制冷剂温室效应评价方法的思考

Consideration on speed estimation and flexibility evaluation method of refrigerants climate performance

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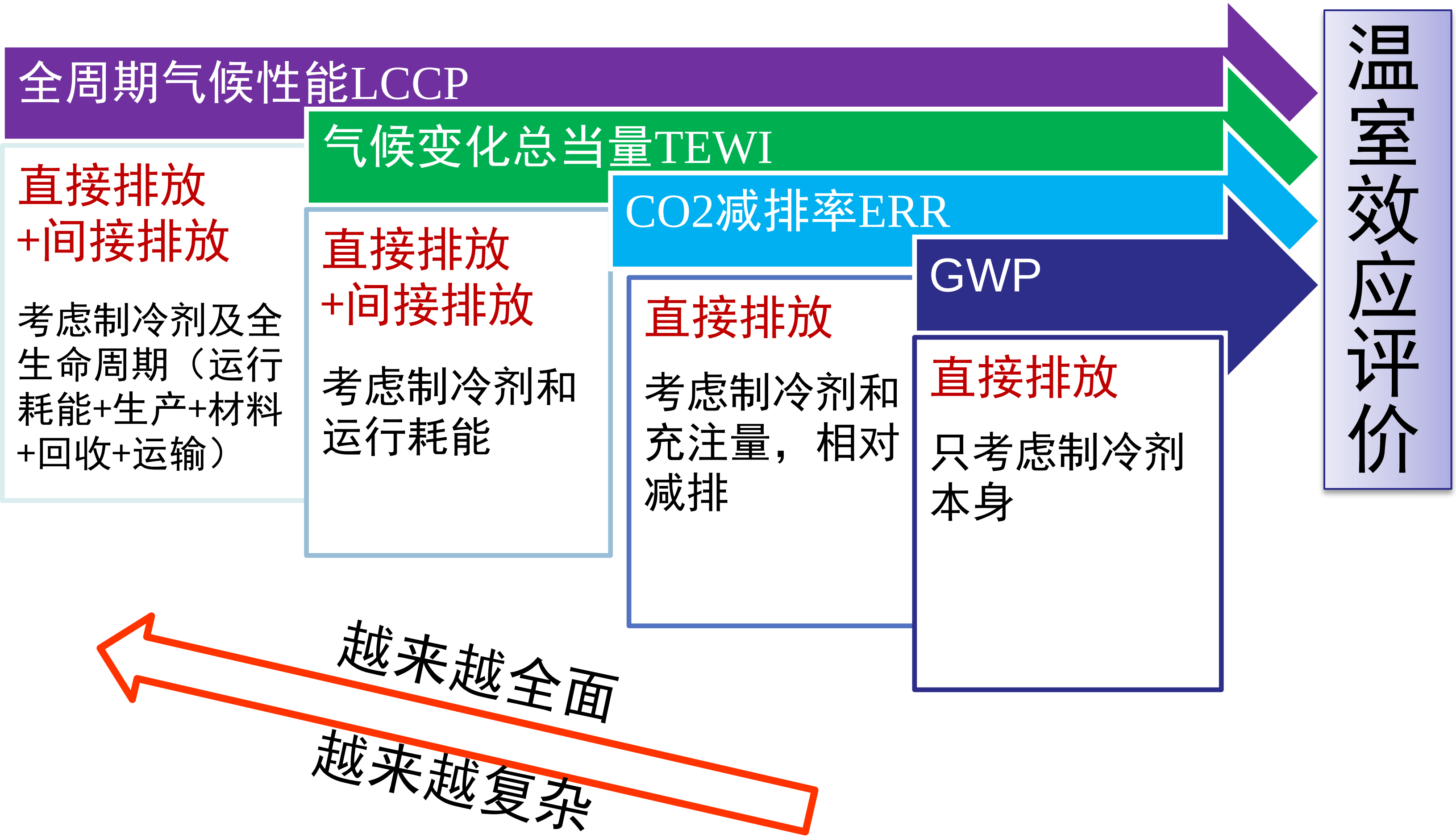
制冷剂温室效应评价方法

Evaluation method of refrigerants climate performance



It is more comprehensive but also more complex that climate performance evaluation methods develop from GWP, ERR, TEWI to LCCP.

LCCP的影响因素
Effect factors for LCCP

$$LCCP = GWP \times (L \times ALR + EOL) + L \times AEC \times ER + MM \times m + RM \times mr + RFM \times C + L \times ALR \times RFM + (C - EOL) \times RFD$$

$GWP =$ 制冷剂全球温室效应[kg CO_{2e}/kg]

$L =$ 设备平均使用寿命[yr]

$ALR =$ 平均年泄漏率[kg]，各应用领域不一样

$EOL =$ 设备终了制冷剂排放率[kg]，各国数据不同

$AEC =$ 年平均能源消耗[kWh]，直接关联COP

$ER =$ 单位电力温室气体排放[kg CO_{2e}/kWh]，与区域相关

$MM =$ 使用设备材料的温室气体排放率[kg CO_{2e}/kg]，与区域相关

$m =$ 材料设备重量[kg]，各设备不一样

$RM =$ 回收材料温室气体排放[kg CO_{2e}/kg]，各国数据不同

$mr =$ 回收材料重量[kg]

$RFM =$ 制冷剂加工生产的温室气体排放[kg CO_{2e}/kg]

$C =$ 制冷剂充注量[kg]

$RFD =$ 制冷剂回收产生的温室气体排放率[kg CO_{2e}/kg]

与制冷剂性质相关

Associated with refrigerant properties

GWP, AEC, m, C

与基础统计数据有关

Associated with basic investigations statistical data

L, ALR, EOL, ER, MM, RM, mr, RFM, RFD

LCCP计算需要大量的数据支撑

LCCP analysis requires a lot of data to suport

基础数据（如电力排放，材料消耗排放……）

大量行业调研数据（年泄漏量，制冷剂回收量……）

所有原材料均以1kg为单位（电为1kWh）

Major Articles*	类型	主要产品	Units	电	钢（混合）	铸铁	铝	铜	橡胶	塑料
(r) Iron (Fe ore)		铁矿石	kg	7.34E-04	1.09E+00	1.11E+00	3.48E-02	-3.52E-01	1.55E-02	4.99E-04
aluminium(Al)		铝	kg	2.67E-05	1.97E-05	1.12E-05	8.74E-01	2.94E-04	1.03E-03	3.56E-04
chromium(Cr)		铬	kg	3.21E-06	8.96E-06	5.20E-06	8.12E-05	1.42E-02	8.22E-04	3.66E-08
cadmium (Cd)		镉	kg	3.01E-09	2.37E-09	1.73E-09	1.38E-07	1.05E-07	3.97E-04	0.00E+00
cobalt (Co)		钴	kg	1.92E-12	8.17E-11	6.00E-11	2.39E-09	4.68E-10	6.99E-09	0.00E+00
copper (Cu)		铜	kg	1.19E-05	1.47E-05	1.13E-05	2.34E-04	1.07E+00	9.34E-04	8.38E-05
fluorine (F)		氟	kg	1.15E-08	1.90E-07	1.81E-07	1.11E-06	3.20E-04	5.48E-06	0.00E+00
gold (Au)		金	kg	3.37E-12	1.93E-10	1.92E-10	1.90E-09	9.84E-09	6.39E-08	0.00E+00
lead (Pb)		铅	kg	6.54E-09	3.69E-07	3.19E-07	4.83E-06	8.41E-06	1.56E-05	8.32E-07
lithium (Li)		锂	kg	4.38E-14	7.82E-12	7.53E-12	7.67E-12	5.41E-10	6.29E-12	0.00E+00
magnesium(Mg)		镁	kg	5.88E-06	1.25E-02	1.28E-02	9.53E-05	6.70E-06	2.88E-08	1.19E-03
manganese(Mn)		锰	kg	9.98E-06	2.07E-02	3.10E-06	1.68E-04	1.40E-04	9.55E-05	3.47E-07
nickel(Ni)		镍	kg	7.52E-06	3.42E-05	2.49E-05	2.20E-04	3.33E-02	1.98E-03	1.23E-05
phosphorus (P)		磷	kg	4.62E-07	1.47E-06	1.04E-06	5.21E-03	1.29E-03	2.23E-05	1.75E-11
ilicium(Si; silicon	资源能耗消耗	硅	kg	6.02E-06	2.09E-06	1.24E-06	9.67E-05	5.75E-01	0.00E+00	0.00E+00
silver(Ag)		银	kg	9.39E-12	5.69E-10	5.56E-10	5.22E-09	2.70E-08	1.72E-07	0.00E+00
sulfur (S)		硫	kg	1.45E-05	2.68E-04	3.27E-04	1.25E-02	-2.72E-01	2.62E-05	6.22E-03
crude oil		原油	kg	3.52E-03	4.05E-02	4.05E-02	4.21E-01	2.87E-01	1.31E+00	4.12E+01
naturalgas*		天然气	kg	5.27E-03	1.14E-02	1.09E-03	1.49E-01	6.70E-03	0.00E+00	4.08E+01
(r) Limestone		石灰石	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Dolomite		白云石	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Zinc (Zn ore)		锌矿石	kg	6.28E-08	2.50E-06	2.33E-06	1.68E-05	2.26E-04	1.23E-02	1.37E-05
by-products (used)		副产品（使用）	kg	0.00E+00	1.28E+00	0.00E+00	0.00E+00	0.00E+00		0.00E+00
Ferrous Scrap (used)		色金属废料（使用	kg	1.22E-19	1.38E+00	5.04E-02	0.00E+00	0.00E+00		0.00E+00
Scrap (used)		废料（使用）	kg	0.00E+00	1.28E+00	1.82E-01	0.00E+00	0.00E+00		0.00E+00
(r) Coal (in ground)		硬煤	kg	5.92E-01	8.78E-01	1.09E+00	1.11E+01	9.50E-01	2.04E-01	1.07E+00
(r)Water Used (total)		总耗水量	litre	8.39E-01	5.28E+00	2.40E+00	0.00E+00	0.00E+00		0.00E+00
(r)energy (total)		总一次能源	MJ	1.93E+01	3.04E+01	3.67E+01	3.81E+02	4.33E+01	6.42E+01	8.31E+01
electricity (net)		净电能	kWh	6.00E-02	5.64E-01	3.49E-01	0.00E+00	0.00E+00		6.68E-01

基于中国生命周期基础数据库（CLCD）数据清单

LCCP analysis requires basic data (such as electricity emissions and material consumption etc.) and a lot of industry research data (annual leakage and refrigerant recovery amount etc.).

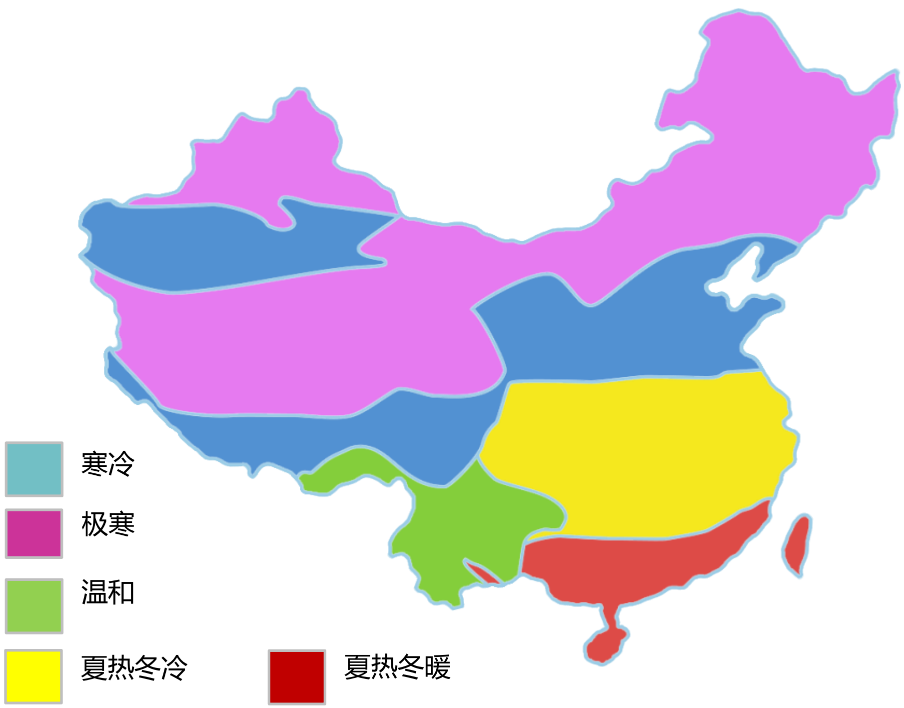
材料	原始加工排放 ($kgCO_2e/kg$)	混合（原始+回收）加工排放($kgCO_2e/kg$)
钢	1.8	1.43
铝	12.6	4.5
铜	3.0	1.64
塑料	2.8	2.61

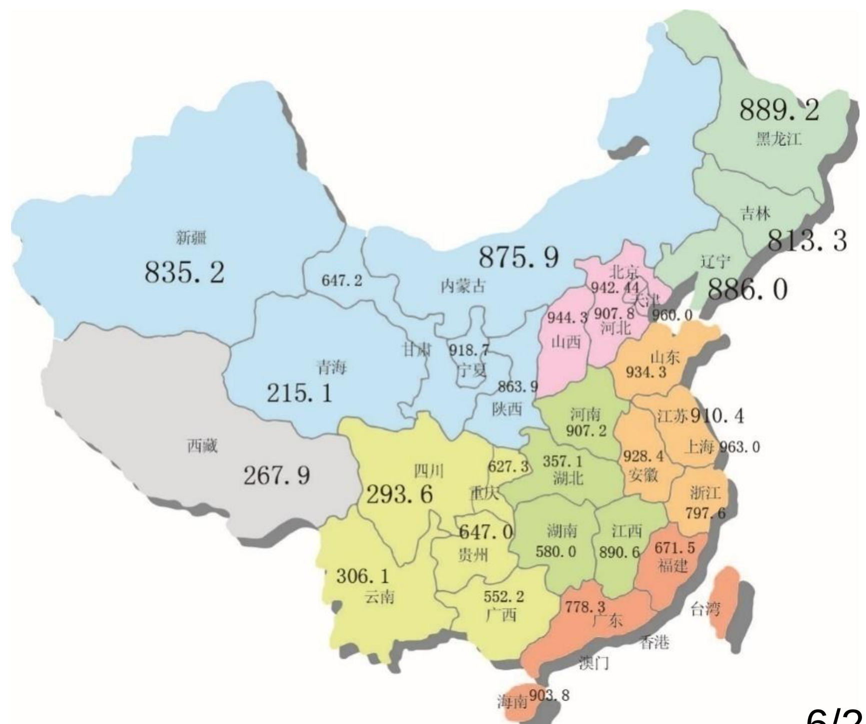
IIF的数据信息

由于地域性基础数据的不同可能造成不同结果
Different results may be obtained due to different data

以中国为例，大温带跨度，各省的电力排放率差别也较大，基于LCCP方法给出的判断也可能不一样。

Regional power generation emissions rates have large differences with big weather zone span, so evaluation results of refrigerant climate performance may be different on based on LCCP method.





LCCP计算中关键参数影响较为敏感
LCCP analysis is sensitive to the key parameters

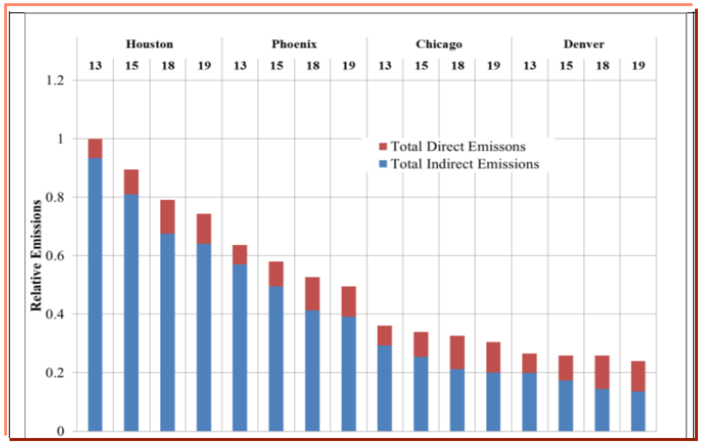
例如：效率很重要，但很复杂
不同产品类型，效率的差别很大
相同类型，不同工况差别也很大
不同工质需要不同匹配

Efficiency is very important, but also complex.

There is large difference of efficiency between different types of products.

There is large difference of efficiency between different conditions even for the same kind of product.

Different refrigerant requires different design and optimization.



不同SEER和区域下直接排放和间接排放比例差别较大（R410A的热泵机组）

Stephen Anthony Kujak,Panayu Robert Srichai,Kenneth J.Schultz. Assessment of Life Cycle Climate Performance (LCCP) Tools for HVAC&R Applications With The Latest Next Generation Refrigerant. International Refrigeration and Air Conditioning Conference. Purdue University. 2014

LCCP评价方法正在工具化和标准化
LCCP evaluation methods need to be standardized

就制冷系统各个应用领域，目前开发了相应的计算工具GREEN-MAC-LCCP； ORNL Supermarket LCCP； AHRI HP LCCP。

目前，UNEP和IIR正在开展标准化方面的工作。

For refrigeration application product segments, GREEN-MAC-LCCP, ORNL Supermarket LCCP, AHRI HP LCCP ,etc. LCCP tools have been developed.

Now, the UNEP PTOC and IIR have formalizing and standarding LCCP evaluation calculations.

利用LCCP进行实际分析判断较少
LCCP less practical utilization

消费者
不了解

No understand
for consumers

研究机构
缺乏数据

lacking sufficient
data for researcher

企业
太复杂

Too complex for
manufacture

决策者
不好用

Difficult to use
for policy maker

问题的提出
Issue

制冷剂温室效应评估的主要目的之一是为决策者选择制冷剂替代方案服务，当评估方法变得过于复杂无法操作时，这种选择就困难了。

需要更简便直接、可操作性强的方法。

Refrigerants climate performance reasonable evaluate in order to Consider refrigerant alternatives for future policy makers. But It would seem to be an insurmountable challenge now when evaluation methods are too complicated to operate.

The more simple, direct and flexibility evaluation method is required

间接排放的简化

Consideration of indirect CO2 emission

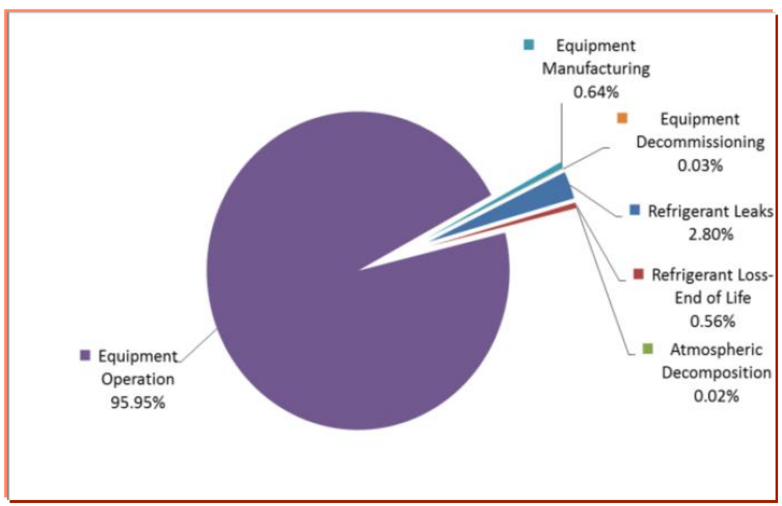
- 间接排放中制冷剂生产、回收、材料使用等相对于使用耗能非常小，通过对比化考虑，可以适当简化。
  CO2e produced of refrigerant produced, manufacturing and material using are very small relative to energy consumption contributions，which can be simplified by use the method of corresponding state.

$$LCCP = GWP \times (L \times ALR + EOL)$$

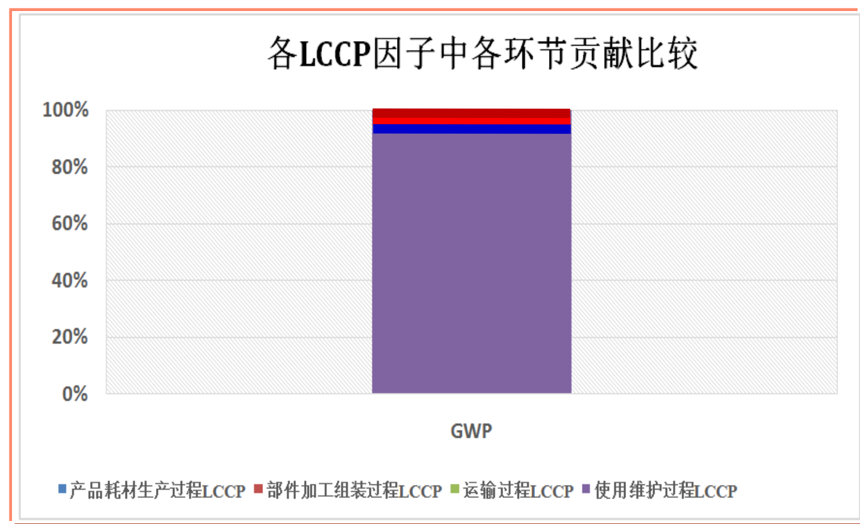
$$+ L \times AEC \times ER + MM \times m + RM \times mr + RFM \times C + L \times ALR \times RFM + (C - EOL) \times RFD$$

$$\delta$$

$$X, Y \gg \delta \Longrightarrow \frac{X+\delta}{Y+\delta} \approx \frac{X}{Y}$$



基于AHRI热泵LCCP工具计算的算例（地点Houstion，使用R32/R1234yf混合工质。热泵的能效SEER为13）



基于中国相关数据计算的算例（地点中国，使用制冷剂为R22，冷水机组的COP为3.48）

LCCP计算方法的简化
Consideration of indirect CO2 emission

- 简化后的LCCP计算，哪些是关键参数? 如果建立关键因素与制冷剂固有性质之间的关联式，用一般性统计数据代替个别设备的数据。便于替代效果的评估。

Which is the key parameters when LCCP calculation simplified? if set up fundamental parameters and key performance and use the general statistics instead of the individual equipment data.

$$LCCP = D(GWP, M) + IND(T_c, P)$$

哪些关键参数？ GWP、M、Pe、Pc？

Which are key parameters?

评估结果的输出方式
The output of the evaluation results

- LCCP方法给出的是某一类型和容量的机组在某运行条件下的具体排放数据，然而对于决策者来说，更需要的是对于当前制冷剂替代后减排了多少的评价；
- 是否可以基于LCCP的概念，以相对替代减排率的方式输出结果

- The output of LCCP method evaluation result is specific emissions data on given operational conditions for some type and capacity units, however, policy makers need emission reduction evaluation for the current refrigerant substitute more than the specific data.
- Whether can be design alternative emission reduction rates as output based on the concept of LCCP?

$$ERR^{LCCP} = \frac{LCCP_0 - LCCP_a}{LCCP_0}$$

主要内容 Contents

影响LCCP的制冷剂关键基础物性
Refrigerant key properties affect LCCP

☆影响排放的主要因素包括GWP值，泄漏率和能源消耗
☆制冷剂种类上的性能是：GWP、充注量、COP、容积制冷量

- 充注量：与制冷剂种类、应用类型、设备容量等相关；
- COP：与制冷剂种类、应用类型、设备容量、优化技术水平相关；
- 容积制冷量：与制冷剂种类、设备尺寸、充注量、COP有一定关联

☆基于热力学分析，这些关键性能又可与工质某些固有基础物性建立关联

☆ Important factors in emission impact including: GWP, leakage and energy consumption
☆ Performances of refrigerant including: GWP, charge, COP and volumetric capacity

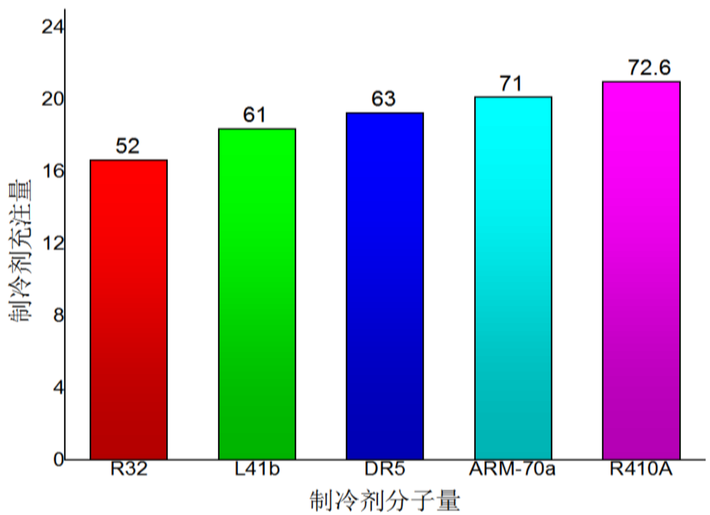
- Charge: associate with refrigerant, application type and equipment capacity
- COP: associate with refrigerant, application type, equipment capacity and technical level
- Volumetric capacity: associate with refrigerant, affect equipment size and charge

☆ These key properties can be associated with refrigerant fundamental characteristic using of thermodynamic analysis

分子量与充注量
Molecular weight VS Charge

- 充注量主要与设备尺寸，应用类型等因素相关；
- 对于同一设备类型，由制冷剂不同所致充注量不同的最大影响因素是制冷剂液相密度（潜热影响相对较少）；
- 关联制冷剂液相密度的基本物性是制冷剂分子量；
- 可以建立充注量与分子量之间的对比关联。
- Charge related to the amount of equipment size, application type etc. ;
- For the same type of unit, Maximum factor is refrigerant liquid density impact on charge for different refrigerant (The reduction in density is far more important than the latent heat)
- Molecular is associated with liquid density.
- The relevance between charge and molecular can be set up.

$$\frac{C_a}{C_o} = \frac{M_a}{M_o}$$



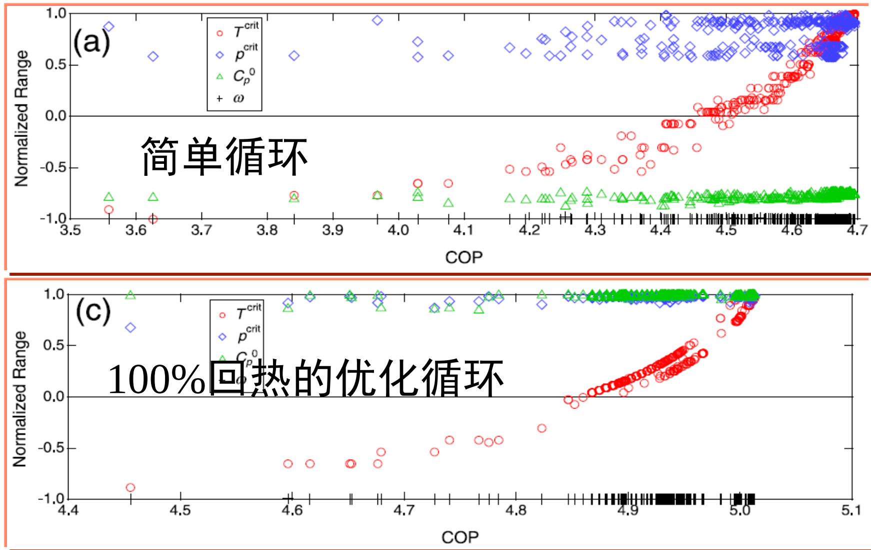
同一设备替代制冷剂最佳充注量与分子量关联对比
（AHRI低GWP研究项目测试报告1，R410A替代分析）

临界温度与COP
Critical temperature VS COP

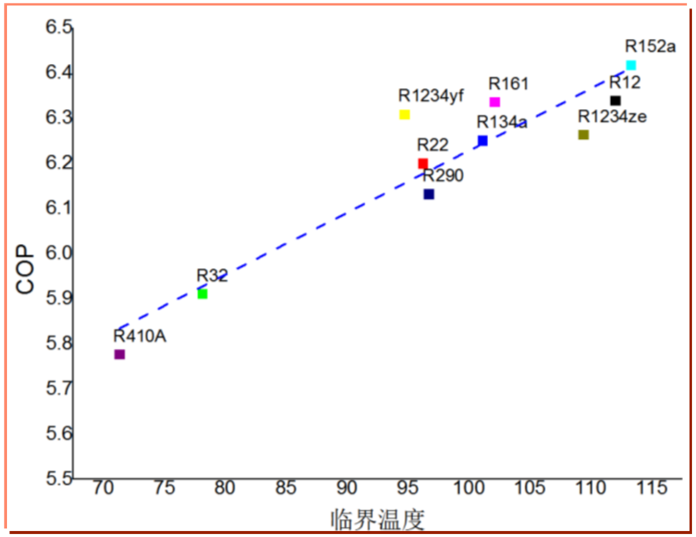
☆影响制冷系统COP的因素很多，从制冷剂本身的热物性考虑，相比其他参数，临界温度与COP有较高的相关度，可以选制冷剂临界温度作为控制COP的关键参数。

☆ There are many factors on affecting the COP of refrigerate system. From the refrigerant thermodynamic properties consideration, the critical temperature and the COP has a high correlation compared to other parameters, so the critical temperature of the refrigerant can be selected as a key parameter to control the COP

$$\frac{COP_a}{COP_o} = f\left(\frac{T_{c,a}}{T_{c,o}}\right)$$



COP与制冷剂临界温度的相关性（ Piotr A. Domanski ）



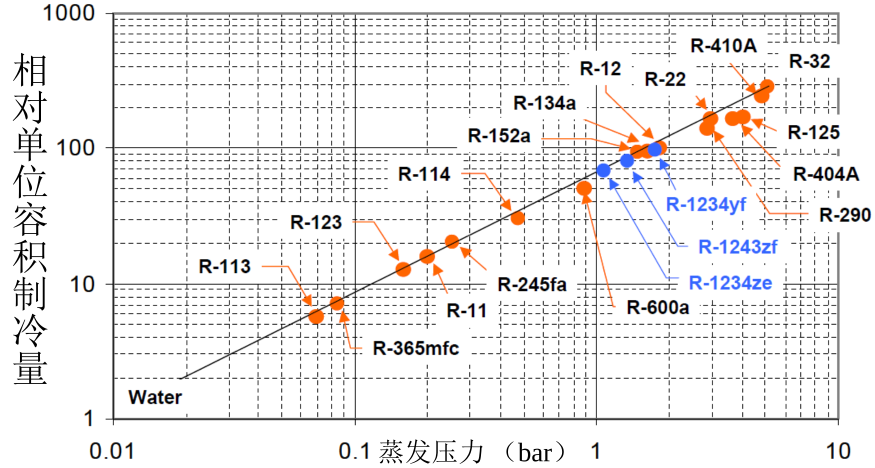
COP与制冷剂临界温度的相关性

蒸发压力与单位容积制冷量
Evaporation Pressure VS Volume Cooling capacity

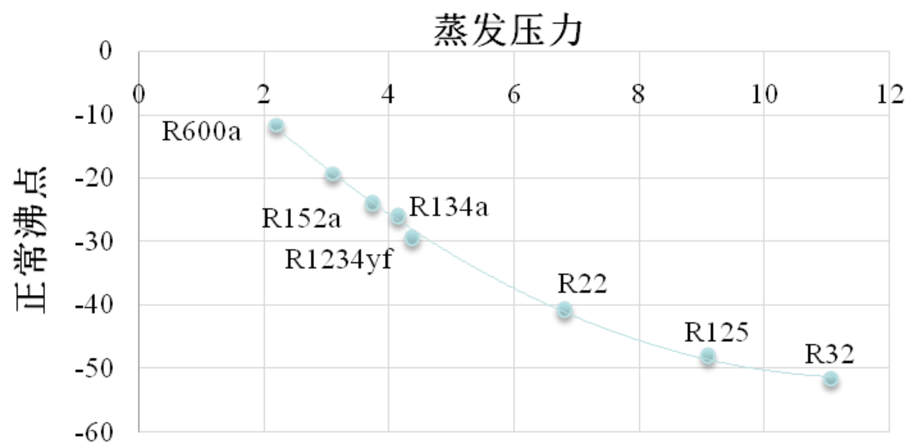
☆容积制冷量与蒸发压力有较强的关联规律，而蒸发压力与制冷剂正常沸点可以通过转换获得，可以选择制冷剂正常沸点作为影响单位容积制冷量的关键影响参数。

☆ Right picture show that it is a strong positive dependence of volumetric capacity on evaporation pressure. Furthermore, evaporation pressure can be obtained through the conversion of refrigerant normal boiling point, so normal boiling point can be selected as key parameter impact of volumetric capacity

$$\frac{m_a}{m_o} = f\left(\frac{VCC_a}{VCC_o}\right) = f'\left(\frac{P_a}{P_o}\right) = g\left(\frac{T_{b,a}}{T_{b,o}}\right)$$



容积制冷量与蒸发压力的相关性[1]



部分制冷剂蒸发压力与正常沸点关联

[1] Brett Van Horn. A Primer on HFOs Hydrofluoro-olefins Low-GWP Refrigerants. 2011 ASHRAE Winter Conference, 2011

主要内容 Contents

LCCP计算模型的合理简化
Reasonable simplified of LCCP calculating model

为建立可操作性的制冷剂温室效应减排的评价方法，需要对LCCP的计算进行合理的简化，其中简化遵循以下原则：

- 在当前制冷技术应用水平上，制冷剂生产排放、泄漏率、回收等基础数据不会受制冷剂的替代产生明显的改变；
- 直接排放中的泄漏率和终了排放之和设定固定值，即只考虑充注量变化；

In order to establish flexibility evaluation methods of refrigerant climate performance, LCCP calculation need reasonable simplified, and which consider the following principles:

- In the current application technology level, emission of refrigerant production, leakage rate, and recycling produce significant changes because of alternative refrigerants application.
- Leakage rate of direct emission and end of life emission have been the fixed value, that is only considering the amount of charge.

设备类型	平均年泄漏率（%）	终了排放率（%）	平均设备使用年限
家用整体式	2.5	15	15
家用分体式	4	15	15
整体式	2	15	15
商用单元机	5	15	15
商用整体式	5	15	10
商用分体式单元	5	15	10
冷水机组	5	15	15

制冷剂温室效应评价方法建立
Design on refrigerant climate performance evaluation

通过建立对比关系，可以消除非制冷剂影响的相同关联参数，简化计算内容。适当变换可得表达式：

The same parameters, which not associated with refrigerant, can be eliminated and simplified by establishing contrast relationships. The expression can be obtained using proper transformation:

$$ERR^{LCCP}=\frac{LCCP_o-LCCP_a}{LCCP_o}=1-\frac{LCCP_a}{LCCP_o}=1-\frac{D_a+IND_a}{D_o+IND_o}=1-\frac{\frac{D_a}{D_o}\cdot\frac{D_o}{IND_o}+\frac{IND_a}{IND_o}}{\frac{D_o}{IND_o}+1}$$

如果不考虑间接排放

If not consider indirect emission

$$ERR^{LCCP}=ERR$$

制冷剂温室效应评价方法建立

Design on refrigerant climate performance evaluation

$$ERR^{LCCP}=\frac{LCCP_o-LCCP_a}{LCCP_o}=1-\frac{\frac{D_a}{D_o}\cdot\frac{D_o}{IND_o}+\frac{IND_a}{IND_o}}{\frac{D_o}{IND_o}+1}$$

$$\frac{D_a}{D_o}=\frac{GWP_a\cdot C_a}{GWP_o\cdot C_o}=\frac{GWP_a\cdot M_a}{GWP_o\cdot M_o}$$

由物质性质决定

Based on Property

$$\frac{D_o}{IND_o}$$

取当前技术水平的统计固定值

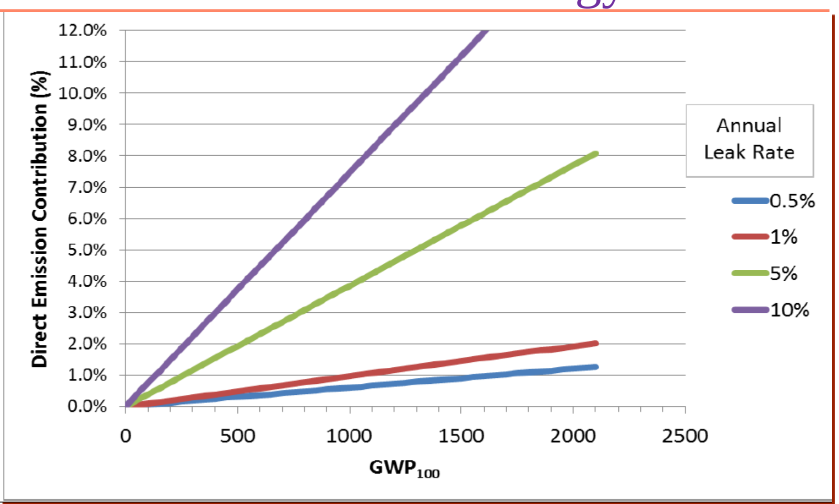
Take statistical fixed value based on the current technology level

包括能耗消耗和材料消耗

$$\frac{IND_a}{IND_o}=f\left(\frac{T_{c,a}}{T_{c,o}},\frac{P_{b,a}}{P_{b,o}}\right)$$

由物质性质关联

Based on Property



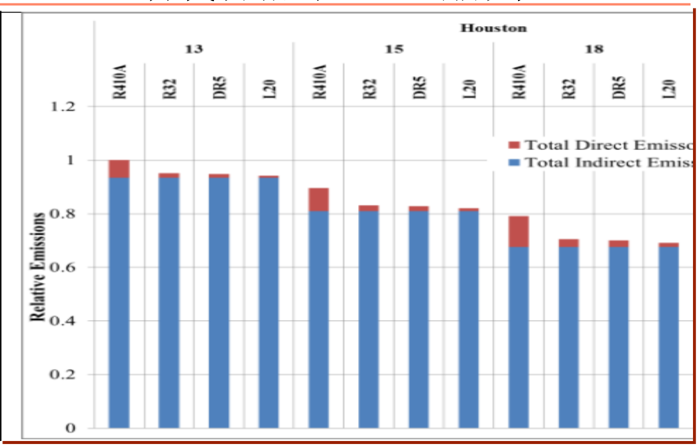
不同年泄漏率下的直接排放所占总排放的比例随GWP的变化（地点为Houston）

例：中国平均电力排放692g/kWh，R22单元式空调机，最高能效标准下，该值约为8%

几种低GWP替代制冷剂减排率ERR^{LCCP}算例

Example analysis on ERR of low GWP alternative refrigerant

文献基于LCCP方法计算的几种低GWP替代物相对R410A排放值

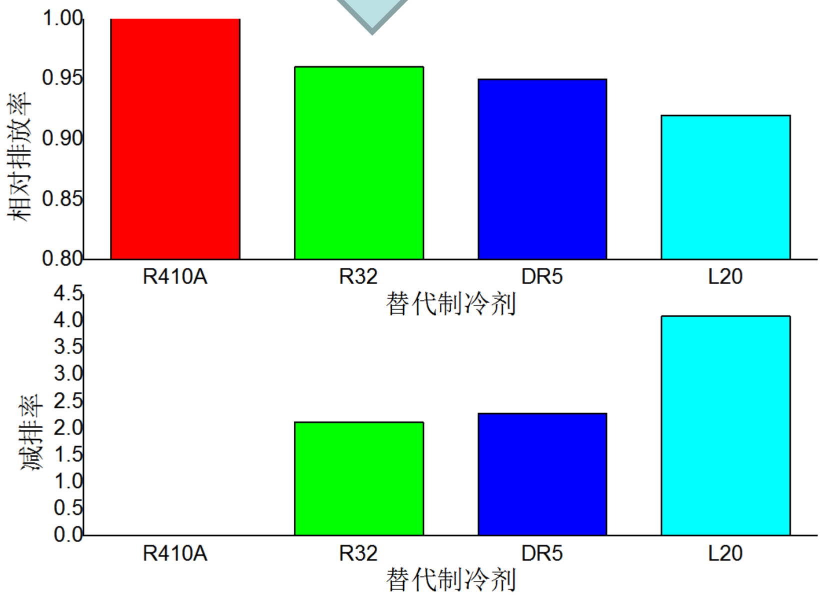


从右边的对比图可以看出：两种方法获得的结果有较好地一致性。

It can be seen from on the right figure that the analysis results by the two methods show better consistency.

基于ERR^{LCCP}方法计算的几种低GWP替代物减排率（被替代物R410A）

制冷剂代号	组分	比例%	GWP	ERR
DR-5	R-32/R-1234yf	(72.5/27.5)	490	2.27%
L-41a	R-32/R-1234yf/R-1234ze（E）	(73/15/12)	494	2.32%
L-41b	R-32/R-1234ze（E）	(73/27)	494	2.90%
HPR1D	R-32/R-744/R-1234ze（E）	(60/6/34)	407	1.30%
R-32	R-32	(100)	675	2.12%
L-20	R-32/R-152a/R-1234ze（E）	(45/20/35)	331	4.09%



两种计算方法对比

Stephen Anthony Kujak,Panayu Robert Srichai,Kenneth J.Schultz. Assessment of Life Cycle Climate Performance (LCCP) Tools for HVAC&R Applications With The Latest Next Generation Refrigerant. International Refrigeration and Air Conditioning Conference. Purdue University. 2014

结　论 Conclusions

- LCCP方法是科学地、完备地温室效应评价方法，对于科学研究是有意义的。但由于其计算复杂性和数据获取的困难，作为决策者对替代方案温室效应的评估不太适用，应适当简化；

  LCCP is scientific and comprehensive evaluation method, which is meaningful for scientific research. But it should be appropriately simplified because of computational complexity and difficulties of data acquisition, and that as not applicable to assess the alternatives climate change effect by policy makers

结　论 Conclusions

- 替代制冷剂的LCCP与被替代物质的LCCP的比值与两种制冷剂的基础物性有较强的相关性，可利用此进行可操作性简化；
- There is a strong positive correlation between the ratio of LCCP value of alternative refrigerants to of substance LCCP and the two refrigerants' basic thermodynamic properties, so the assessment can be operability simplified by exploit this method.
- 初步分析，经简化处理的替代制冷剂温室效应减排的评价方法与原LCCP方法有较好地一致性，且方法简单、具有较强的可操作性，有待进一步检验。
- Preliminary analysis shows that the flexibility evaluation method by simplify has better consistency with the LCCP method, and the method is simple and a strong operational, but pending further examination.

谢谢！欢迎批评指正

Thank You