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Kaimi Gao

Nilesh Purohit

Elizabet Vera Becerra

Ronald Vogl

Ankit Sethi

See next page for additional authors

Authors
Kaimi Gao, Nilesh Purohit, Elizabet Vera Becerra, Ronald Vogl, Ankit Sethi, and Ryan Hulse

Performance Evaluation of R471A in a refrigerated open display cabinet

Kaimi GAO*, Nilesh PUROHIT, Elizabet Vera BECERRA, Ronald VOGL, Ankit SETHI, Ryan HULSE

Honeywell Buffalo Research Laboratory
Buffalo, NY 14210, USA
Kaimi.Gao@honeywell.com

ABSTRACT

R471A is an A1 long term sustainable refrigerant with GWP<150 suitable for replacement of R404A and R134a in new installations for medium temperature application. This article presents an evaluation of R471A in a commercially avaibale R404A refrigerated open display cabinet. Performance evaluation of display cabinet showed lower energy consumption for R471A than R404A while maintaing similar product temperature. The 24-h energy consumption for system with R471A is 8% to 18% lower compared to R404A depending on the outdoor conditions. Life Cycle Climate Performance shows up to 60% lower total emisions for system with R471A. The results indicate that R471A is a promising replacement for R404A in medium temperature refrigeration application leading to significant reduction in both the direct and indirect emissions.

Keywords: R471A, HFO-Refrigerants, LCCP, Display Case, Supermarkets

1. INTRODUCTION

Use of high Global Warming Potential (GWP) refrigerants such as R404A in conventional centralized direct expansion (DX) refrigeration systems leads to significant amount of carbon emissions due to high system leak rates. To comply with the various environmental regulations, the focus is to adopt low GWP refrigerants and ban/phase-out the use of high GWP refrigerants (US EPA, 2015; UNEP, 2016; Purohit et al., 2018). Such a situation is a persistent challenge for commercial refrigeration applications like supermarket refrigerated display cases. One of the well proven mitigation strategies is to retrofit high GWP R404A in existing refrigeration systems with lower GWP alternatives such as R448A (Abdelaziz and Fricke, 2014). Retrofitting R404A with R448A in centralized architectures could result in about 11% improvement in energy efficiency as well as significant reduction in carbon emissions (Sethi et al., 2016; Petersen et al., 2018). However, the end solution requires a safe and business-as-usual refrigerant which complies with the regulations that limit the GWP to 150 in commercial refrigeration systems (Cabello et al., 2022).

R471A is a non-flammable refrigerant (R1234zeE/R227ea/R1336mzzE: 78.6%/4.4%/17%, by mass) which has a GWP of 148 (AR5). R471A is a non-flammable safer refrigerant with low operating pressures offering lower leak rates and possesses capability to further reduce emissions. R471A is designed for use in the new systems, including - for medium temperature applications. Holistically the most promising method to achieve lowest carbon emissions in a refrigeration system is to design and modify the existing system architectures to enable smooth adoption of very low GWP refrigerants. One such modified system is micro cascade where slightly flammable refrigerants such as R1234yf and R1234zeE could be used safely. Purohit et al., (2019) reported that a micro cascade configuration using R515A and R1234yf has better energy efficiency in comparison to centralized architecture, uses lower refrigerant charge amount and has lower leakage rate leading to about 75% reduction in carbon emissions.

This article presents first in kind experimental evaluation of R471A in a commercial R404A medium temperature refrigerated open display cabinet. Minor modifications to the R404A systems were made owing to the lower operating pressures of R471A. In the first section, thermodynamic properties of R471A are contrasted to R134a and R404A. In the following sections experimental test setup, test procedure and the test results with respect to baseline R404A are discussed. Finally, LCCP is carried out based on the experimentally measured energy consumption of R471A system for four distinct locations selected as a representative of low, moderate, moderately high, and high ambient climate conditions.

2. R471A PROPERTIES AND THERMODYNAMIC PERFORMANCE

Table 1 compares thermodynamic properties of R471A to R134a and R404A which is proposed in this article to be used in new supermarket refrigeration systems. The thermodynamic data are derived from the NIST property database REFPROP 9.1 (Lemmon et al., 2013). GWP of R471A is 89% and 96% lower than R134a and R404A, respectively. R471A has a boiling temperature of -16.9℃ and has an average 37% and 67% lower vapor pressure than R134a and R404A, respectively. Lower operating pressure offers lower leak rates for R471A system however, the system may require re-sizing of suction lines. Vapor densities of R471A are 32% and 70% with respect to R404A and R134a, respectively. Liquid densities of R471A are in close match with R134a and 15% higher than R404A. R471A being non-flammable can be used directly in R134a and R404A like systems with adjustments in the compressor displacement and/or other adjustments, such as to the suction line to meet the capacity requirements.

Table 1 Comparison of properties of R471A with R134a and R404A

Refrigerants	R404A	R134a	R471A
ASHRAE safety classification	A1	A1	A1
GWP (AR5)	3940	1300	148
Boiling point (°C)	-46.2	-26.1	-16.9
Vapor pressure (kPa) @ -8°C	461.3	216.9	129.0
Vapor pressure (kPa) @ 45°C	2044.3	1159.9	761.4
Vapor density (kg/m^3) @ -8°C	23.4	10.8	7.5
Vapor density (kg/m^3) @ 45°C	118.1	57.7	42.7
Liquid density (kg/m^3) @ -8°C	1179.7	1320.8	1290.4
Liquid density (kg/m^3) @ 45°C	933.6	1125.1	1121.3

Table 3 compares thermodynamic performance of R471A to R134a and R404A with no losses in refrigerant lines and heat exchanger. The analysis was carried at the medium temperature condition shown in Table 2.

Table 2 System Parameters - Assumptions made for thermodynamic analysis

System Parameters - Assumptions for Thermodynamic Analysis	Unit	Value
Condensing Temperature	°C	45
Condenser Sub-Cooling (system with receiver)	K	0
Evaporation Temperature	°C	-8
Evaporator Superheat	K	5.5
Temperature Rise in Suction Line	K	10
Compressor Isentropic Efficiency	-	65%
Compressor Volumetric Efficiency	-	100%

Table 3 Thermodynamic performance of R471A vs R134a and R404A at 100% match in refrigeration capacity

Ref.	Compressor Displacement	COP	ΔT Discharge (°C)	Mass Flow Rate	Discharge Pressure	Evaporator Glide (°C)	Condenser Glide (°C)
R404A	100%	100%	0	100%	100%	0	0
R471A	247%	115%	-5	84%	39%	2.4	2.3
R134a	100%	100%	0	100%	100%	0	0
R471A	157%	99%	-10.6	115%	68%	2.4	2.3

The volumetric capacity of R471A is 40% with respect to R404A and 64% when compared to R134a. This suggests larger compressor displacement for R471A to match the capacity with 1.57 times larger displacement when comparing to R134a while 2.47 times than R404A. Thermodynamically the system with R471A has 15% higher COP than a system using R404A while the same is a match to a system using R134a for medium temperature applications. The discharge pressures of R471A are 61% lower to R404A and 32% lower to R134a. Mass flow rate in a system with R471A is 84% and 115% to that in a system with R404A and R134a, respectively when the refrigeration capacities are matched. Evaporator and condenser glides for R471A are less than 2.5°C which are nearly half of the industry well excepted glides for R448A (Sethi et al., 2016). The discharge temperature of R471A is 5°C lower to R404A and 10°C lower to R134a indicating that no discharge temperature mitigation will be required. These thermodynamic calculations do not account for losses in heat exchanger, compressor, and refrigerant lines and hence experiments were performed in an open display case to better understand the real performance of R471A.

3. EXPERIMENTATION

A medium temperature supermarket refrigeration system was designed (Fig. 1) using representative open display cabinet to evaluate performance of R471A as a low GWP replacement for R404A. The baseline system with R404A has an air-cooled condensing unit with a fixed speed scroll compressor connected to an off the shelf selected 8 feet long multideck open display cabinet. The system has a capacity of 3500 W and EER of 6.7 at rating conditions. The tests with R471A were carried out with a R134a based scroll compressor (with smaller motor size) that has a 60% larger displacement than the R404A compressor. R471A has a lower operating pressure than R404A (Table 1) hence a detailed system model (Genesym^{TM}) was used to design the heat exchanger coil in both indoor and outdoor units (Spatz and Yana Motta, 2004). Tube diameter for indoor coil was changed from 9.25 mm to 12.5 mm while coil circuitry was modified for outdoor unit to avoid excessive pressure drop (Fig. 2). A larger diameter suction line was chosen for R471A while the liquid line had no change. Superheat for R471A was matched with baseline, R404A and no change was made to the distributor. The modifications made to R471A system are listed in Table 4.

Fig. 1 Schematic of test setup

Table 4 Modification made to R471A system

Component	Type	Modifications for R471A system with respect to R404A system
Compressor	Scroll	Compressor Displacement: 6.1 m^3/hr for R404A and 15.1 m^3/hr for R471A
Evaporator	Finned Tube	Tube diameter changed from 9.525 mm to 12.7 mm
Condenser	Finned Tube	Circuitry modified to reduce pressure drop; tube diameter (9.525 mm) (Fig. 2)
Liquid Line	Copper	No change in tube diameter (12.7 mm)
Suction Line	Copper	Tube diameter from 22.225 mm to 28.575 mm

All tests were performed under controlled conditions using environmental chambers to match the superheat of both baseline and alternate refrigerant using needle valve. Temperature and absolute pressure sensors were installed at inlet and outlet of the evaporator, inlet and outlet of the compressor, inlet and outlet of the condenser and inlet of the expansion device. The display case load was simulated using product simulators and filler load as shown in Fig. 3. A total of 30 thermocouples were installed to monitor product temperature running 6 sensors per 4 shelves and 6 sensors at the case bottom. Coriolis flow meter was installed to measure the refrigerant flow. The test setup was equipped with an Agilent data acquisition system and measurements were recorded at every 60 sec. The range and accuracy of all the measurements is listed in Table 5. Uncertainty in capacity and COP measurement was found to be ±4%.

The performance evaluation tests were carried out according to ASHRAE Standard 72 (ASHRAE 2005) in a controlled test chamber maintained at dry-bulb and wet-bulb temperatures of 24°C and 18°C, respectively. The average product temperature was maintained around 5°C (as per standard) by maintaining the discharge air temperature. The controller was programmed to have 4 defrosts per day (every 6 hours) for a 30-minute duration. The defrost termination was set at product temperature of 7°C. The system was tested at three outdoor conditions maintained from 21°C to 38°C. For performance rating, measurement of the 24-h energy consumption between the defrost cycles and the product temperatures were recorded. At start of test first the indoor chamber followed by the outdoor was allowed to achieve the set conditions. System was then charged with optimal refrigerant to ensure positive sub-cooling at the inlet of expansion valve. Followed the system was allowed to pull down the temperature in case and operate in a steady state condition as per the set-point for minimum of 12-h. At this point to complete the test all system parameters were recorded at every 1 minute for 24-h after the start of first defrost without any adjustments to controls.

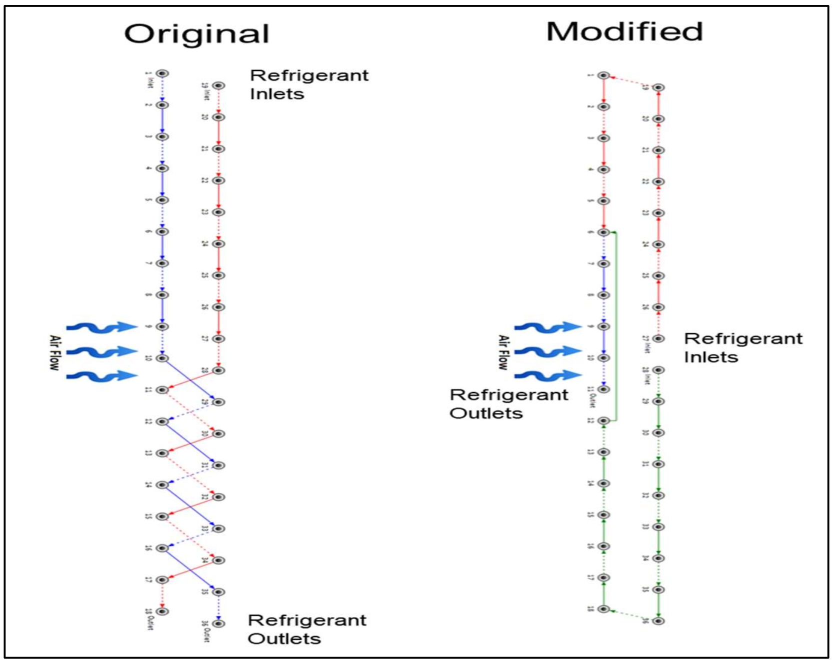

Fig. 2 Modified circuitry for R471A – Outdoor Unit

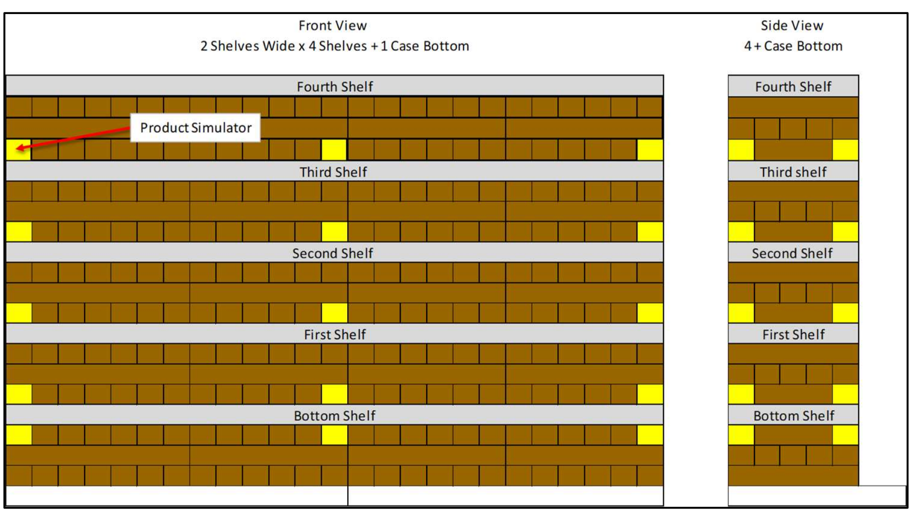

Fig. 3 Location of product temperature simulator inside the display cabinet

Table 5 Measurement accuracies

Quantity	Range	Accuracy
Pressure	0 to 3447 kPa	±2 kPa
Pressure Drop	0 to 103 kPa	±2 kPa
Temperature	-20°C to to 125°C	±0.2°C
Power	0 to 8 kW	±0.2%
Mass Flow Rate	0 to 1000 kg/h	±0.1%

The system was first tested with the baseline refrigerant, R404A, to benchmark the baseline performance. All the system parameters like 24-h power consumption, product temperature, air temperatures, and refrigerant state point measurements were recorded. The product temperature is the average of all 30 product test simulators. Table 6 shows the summary of 24-h performance of R471A with respect to R404A. R471A was capable of maintaining similar air temperatures with an average 0.5°C lower product temperatures. The total power consumption for R471A was lower than R404A with a maximum of 18% lower at the highest outdoor temperature of 38°C. At high ambient conditions, the performance of R471A improved in comparison to that of R404A. The compressor power consumption for system with R471A was 10% to 20% lower for the ambient temperatures ranging from 21°C to 38°C while the total power consumption including fan was lower in range from 8 to 18%. The compressor discharge temperature was also lower for R471A.

Table 6 Summary of 24-h system performance of R471A vs R404A

Fluid	Outdoor Ambient (°C)	Compressor Power (W)	Total Power (W)	Product Temp (°C)	Return Air Temp (°C)	Discharge Air Temp (°C)
R-471A	38	1564	1880	5.6	9.7	4.6
	29	1367	1694	5.6	9.6	4.6
	21	1152	1480	4.8	9.3	3.9
R404A	38	1972	2297	6.2	10.8	4.9
	29	1518	1848	6.2	10.7	4.7
	21	1277	1615	5.1	10.0	3.6
R471A wrt R404A	38	79%	82%	-0.7	-1.2	-0.3
	29	90%	92%	-0.6	-1.1	-0.2
	21	90%	92%	-0.3	-0.7	0.4

Other parameters related to the performance of heat exchanger are shown in Table 7. The mean evaporation temperature for R471A was on an average 1°C lower than R404A due to the lower return air temperatures. Overall heat transfer performance in evaporator for R471A was lower than R404A (Table 7). This is attributed to the choice of bigger tube diameter for R471A to avoid excessive pressure drops which resulted in deterioration of heat transfer.

Condenser circuitry for R471A was modified while keeping the same heat transfer area to avoid excessive pressured drop. The adjustments made to the outdoor coil circuitry for R471A led to 40% reduction in pressure drop. The average saturated discharge temperature with the modified coil was 2°C higher for R471 owing to the lower overall heat transfer (Table 7) which could be improved by further optimization of the coil. A part of the higher condensing pressure for R471A was due to the 1°C to 2°C higher sub-cooling. The saturation temperature drop in condenser for R471A was also almost double that of R404A at nearly equal pressure drop.

The tests conducted for an open display case showed superior performance for R471A with minor modifications. The performance of heat exchangers was found satisfactory. Other modifications could maximize thermal efficiency. Further, investigation on charge for R471A is also suggested to optimize the performance results. Experimental data collected in this study was used to formulate regression equations to correlate total power consumption of the system with outdoor ambient conditions for both R404A and R471A. These equations were then used to perform LCCP analysis as discussed in next section.

Table 7 Summary of 24-h heat exchanger performance of R471A vs R404A

Other System Performance	Outdoor Ambient 38°C		Outdoor Ambient 29°C		Outdoor Ambient 21°C	
	R404A	R471A	R404A	R471A	R404A	R471A
Evaporator Return Air Temp (°C)	10.8	9.7	10.7	9.6	10.0	9.3
Evaporator Saturation Temp (°C)	-1.7	-3.2	-2.5	-3.0	-4.9	-4.9
Saturated Discharge Temperature (°C)	51.1	53.3	42.8	45.0	35.0	36.7
Condenser Sub-Cooling (°C)	2.3	4.0	3.4	4.4	2.9	5.8
Condenser Pressure Drop (kPa)	44.1	55.2	65.5	68.9	74.5	67.6
Sat. Temp Drop in Condenser (°C)	2.0	4.1	3.2	6.1	4.1	7.2
UA – Evaporator ($W K^{-1}$)	480	486	502	560	504	483
U – Evaporator (%)	100%	76%	100%	84%	100%	72%
UA – Condenser ($W K^{-1}$)	577	448	550	466	568	490

4. LIFE CYCLE CLIMATE PERFORMANCE ANALYSIS

Comparative assessment of total emissions which include both direct and indirect emissions for an open refrigerated display cabinet working with R404A and R471A was conducted. The direct emissions are due to the refrigerants leaking from the system over the lifetime while the indirect contribution come from the emissions that is emitted to supply power consumed by refrigerated units. Four different geographical locations were selected each as a representative of low, moderate, moderately high, and high climate conditions. The year-round indirect emissions were calculated using bin data (BinMaker (r) Pro v. 3.0.1) and the performance curves based on experimental data for both R404A and R471A. The bin data for the selected locations viz Frankfurt, Atlanta, Teheran and New Delhi are shown in Fig. 4. The bin data for Frankfurt shows more than 60% of temperatures below 10°C while the temperatures in New Delhi are higher than 25°C for more than half of the year.

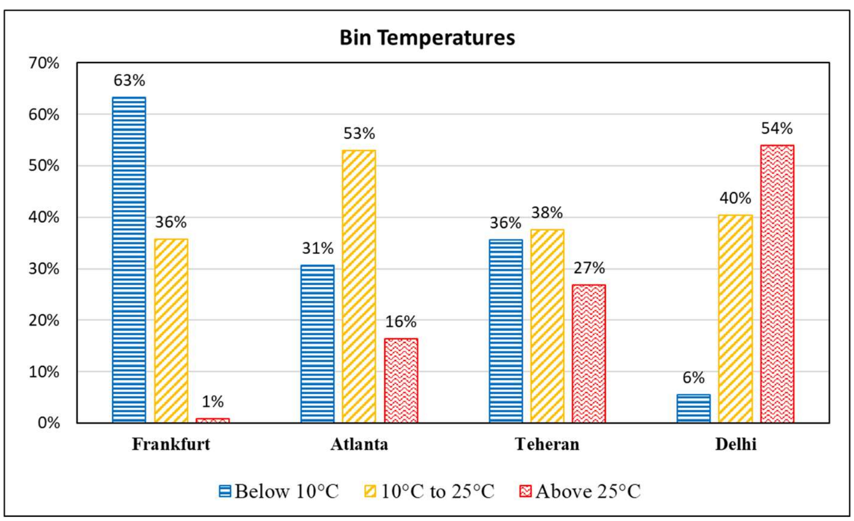

Fig. 4 Bin data for Frankfurt, Atlanta, Teheran and New Delhi

The annual leakage rate and end of life losses of 15% were considered while the local electricity emission factors for different geographical locations were derived from (MCT, 2014; eGRID, 2016; IEA, 2017). The refrigeration load was modelled as a function of ambient temperature derived from the actual display case data. System lifetime of 15 years was considered for LCCP analysis. Other assumptions made to complete LCCP analysis were adopted from the published study (Purohit et al., 2018). Below equations were used to estimate LCCP:

$$Direct\ Emissions = Refrigerant\ Charge\ (kg) \times ((Annual\ Leak \times Lifetime) + End\ of\ Life\ Losses) \times GWP \quad (1)$$

$$Indirect\ Emissions = Annual\ Energy\ Consumption \times Lifetime \times Emission\ Factor \quad (2)$$

Table 8 shows the calculated total emissions and the total energy consumption for the refrigerated open display case working with R471A and R404A. As observable from Table 8 that the total energy consumption for system with R471A was 1%, 3%, 5%, and 9% lower than R404A when operated in the climatic conditions of Frankfurt, Atlanta, Tehran, and New Delhi, respectively. The total energy savings with R471A reaches maximum when the system operates at New Delhi which is consistent to thermodynamic properties of R471A vs R404A as half of the year the ambient temperature in New Delhi is greater than 25°C. The total emissions for R471A were on average 50% to that of R404A with a maximum reduction of 62% when the system was operated in Atlanta. This is attributed first to the typical carbon emission factor and secondly, to the proportional energy savings which combinedly reflects savings in total emissions. Table 8 also lists the split of direct and indirect emissions for system working with R404A and R471A. For systems with R404A direct emissions ranges from 30% to 60% of the total emissions while the same for systems with R471A were less than 6%. The relative contribution of the direct emissions was only 2% for the system with R471A operated at New Delhi due to relatively higher energy consumption. The total energy savings and lower emissions for R471A shows promising results which are expected to foster for the systems designed optimally for R471A.

Table 8 Summary of LCCP for R471A vs R404A

	Frankfurt		Atlanta		Teheran		New Delhi	
	R404A	R471A	R404A	R471A	R404A	R471A	R404A	R471A
Energy Consumption (MWh)	144	142	170	164	178	169	213	195
Direct Emissions (tCO2)	142	5	142	5	142	5	142	5
Indirect Emissions (tCO2)	97	96	84	82	131	124	283	259
Total Emissions (tCO2)	239	101	226	87	273	129	425	264
	R471A Energy Consumption and Emissions relative to R404A							
Energy Consumption (-)	100%	99%	100%	97%	100%	95%	100%	91%
Total Emissions (-)	100%	42%	100%	38%	100%	47%	100%	62%
	Split of Direct and Indirect Emissions							
Direct Emissions (-)	59.5%	5.2%	62.7%	6.0%	52.0%	4.0%	33.4%	2.0%
Indirect Emissions (-)	40.5%	94.8%	37.3%	94.0%	48.0%	96.0%	66.6%	98.0%

5. CONCLUSION

This paper evaluated performance of R471A in a commercially available R404A refrigerated open display case. R471A is a non-flammable long term solution with GWP<150 for medium temperature refrigeration applications. Minor modifications were made to the R404A system when running with R471A due to its lower operating pressures. In this analysis, the energy consumption for R471A was found to be lower than R404A while maintaining the similar product temperatures. Experimental data recorded for R471A showed 8% to 18% lower 24-h energy consumption for the ambient temperatures ranging from 21°C to 38°C. In comparison to R404A the Life Cycle Climate Performance of R471A showed up to 60% lower total emisions. The results indicates that R471A is a promising replacement for R404A in medium temperature applications, especially for regions with high ambient conditions, leading to significant reduction in both the direct and indirect emissions. Further optimization of system design for R471A is highly recommended to achieve the best thermodynamic efficiency.

NOMENCLATURE

A	Area	ΔT	Temperature Difference
GWP	Global Warming Potential	Sat.	Saturation
LCCP	Life Cycle Climate Performance	U	Overall Heat Transfer Coefficient

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