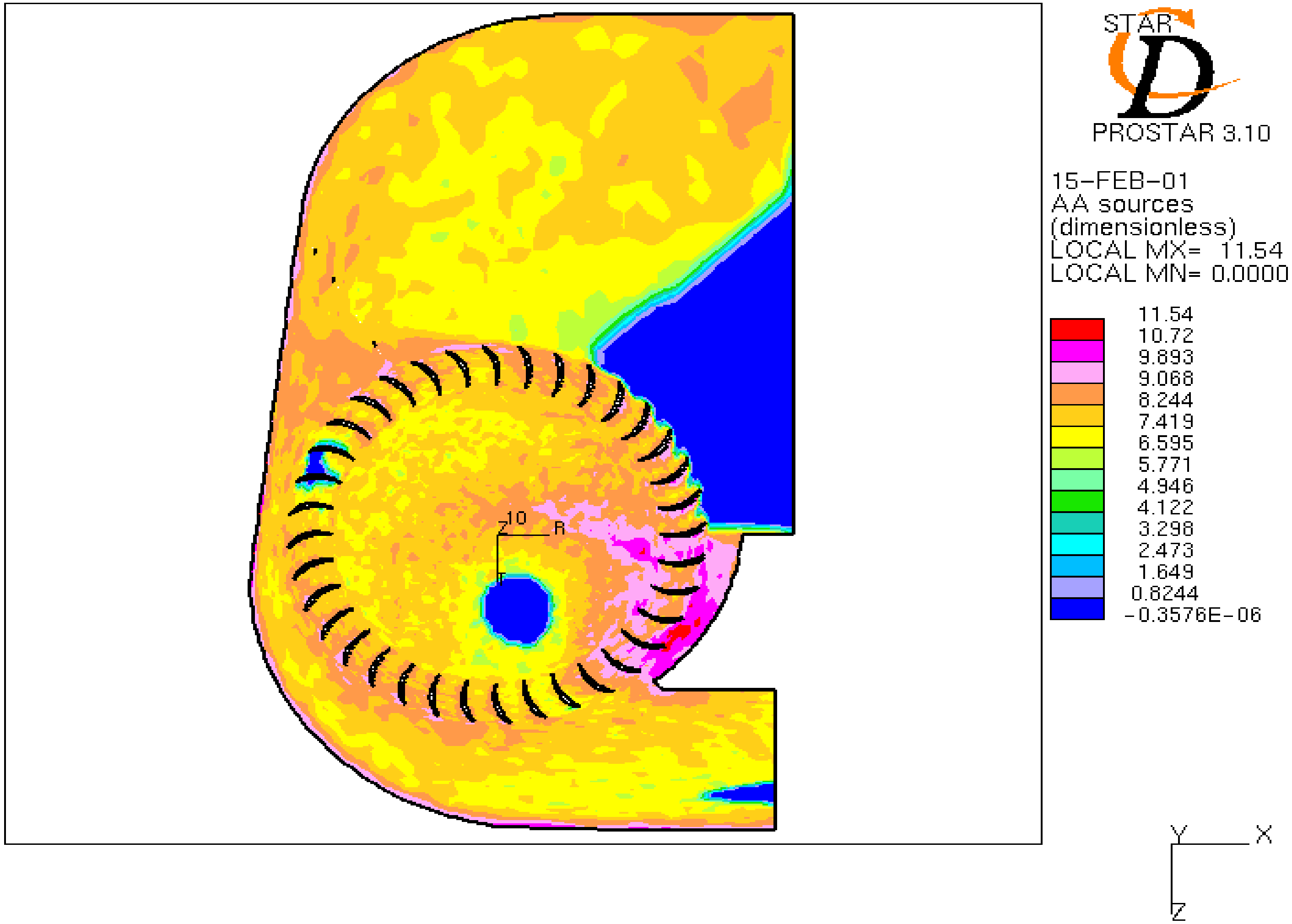


Pressure fluctuations
on the volute tongue



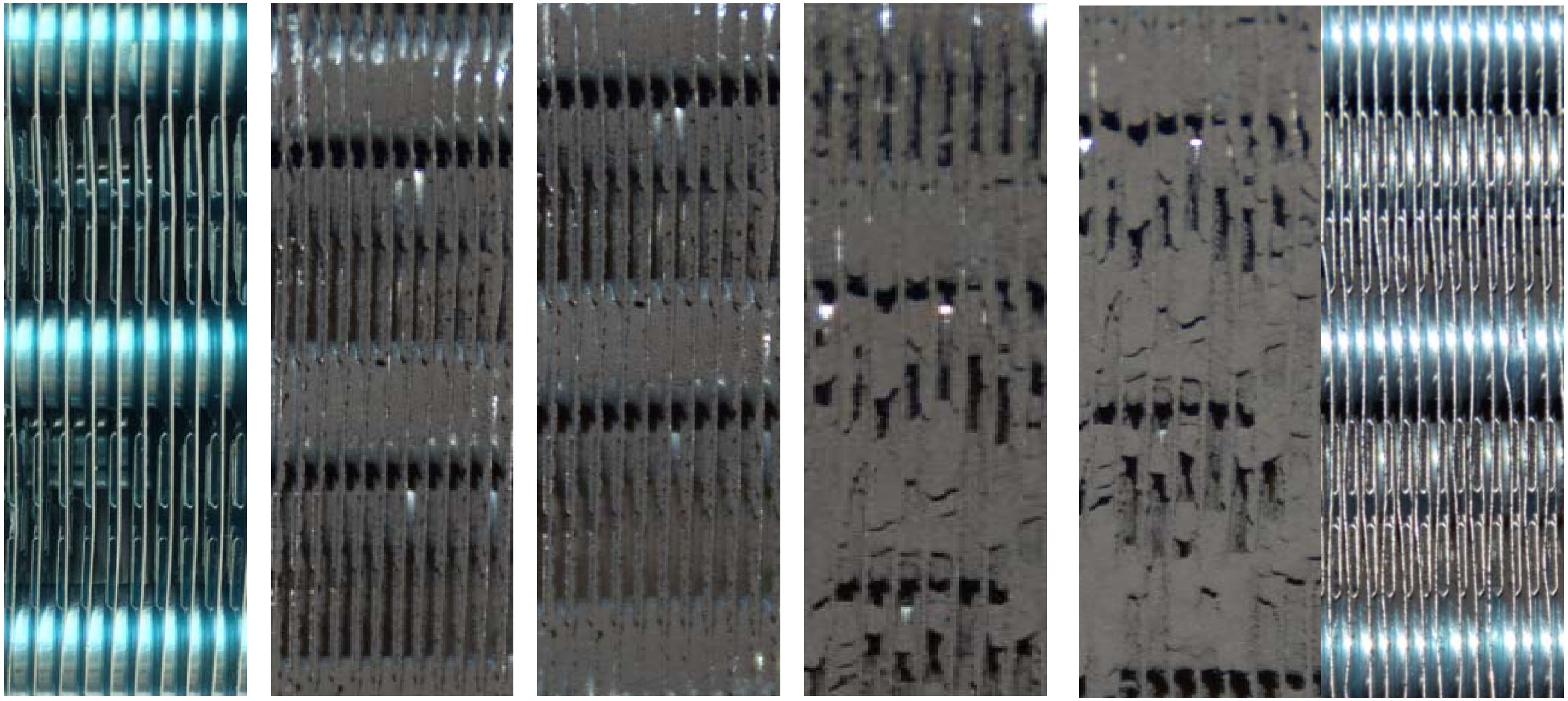
Sound pressure level spectra
on the volute tongue

分体空调室内机噪声


STAR
PROSTAR 3.10
15-FEB-01
AA sources
(dimensionless)
LOCAL MX= 11.54
LOCAL MN= 0.0000
11.54
10.72
9.893
9.068
8.244
7.419
6.595
5.771
4.946
4.122
3.298
2.473
1.649
0.8244
-0.3576E-06
Y
X
Z

翅片管换热器积灰

- 实验**1**：管排数2、 *FP*为1.3mm百叶窗片换热器积灰过程



迎风面 T=0min | 迎风面 T=15min | 迎风面 T=40min | 迎风面 T=60min | 迎风面 背风面 T=90min

翅片管换热器积灰

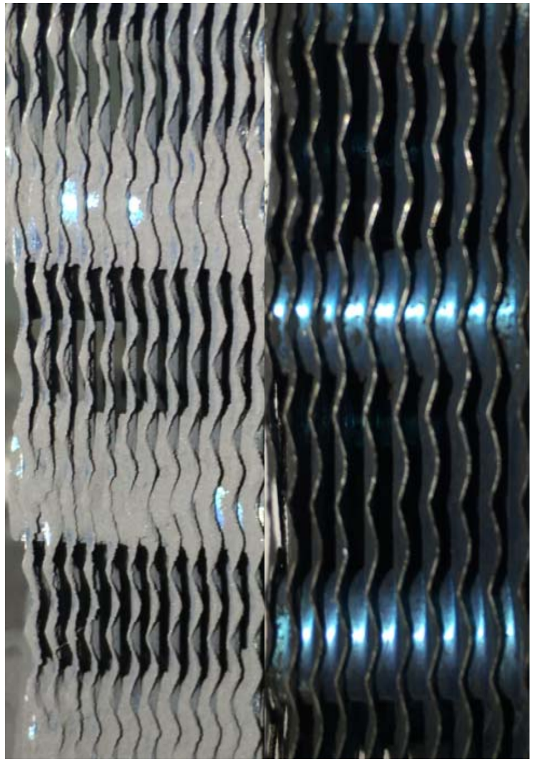
- 实验2：管排数2、 FP为1.5mm波纹片换热器积灰过程

迎风面 T=0min

迎风面 T=15min

迎风面 T=40min

迎风面 T=60min

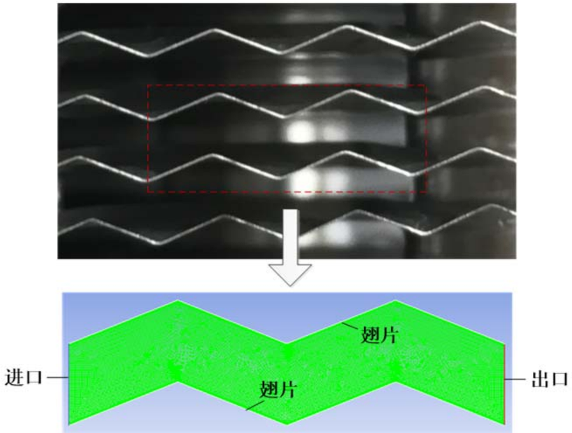


迎风面 背风面 T=90min

模拟结果的验证

➢ 颗粒物沉积厚度对比

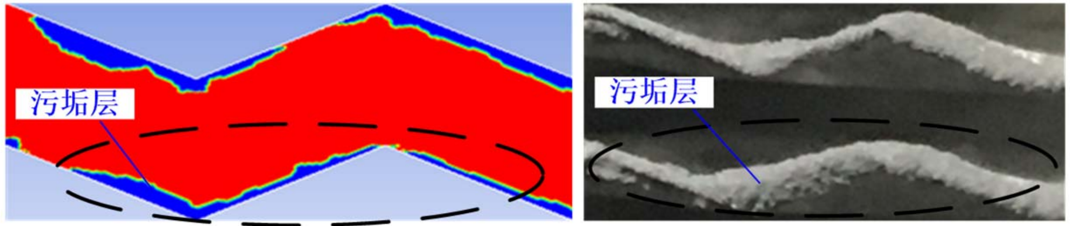
模拟对象



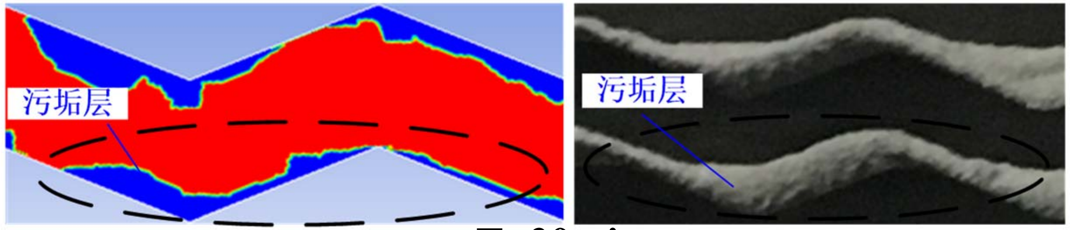
条件设置

- 结构参数：翅片间距3mm、波纹高度1.5mm；
- 对比工况：风速2m/s、喷粉浓度5.7g/m³、喷粉时间为60min.

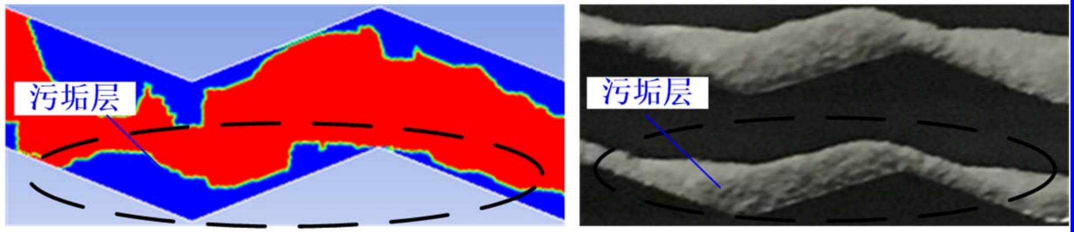
模拟结论



T=10min



T=30min



T=60min

对比结论：具有一定的吻合度.

结　论

- 小管径可以大大节省铜材料，降低生产成本；
- 小管径铜管内的换热和压降特性与大管径管不尽相同，直接将换热器中的换热管替换成小管径换热管会增加压降损失；
- 用小管径代替大管径时，应适当增加制冷剂流路的分路数；
- 小管径的翅片结构与大管径的翅片也不同，需要专门设计；
- 精准设计小管径换热器，需要开发析湿模拟软件、换热器三维分布参数仿真与优化设计软件、制冷空调装置整机仿真软件；
- 未来小管径制冷空调装置的开发，还应当关注噪音的降低与长效性能的提高。

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谢 谢！