上海交通大学 SHANGHAI JIAO TONG UNIVERSITY

间冷冰箱的节能技术

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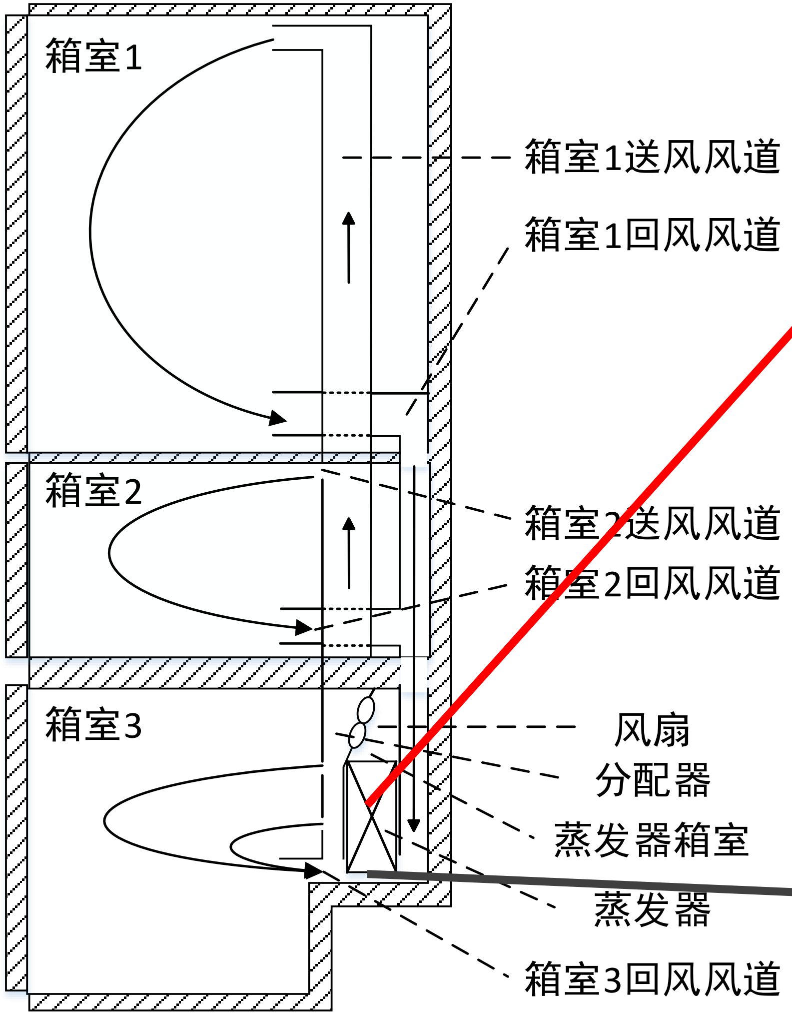
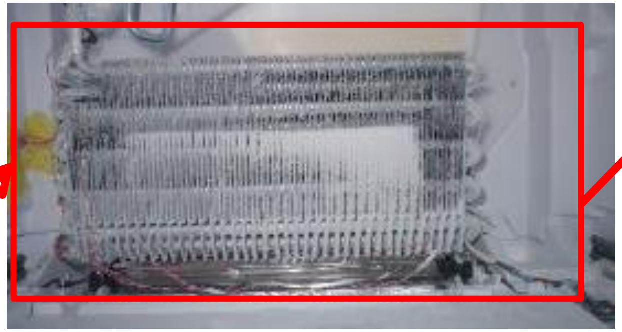
目录

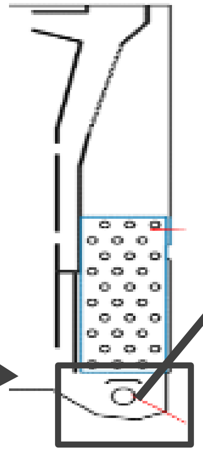
除霜效率的影响因素



蒸发器上的结霜分布



A. 蒸发器左右结霜分布不均匀，除霜过程能量浪费大，除霜效率低



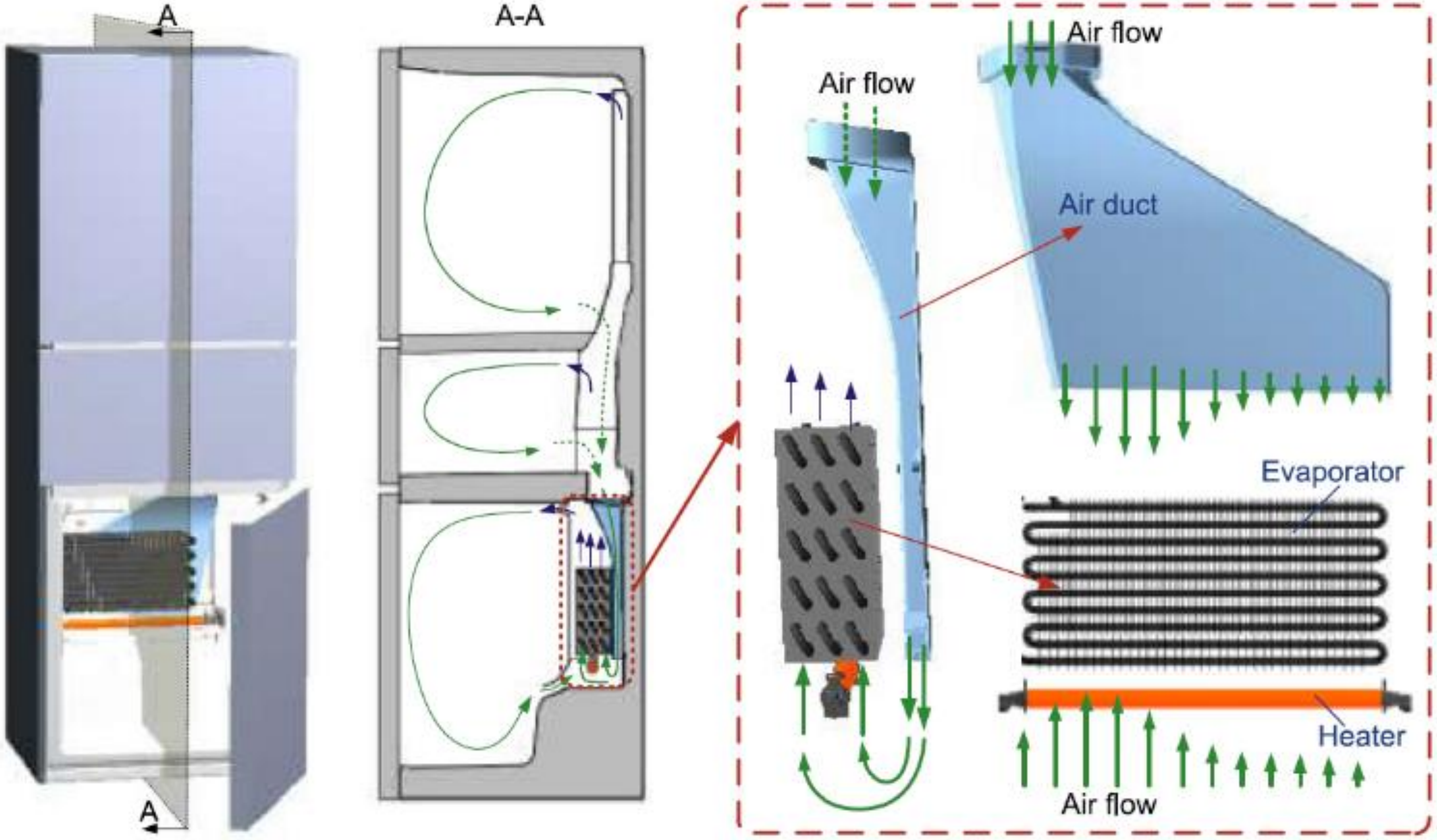
电加热管

B. 电除霜加热管的加热功率和安装位置不合理，导致除霜过程能量浪费大，除霜效率低

C. 除霜过程的控制逻辑

霜层分布是如何形成的

湿空气经过回风道，回到蒸发器室，并在蒸发器表面冷凝结霜。回风道出口处的风量分布直接决定蒸发器上的霜层分布。

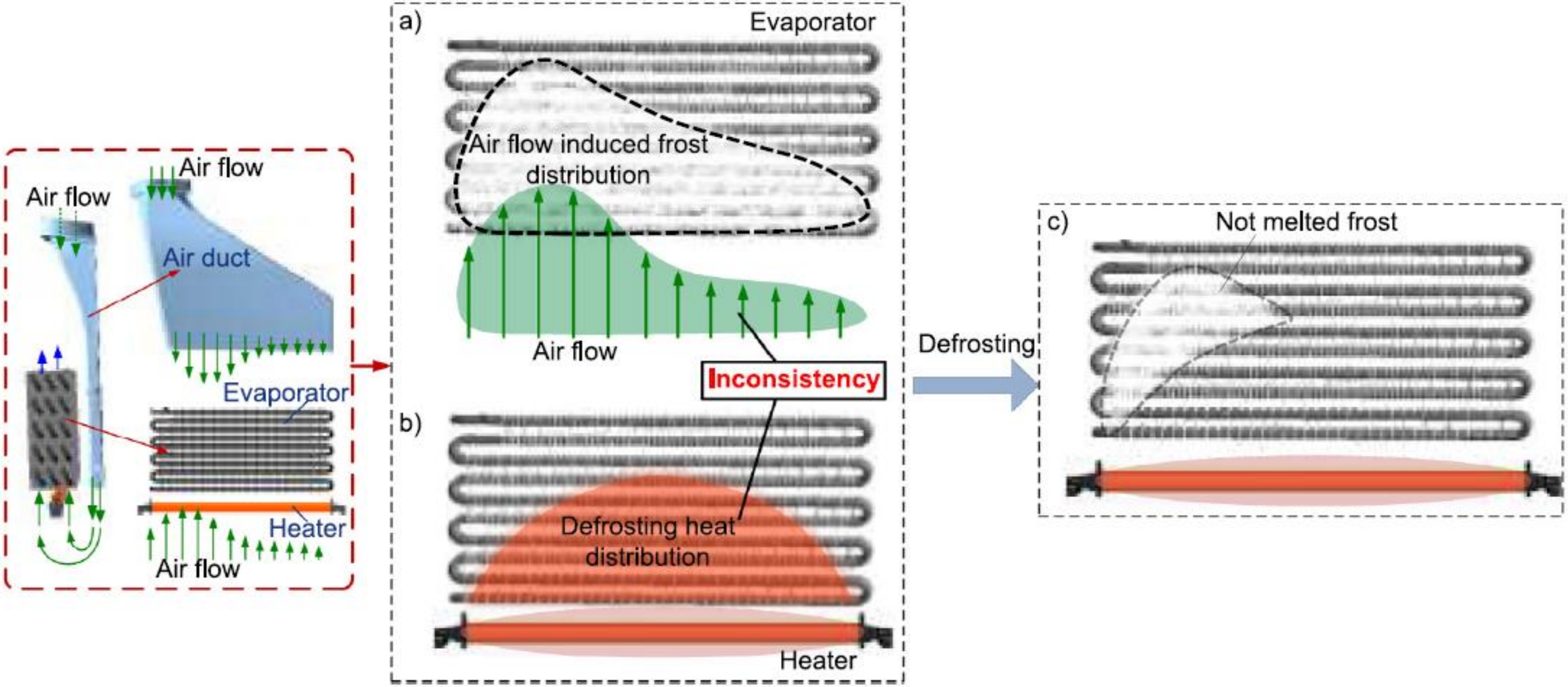


a) 间冷冰箱　　b) A-A截面　　c) 间冷冰箱中的回风道、蒸发器和除霜加热器

间冷冰箱中的空气循环示意图

霜层分布是如何影响除霜效率的

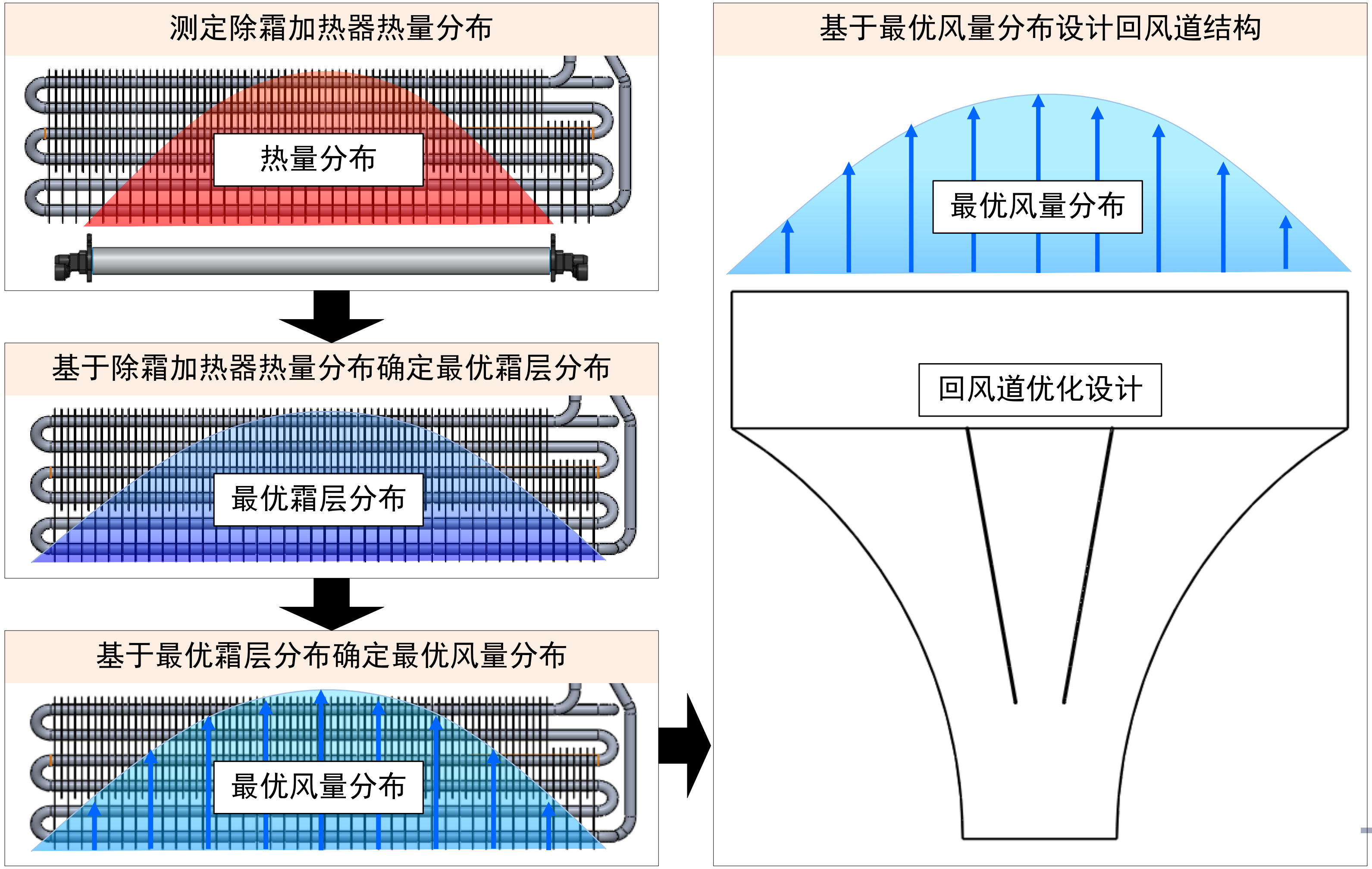
霜层分布与除霜热量分布不匹配，导致不同位置处的除霜过程不同步，除霜加热量的利用率低。



间冷冰箱除霜过程存在的问题

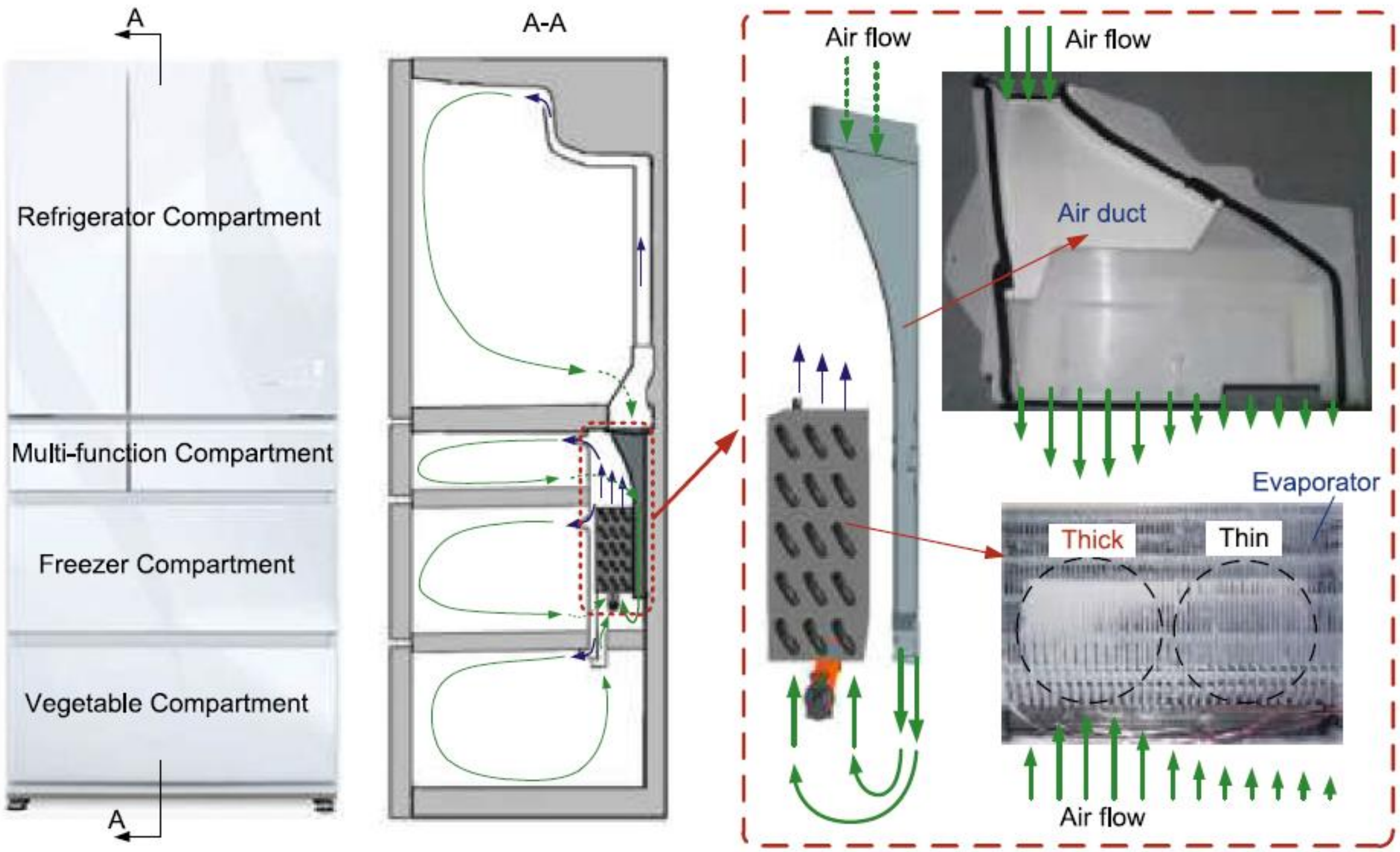
除霜性能优化的思路

基于除霜加热器的除霜热量分布确定PC回风道的最优风量分布，在PC回风道中设计添加导流板，使PC回风道出口风量分布达到最优分布，使除霜性能提高。



优化案例

针对某型号多门冰箱，采用上述思路对其除霜性能进行优化。原型机的回风道和结霜分布如下所示。



a) Refrigerator　b) A-A section of the refrigerator　c) Schematic of air duct and the evaporator

原型机的回风道和结霜情况

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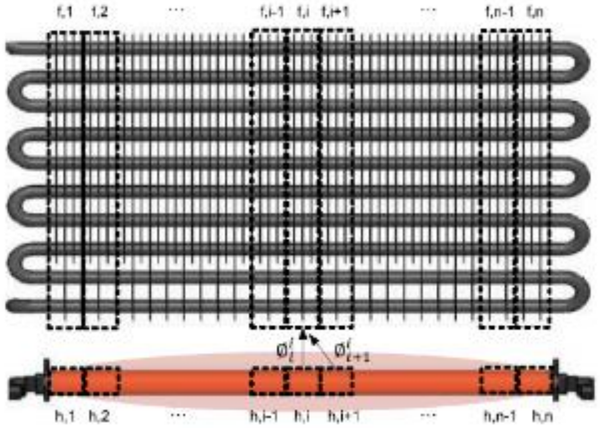
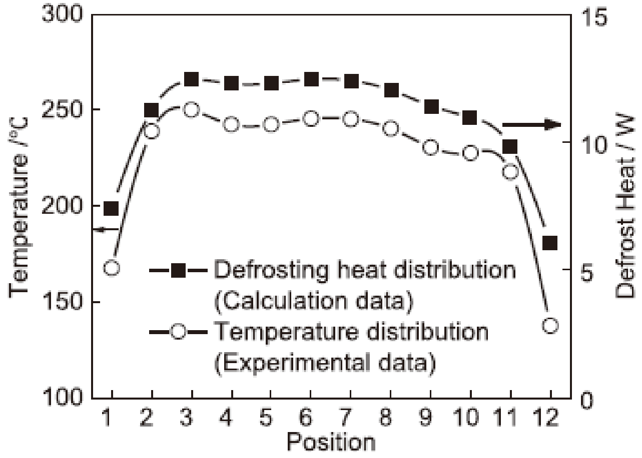
除霜性能优化的过程



$$\varnothing_{defrost,i} = \sum_{(h,i)-(h,1)}^{(h,n)} \left(\frac{\sigma[T_{h,i}^4 - T_{f,wts}^4]}{\frac{1-\varepsilon_h}{\varepsilon_h A_{h,i}} + \frac{1}{A_{h,i}X_{h,i}^{f,i}} + \frac{1-\varepsilon_f}{\varepsilon_f A_{f,i}}} \right) + h_i A_{h,i}[T_{h,i} - T_{air}] - m_{evap,i} c_{p,evap} \Delta T_{evap}$$

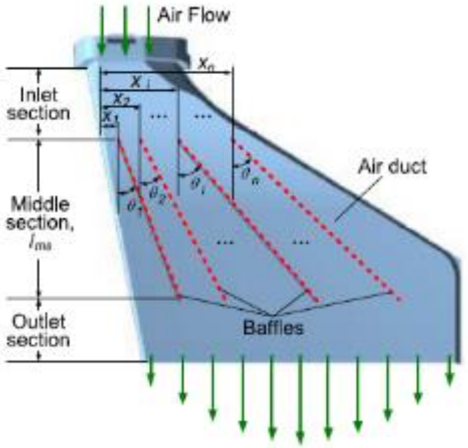
蒸发器及除霜加热器的单元划分



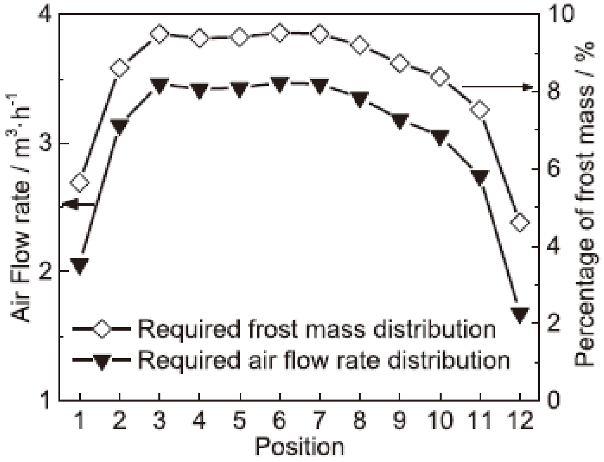
根据温度分布计算出除霜热量分布

$$\tau_{defrost,i} = \tau_{defrost,i+1} = \ldots = \tau_{defrost,n}$$

$$\frac{\dot{V}_{air,i}}{\varnothing_{defrost,i}} = \frac{\dot{V}_{air,i+1}}{\varnothing_{defrost,i+1}} = \ldots = \frac{\dot{V}_{air,n}}{\varnothing_{defrost,n}}$$

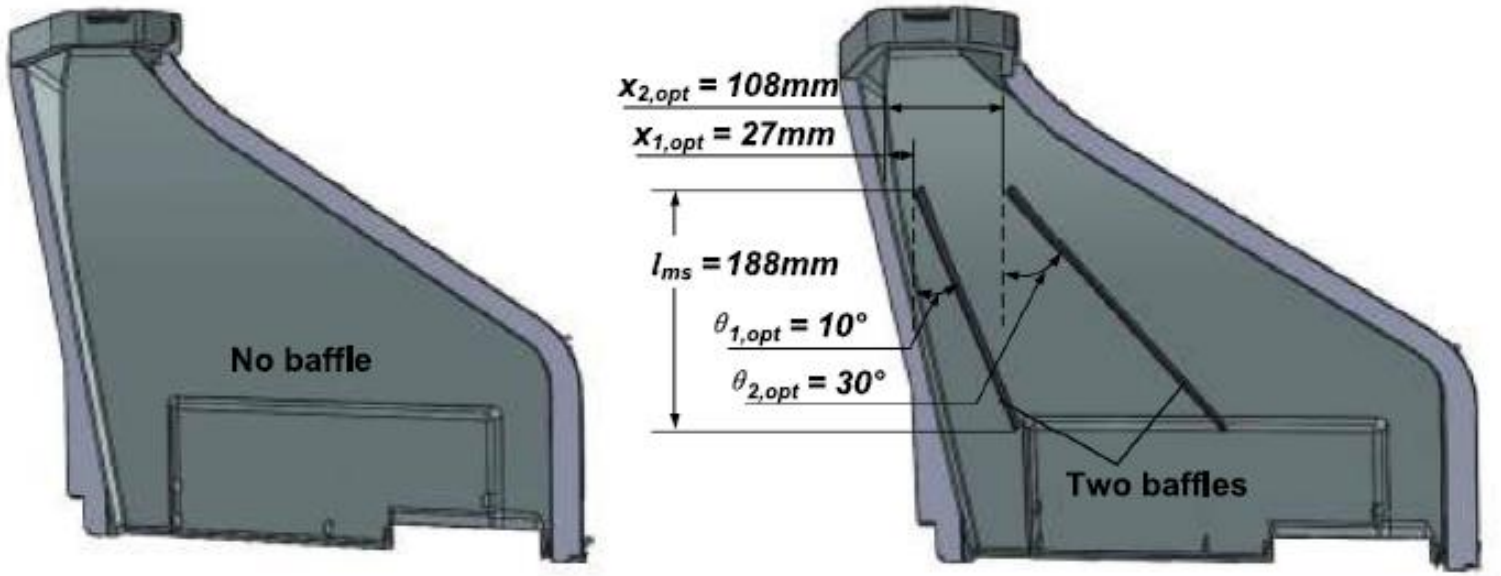


回风道几何结构的参数化



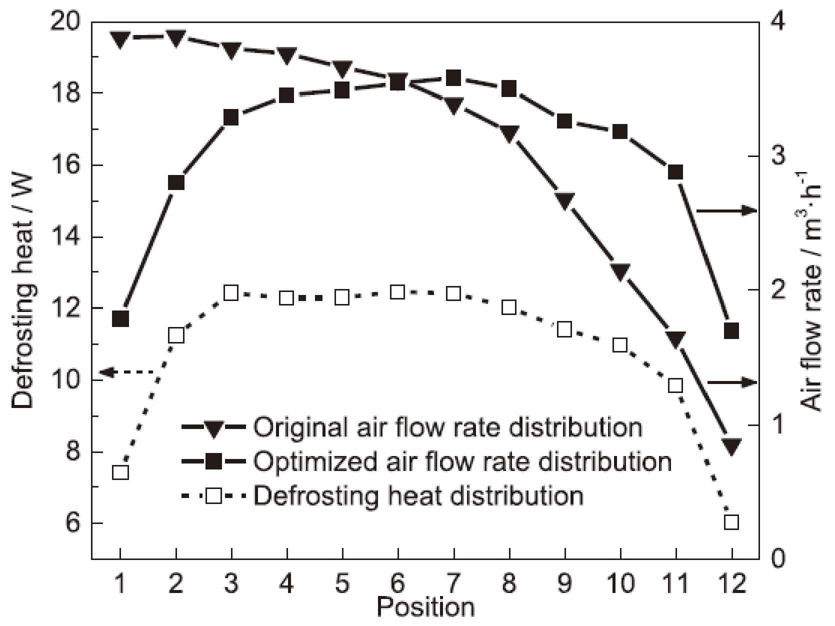
根据除霜热量分布计算出需要的风量分布

回风道结构设计结果



优化前　　　　优化后

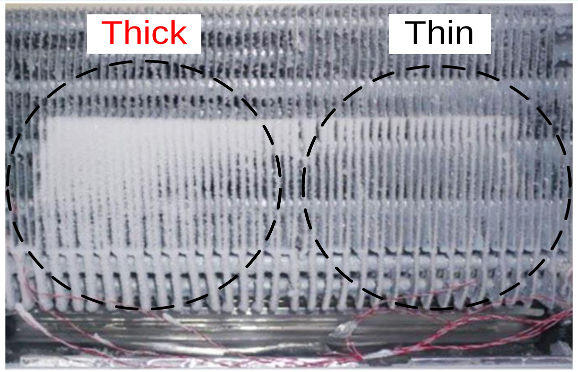
优化前后的回风道结构



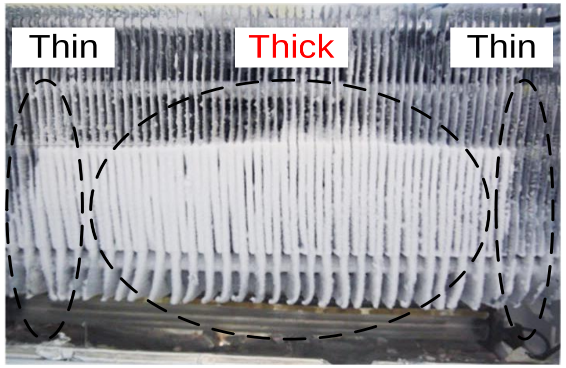
优化前后的风量分布对比

优化效果的验证

优化前后蒸发器上的霜层分布情况

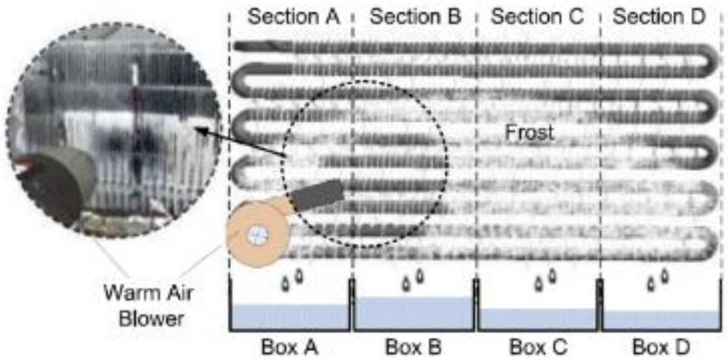


优化前

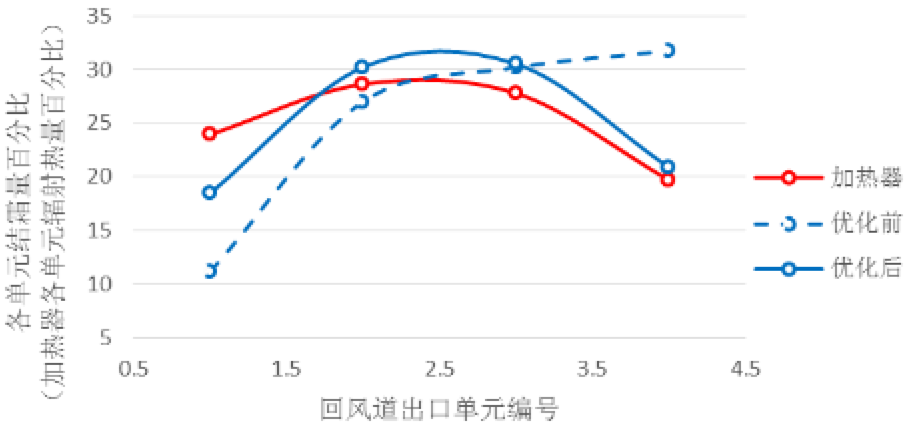


优化后

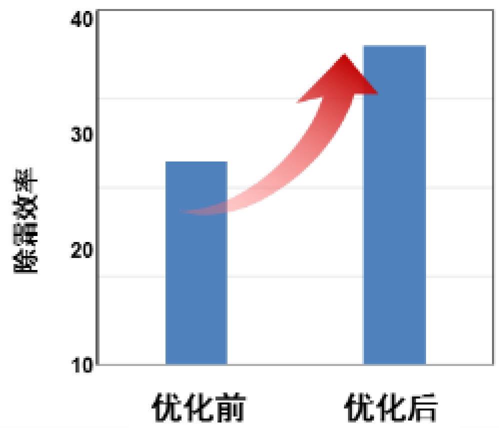
优化效果分析



加速除霜实验



回风道优化前后出蒸发器结霜量分布对比



回风道优化前后出除霜效率对比

优化后，回风道出口风量分布、蒸发器上的霜层分布均与除霜热量分布匹配，除霜效率提高28%。

目录

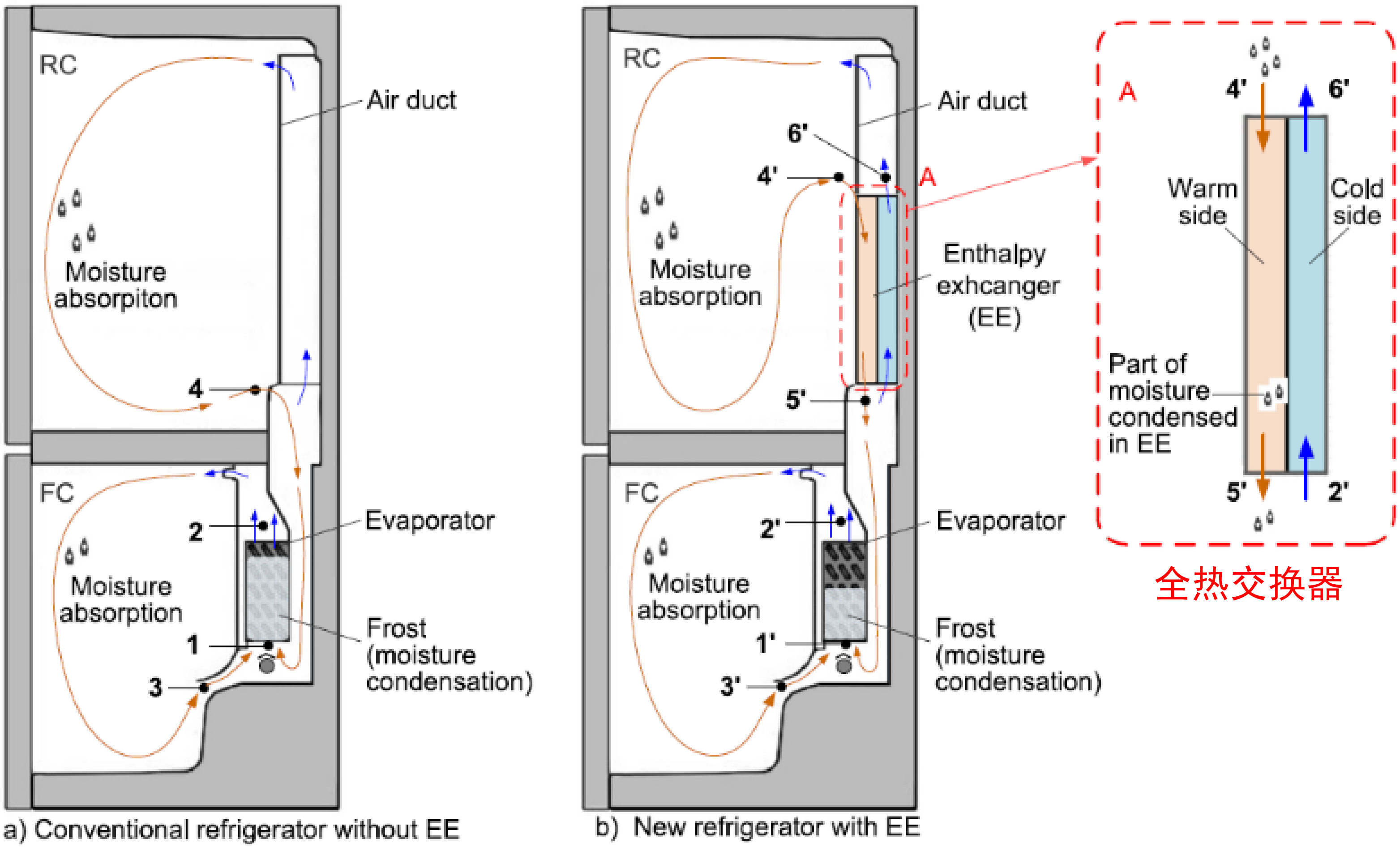
1. 间冷式冰箱的除霜性能优化

2. 基于减少结霜量的全热交换器设计及应用

3. 箱室内均温性能的优化设计

减少结霜量的思路

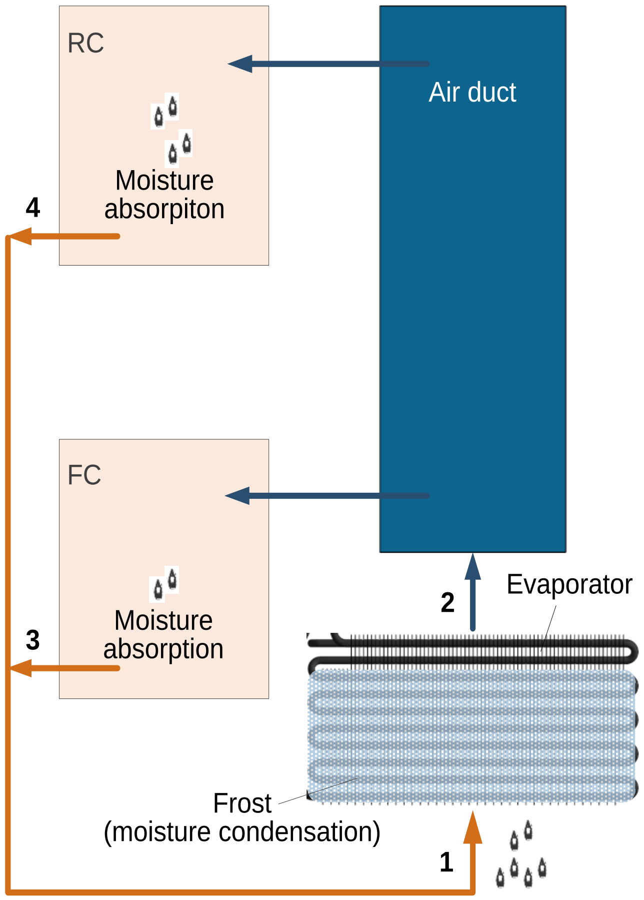
在冰箱中设计添加全热交换器，将部分水汽提前冷凝，减少进入蒸发器的水汽，从而减少蒸发器上的结霜量。



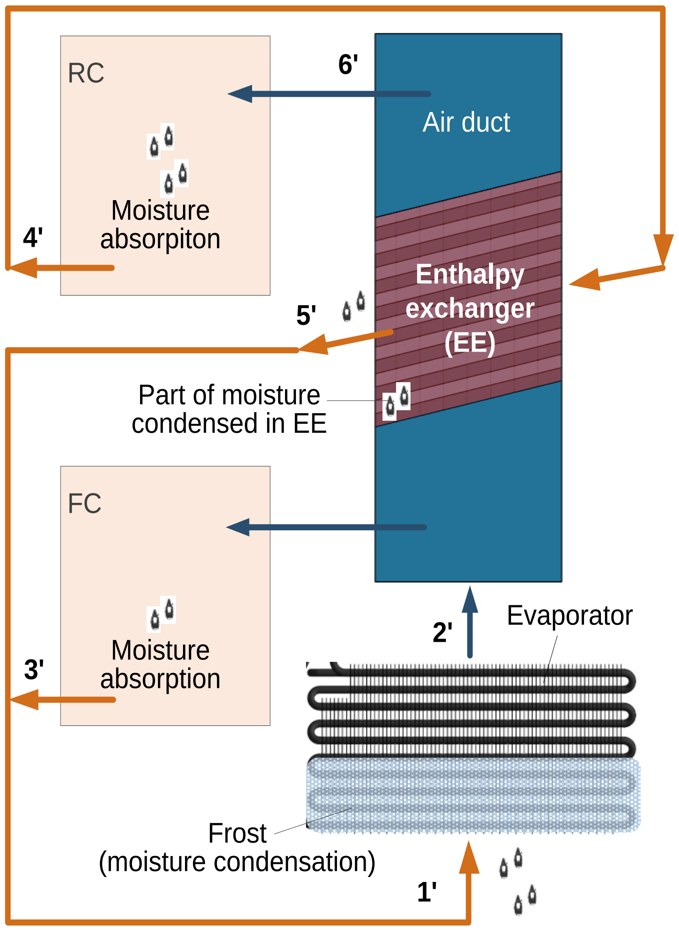
在冷藏室风道中增加全热交换器

减少结霜量的思路

在冰箱中设计添加全热交换器，将部分水汽提前冷凝，减少进入蒸发器的水汽，从而减少蒸发器上的结霜量。



传统冰箱的空气流动情况

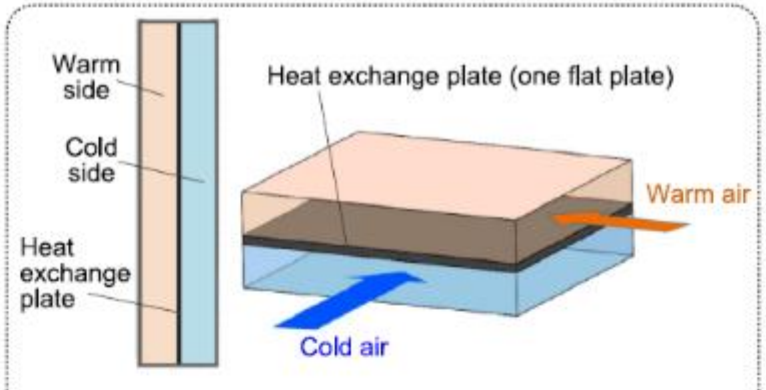


采用全热交换器的冰箱的空气流动情况

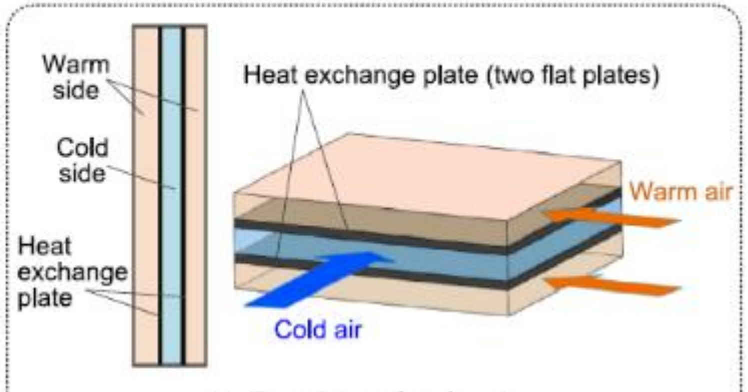
应用全热交换器前后空气流动的变化

全热交换器的结构设计

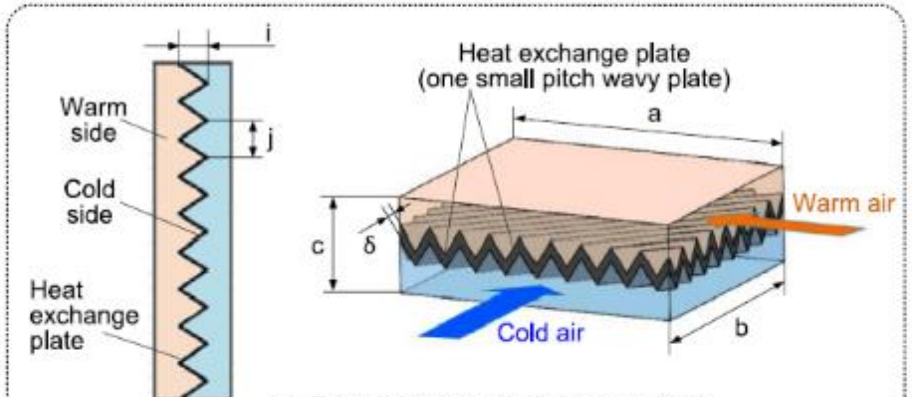
通过对采用平片和波纹片全热交换器建立换热过程仿真计算模型，利用CFD仿真计算出五种全热交换器方案的凝水量，选出最优的全热交换器方案。



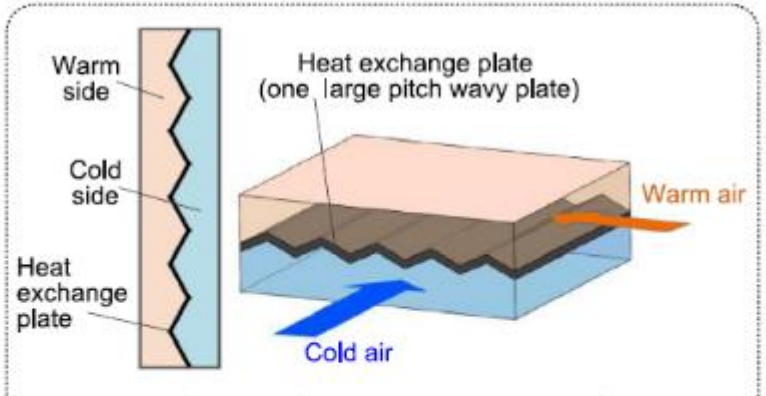
a) Type-1 (one flat plate)



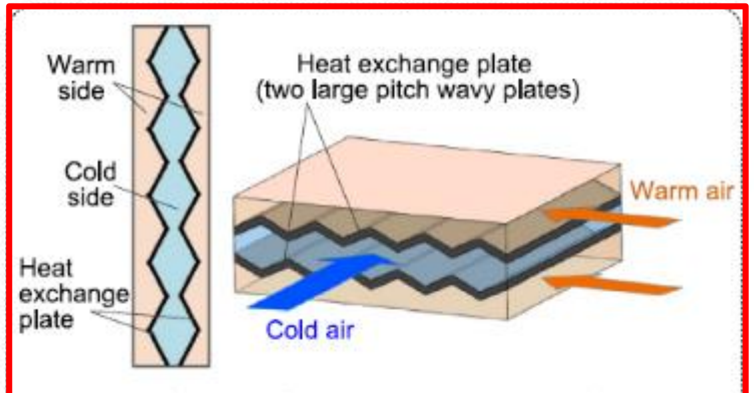
b) Type-2 (two flat plates)



e) Type-5 (one small pitch wavy plate)



c) Type-3 (one large pitch wavy plate)



d) Type-4 (two large pitch wavy plates)

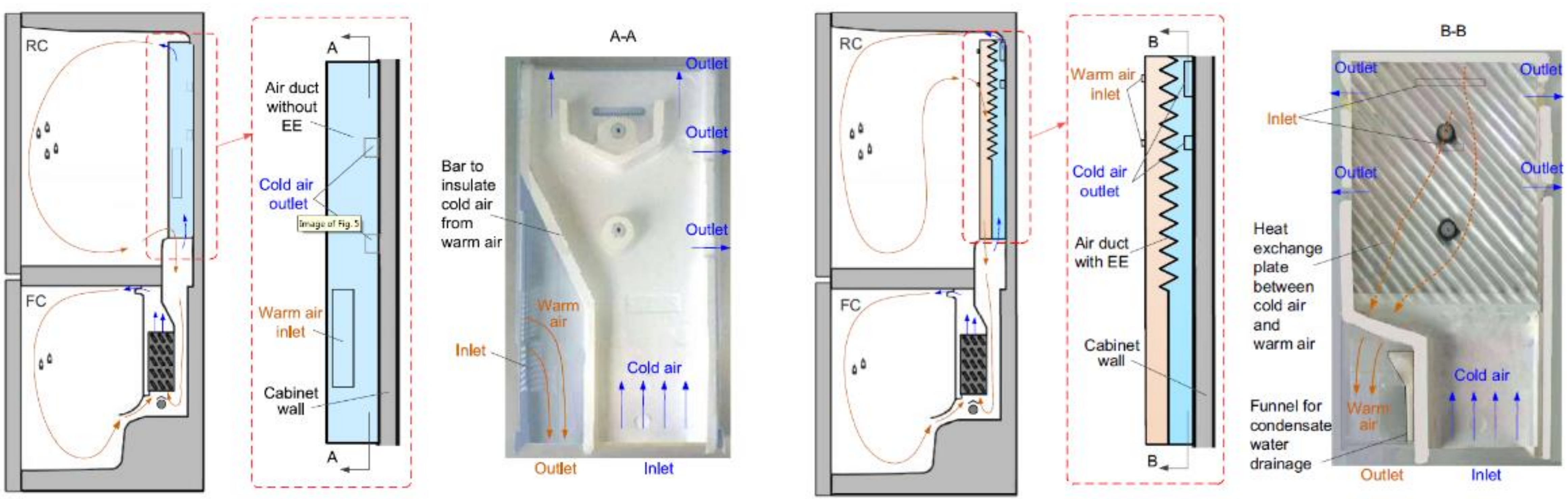
Calculation results of water condensation in EE.

EE types	Outlet temperature °C	Water condensation g/h
Type-1	10.36	5.83
Type-2	9.79	10.80
Type-3	8.52	21.31
Type-4	3.85	53.59
Type-5	4.48	49.73

最优方案

减少结霜量的实验验证

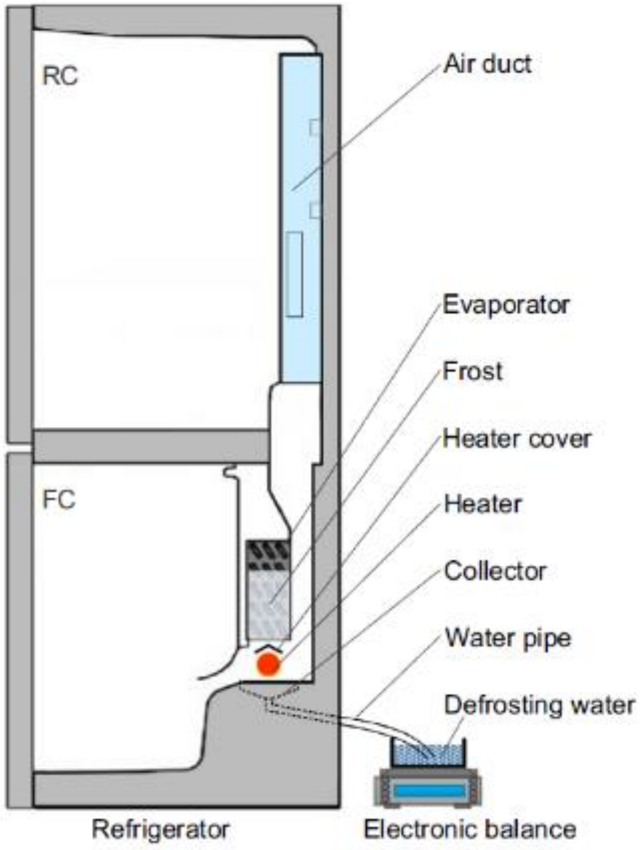
为了验证应用全热交换器减少蒸发器结霜量的实际效果，将方案4的波纹片全热交换器应用于实际冰箱中，并通过实验测量应用前后的结霜量。



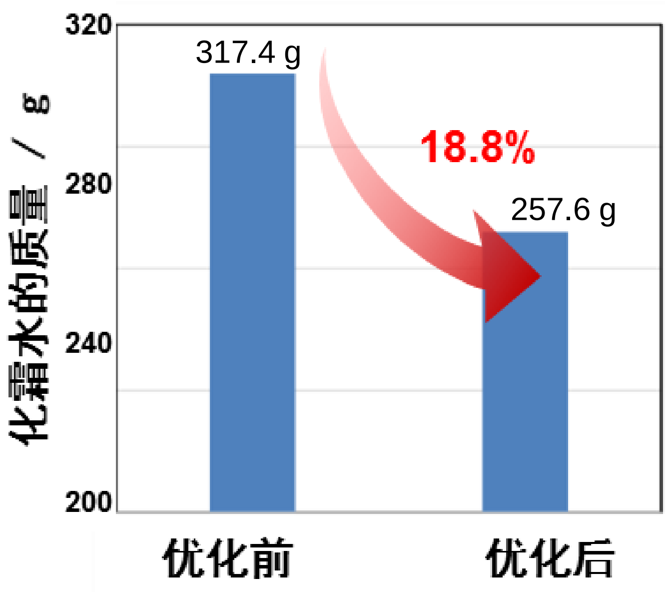
a) Refrigerator without EE　b) Air duct without EE　c) Photo of air duct from A-A view　a) Refrigerator with EE　b) Air duct with EE　c) Photo of air duct from B-B view

减少结霜量的实验验证

为了验证应用全热交换器减少蒸发器结霜量的实际效果，将方案4的波纹片全热交换器应用与实际冰箱中，并通过实验测量应用前后的结霜量。



蒸发器结霜量的实验测量装置



蒸发器结霜量的实验测量结果

通过在风道系统中设计添加全热交换器，可使蒸发器上的结霜量减少18.8%。

目录

背景与目标

背景

- 葡萄酒的品质受温度的影响敏感
  - 大多数葡萄酒的最佳保存温度为10~12 ^{o}C
  - 酒柜内的温度均匀性需控制在2 ^{o}C以内
- 间冷式压缩机酒柜是目前市场上酒柜的主要品种
  - 间冷式压缩机酒柜依然存在4℃以上的温差
  - 某些大容量的酒柜甚至能达到12℃温差以上

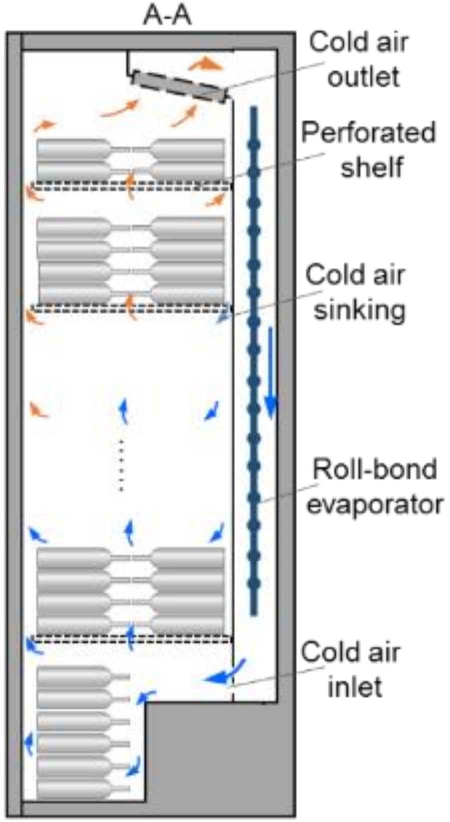
目标

通过对酒柜的流场进行设计，提高箱室均温性能，将最大温差控制在2℃以内。

传统酒柜内的流场

间冷酒柜通过风道系统向箱室送风实现制冷，酒柜内流场的分布情况直接影响了酒柜的均温性能。

a) 间冷式酒柜

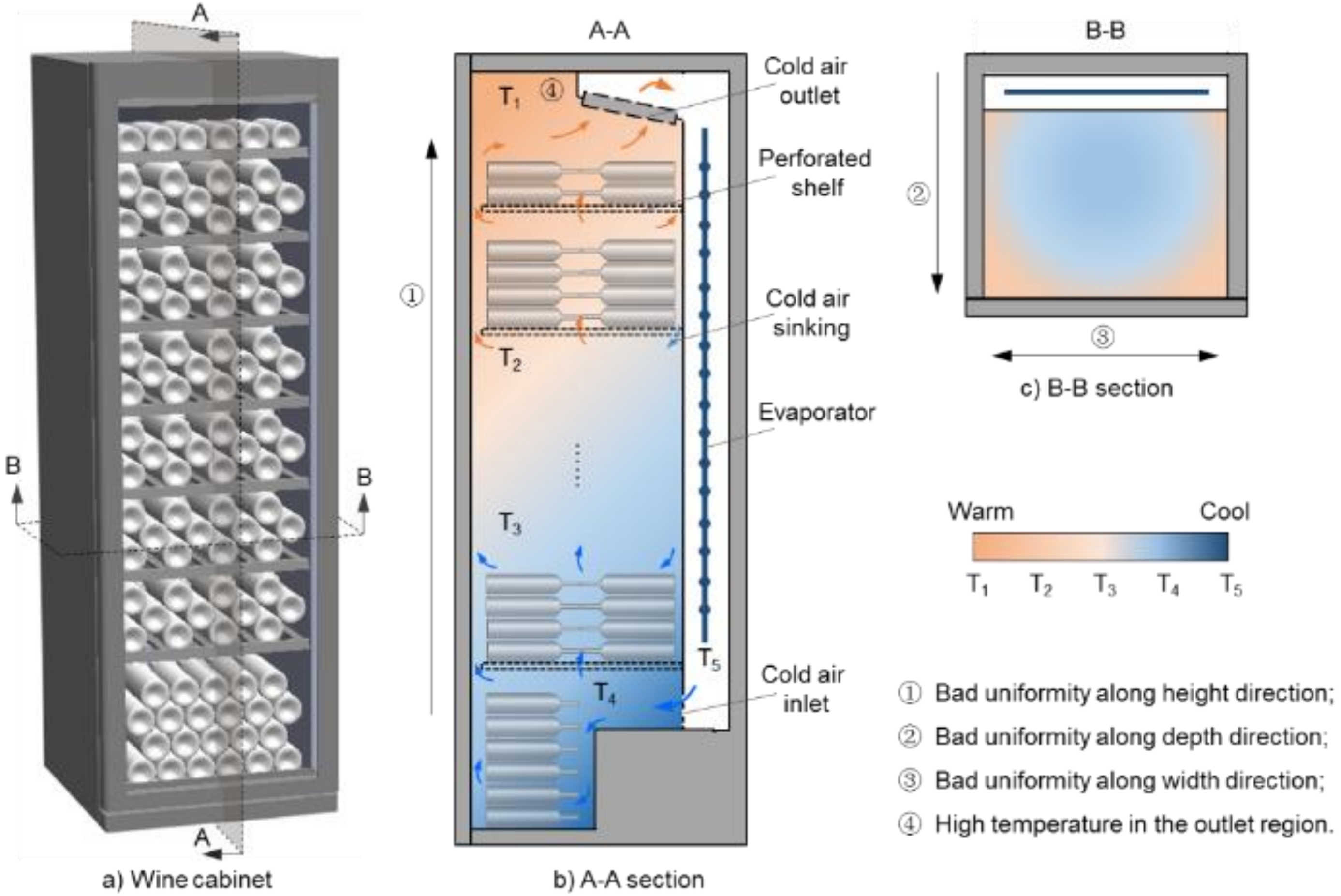


b) 酒柜内的流场

传统间冷式酒柜的结构和流场.

均温性能的问题分析

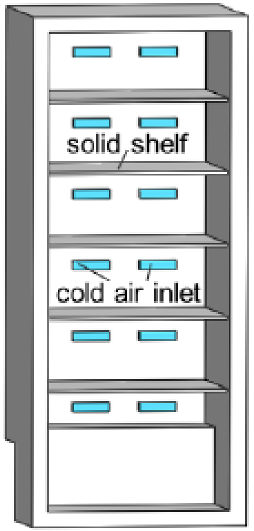
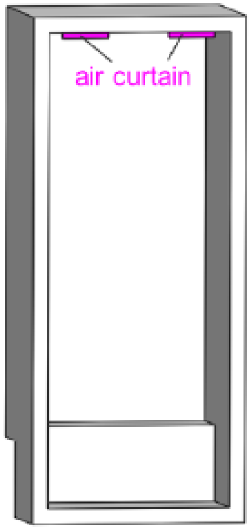
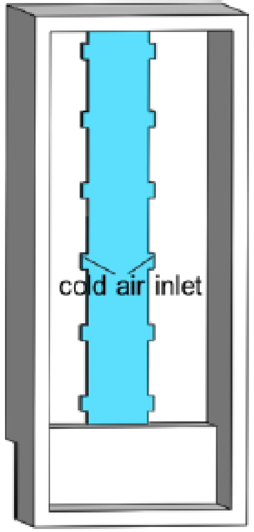
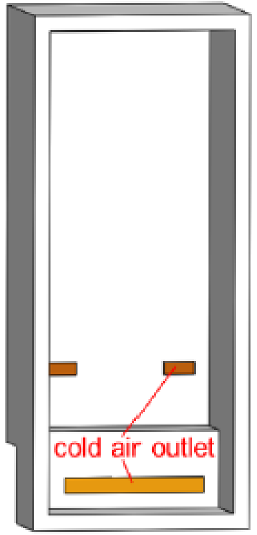
酒柜内温度分布的不均匀性主要体现在四个方面：(a) 沿高度方向；(b)沿宽度方向；(c) 沿深度方向；(d)出口处的局部高温。



传统间冷式酒柜均温性能的问题分析

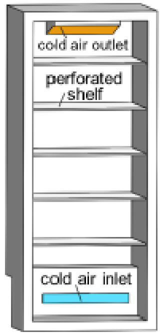
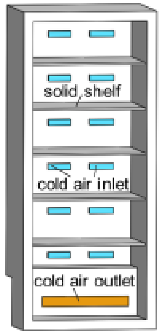
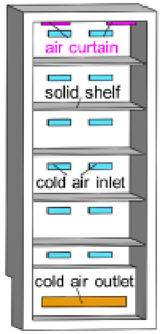
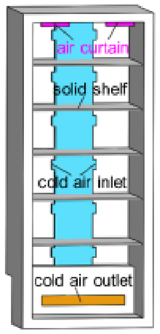
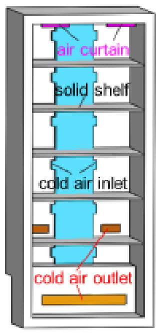
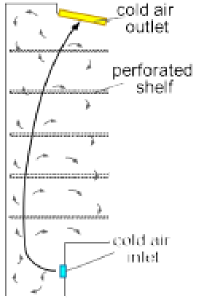
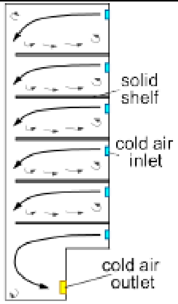
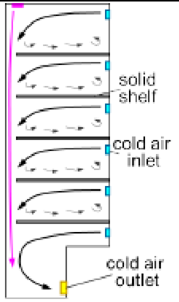
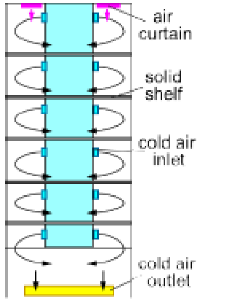
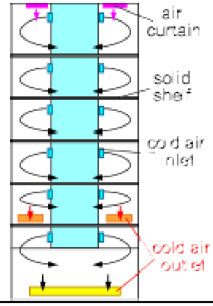
优化思路

根据对酒柜均温问题的分析，针对性地提出四项优化方法，包括：(a)构建多回路的送风方式；(b)设置前端风幕；(c)设计每一层的送风方向；(d)设置多层次的回风口。

	Method (a)	**Method (b)**	**Method (c)**	**Method (d)**
Method description	• Use solid shelves to divide the cabinet into several chambers; • Set cold air inlets in each chamber to supply cooling capacity uniformly along the height direction.	• Add cold air inlets in the top front of the cabinet to form an air curtain against the heat leakage though front glass door.	• Adjust the flow direction of cold air to enhance convection in both sides of the cabinet.	• Add air outlets in different chambers in the bottom of the cabinet to distract the heat in the return air.
Structure illustration				

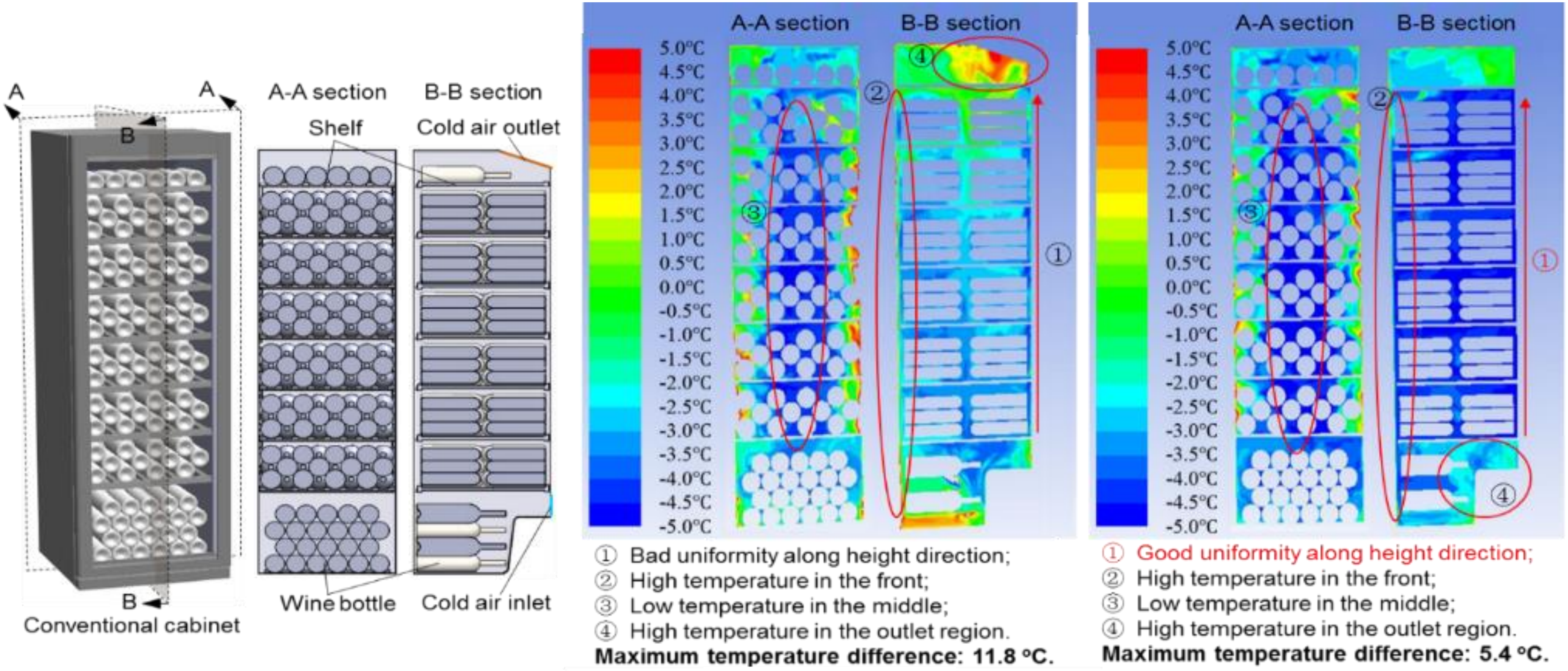
优化方案

基于上述四项优化方法，提出以下四个优化方案。

	原型酒柜	方案一	方案二	方案三	方案四
Scheme description	——	• Method (a)	• Method (a) and (b)	• Method (a), (b) and (c);	• Method (a), (b), (c) and (d);
	• Perforated shelves, airflow is free to travel in the cabinet; • Single-circuit air duct, only one inlet and one outlet.	• Solid shelves, separating the cabinet into several chambers; • Multi-circuit air duct, several forward inlets and one outlet.	• On the basis of scheme 1, add air inlets in the top front of the cabinet.	• On the basis of scheme 2, replace the forward air inlets by sideward air inlets.	• On the basis of scheme 3, add air outlets in different chambers in the bottom of the cabinet.
Structure illustration					
Air flow management					
	• In the central area, air flows from bottom to top, outside the central area, airflow field is disordered; • Cold air sinking and warm air rising occurs in the cabinet.	• In each chamber, air flows from back to front; • In the front of the cabinet, air flows from top to bottom; • Cold air sinking and warm air rising is eliminated.	• On the basis of scheme 1, a cold air curtain is formed in the front of the cabinet.	• On the basis of scheme 2, air in each chamber flows from back to both sides firstly, and then flows to the front.	• On the basis of scheme 3, air flows out of the cabinet through the air outlets in different chambers in the bottom of the cabinet.

优化方案的效果解析

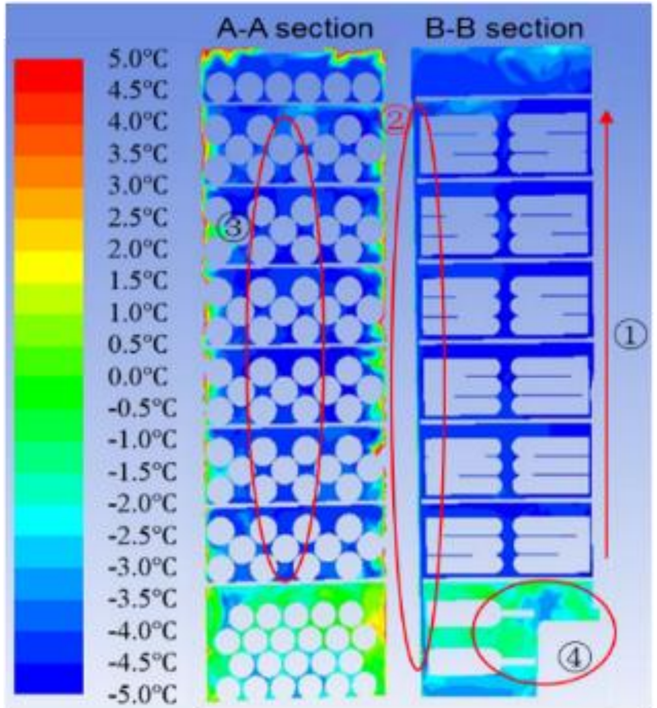
方案一通过构建多回路的送风方式，有效提高了沿高度方向上的均温性能。最大温差由11.8 ℃减小至5.4 ℃。



原型酒柜　　方案一

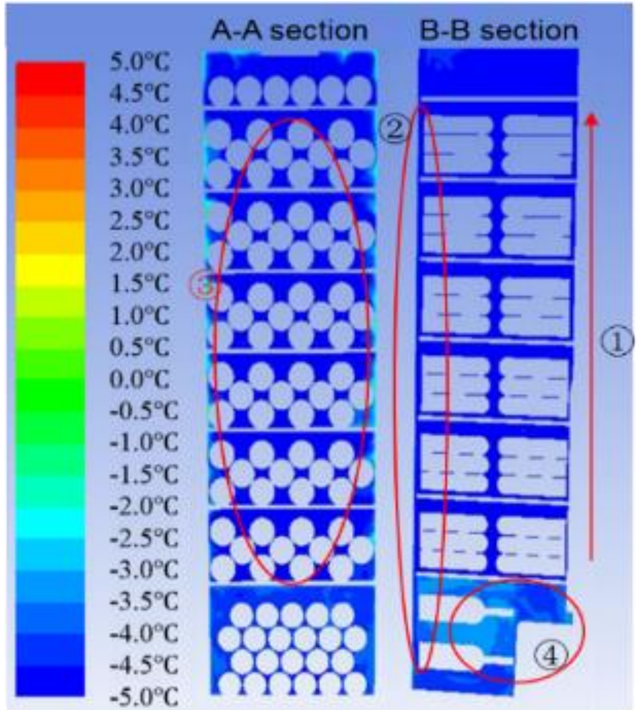
优化方案的效果解析

方案四是四种优化方法的综合方案，使最大温差由11.8 ℃减小至1.8 ℃，效果最优。



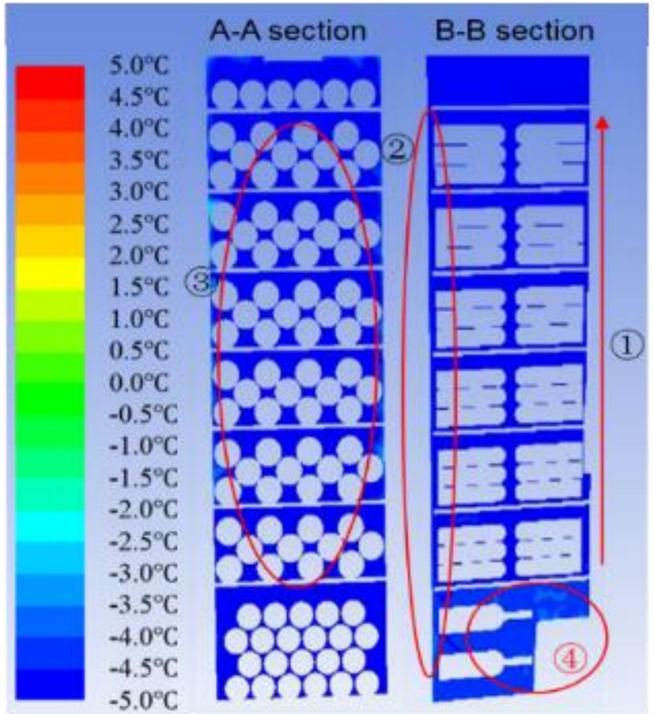
① Good uniformity along height direction;
② Good uniformity along depth direction;
③ Low temperature in the middle;
④ High temperature in the outlet region.
Maximum temperature difference: 3.6 °C.

方案二



① Good uniformity along height direction;
② Good uniformity along depth direction;
③ Good uniformity along width direction;
④ High temperature in the outlet region.
Maximum temperature difference: 2.1 °C.

方案三



① Good uniformity along height direction;
② Good uniformity along depth direction;
③ Good uniformity along width direction;
④ Low temperature in the outlet region.
Maximum temperature difference: 1.8 °C.

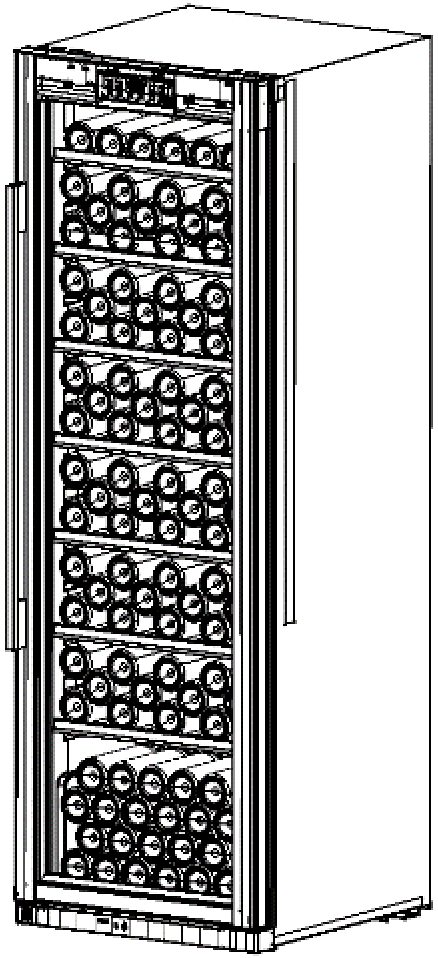
方案四

实验验证

➢ 实验样机酒柜的参数：

- 389L容积
- 酒柜8层
- 制冷温度由8℃至18℃

项目	参数
外形尺寸（mm）	595/640/1850
有效容积（L）	389
装瓶数	171
酒柜层数	8
净重（kg）	91
满载风量（m^3/h）	50
额定制冷量（W）	80
温度控制范围（℃）	8～18
耗电量kWh/24h	0.65



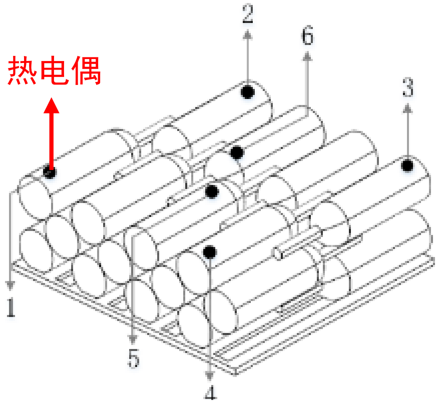
实验验证

➢ 满载酒柜样机测试

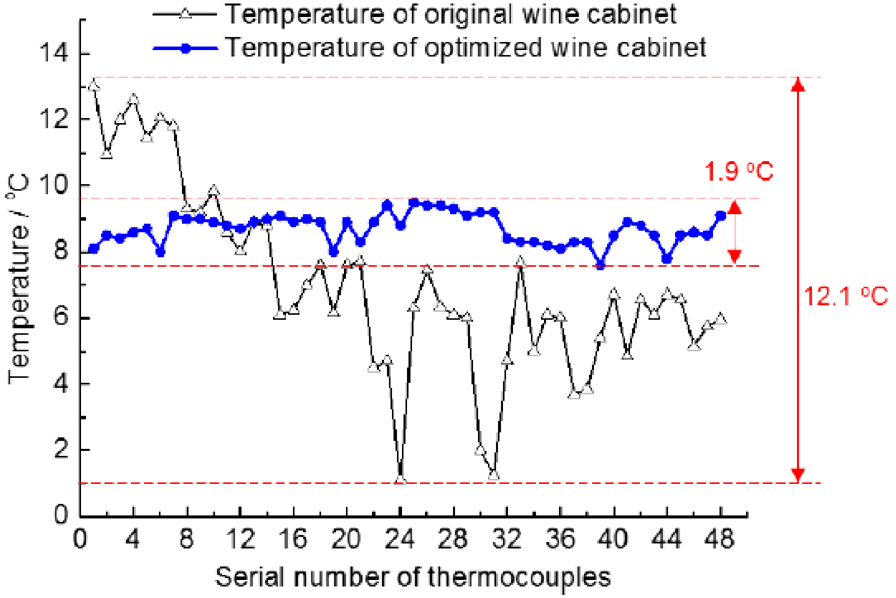
测试环境温度设定为32℃；相对湿度为60%；酒柜内温度设置为8℃

满载酒柜样机测试

测试用葡萄酒瓶替代品



温度测点布置



优化前后酒柜均温性能测试结果

满载实验结果显示，优化后酒柜内最大温差由 12.1 °C 减小至 1.9 °C，满足了红酒保存最大温差2 ℃的要求。

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Q & A