PERFORMANCE OF R1234yf AND R513A AS ALTERNATIVES TO R134a IN AUTOMOTIVE AIR CONDITIONING SYSTEMS IN WINTER

by

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In this paper, the feasibility of two low global warming potential refrigerants R513A and R1234yf as alternatives to R134a was tested in an automotive air conditioning system in winter. The test results showed that the heating capacities of R513A and R1234yf were 2% and 4% lower than that of R134a, and their COP were 3-9% and 6-19% lower than that of R134a, respectively. It revealed that R513A can be used as a transition product to replace R134a, and R1234yf required further improvements to improve the energy efficiency.

Key words: *R513A, R1234yf, R134a, automotive air conditioning systems, micro-channel heat exchanger*

Introduction

The problem of environmental pollution has become increasingly prominent. The replacement of new environmentally friendly refrigerants has become a popular research topic in the refrigeration and air conditioning field. The GWP value of hydrofluorocarbon refrigerants are too high, however, these materials are currently widely used. Studies have shown that the emissions of hydrofluorocarbon refrigerants in the atmosphere account for 2% of global GHG emissions in 2015. If emissions continue to increase in this trend without any further control, the number will increase remarkably to 9-20% by 2050. In October 2016, the international community reached the Kigali Programme based on the framework of the Montreal Protocol, which further promoted the reduction of high GWP hydrofluorocarbon refrigerants. The Kigali Amendment required developed countries to phase out hydrofluorocarbon refrigerants by 2019 and developing countries to freeze and suspend hydrofluorocarbon refrigerants between 2024 and 2028 [1].

The R134a is a hydrofluorocarbon refrigerant, and its GWP value is approximately 1300, which represents a strong greenhouse effect. The R134a is widely used in small refrigeration devices, automotive air conditioning systems and heat pump units [2]. Therefore, the replacement of R134a has become a research focus of in both the academic world and the industrial world. Potential low GWP refrigerants mainly include hydrofluoroolefins and the related mixed refrigerants [3].

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Hydrofluoroolefins with low GWP value are considered as ideal alternatives to R134a. Compared with R134a, the cycle performance of pure refrigerants R1234yf and R1234ze(E) in the same refrigeration system is slightly lower [4]. Researches have mainly focused on R1234yf as a replacement for R134a in automotive air conditioning systems. Some authors [5-7] carried out experiments using different compressors and throttling devices, different forms of condensers and evaporators, and different working conditions, their results showed that the cooling capacity and COP of R1234yf were lower than those of R134a. The R1234yf can also be used as a substitute refrigerant for R134a in small refrigeration devices such as household refrigerators and beverage machines. Belman-Flores [8] presented an experimental study for three identical domestic refrigerators using R1234yf as a drop-in replacement for R134a. The results showed that R1234yf presented an average (for the three refrigerators) of 0.4 °C for the fresh food compartment and 1.2 °C for the freezer among different charges with respect to R134a. Karber, *et al.* [9] studied the performance of R134a and R1234yf in the same household refrigerators and refrigeration devices. The results showed that the power consumption of R1234yf was 2.7% higher than that of R134a.

Recently, mixed refrigerants have become a popular research topic. Devecioglu, *et al.* [10] compared the thermophysical properties of R450A, R513A, and R134a. The results showed that R450A and R134a had the closest performance under specific conditions. In addition, the viscosity of R450A and R513A was lower than that of R134a. The results obtained by Llopis *et al.* [11] showed that R513A and R450A can operate with R134a plants, with increments in energy consumption between –1.6% to +1.2% for R513A and from +1.3% to +6.8% for R450A. Makhnatch *et al.* [12] studied the performance of R450A in a small refrigeration unit that used R134a. The experimental results showed that R450A saved more energy than that of R134a but the cooling capacity of R450A was slightly lower. Mota-Babiloni *et al.* [13] and Shapiro [14] compared R513A, and R134a, and experiments showed that the performance of R513A in the refrigeration system was similar to that of R134a. Meng *et al.* [15] studied the feasibility of replacing R134a with a new mixed refrigerant R1234yf/R134a (mass fraction ratio 89:11) in automotive air conditioning systems using micro-channel heat exchangers. The experimental results showed that the cooling capacities of the mixed refrigerants R1234yf/R134a and R134a were similar. The COP was 4-9% lower than that of R134a. It was concluded that the mixed refrigerant R1234yf/R134a could be directly used in the R134a original automotive air conditioning systems. In the study of Devecioglu *et al.* [16], R444A and R445A had lower COP, but the use of these mixtures in R134a systems was recommended if obtaining the highest COP was not the key objective.

In summary, there have been many studies on low GWP refrigerants as alternatives to R134a, but there are some common problems. The R1234yf and R1234ze(E) show low COP. In the mixed refrigerants study, the GWP is reduced to a certain extent, but these mixtures also have some shortcomings, such as flammability and an overabundance of mixtures, and leakage affects the operation performance. Compared to these mixed refrigerants, R513A is a competitive refrigerant. The R513A is non-flammable and is a binary azeotropic refrigerant consisting of R134a and R1234yf with a mass fraction of 44/56. It runs stably in the refrigeration system and has little influence on the leakage. Studies have shown that R513A performed better than R1234yf. However, research on R513A as an alternative to R134a in automotive air conditioning systems has not yet been reported. In this paper, the performance of R513A, and R134a in cold climate was studied by building an automotive air conditioning systems platform. In view of the relationship between R1234yf and R513A, this paper introduces R1234yf for comparison. It directly compares the performance of R1234yf and R513A to provide feasible suggestions for the selection of low GWP refrigerants in the automobile air conditioning industry.

Thermodynamic analysis

In order to calculate the thermodynamic cycle performance, the properties of the vapor compression system are calculated. According to the temperature and pressure of each state point, the corresponding enthalpy and entropy values are obtained, and the thermodynamic cycle performance is calculated. In this paper, a thermodynamic cycle model under cold climate that is called working mode is introduced for the automotive air conditioning systems. The condensation temperature is 30 ℃ and evaporation temperature is –10 ℃ under working mode. The superheating and supercooling degree are 5 ℃ as typical working conditions. All the thermodynamic properties were obtained from the NIST database REFPROP 9.1 [17]. The main calculation formulas are derived from [18]. The main assumptions are:

- the isentropic efficiency and volumetric efficiency of the compressor are 0.75 and 0.8, respectively,
- the compressor has a constant stroke volume of 33 cc/rev and a constant speed of 3000 rpm,
- there is no pressure drop in the condenser, evaporator, and connecting pipe,
- there is no heat exchange loss between the system and the outside world, and
- the enthalpy of refrigerant before and after throttling valve is unchanged.

The simulation performance parameters of the three refrigerants in automotive air conditioning systems are shown in tab. 1. The volumetric heating capacities of R1234yf and R513A are similar to that of R134a. Additionally, it can be seen that the heating capacities of R1234yf and R513A are similar to that of R134a. Compared with R134a, the pressure ratio of R1234yf and R513A is lower than that of R134a. The pressure ratio mainly affects the compressor volumetric efficiency. It can be concluded that when R1234yf and R513A replace R134a, the compressor volumetric efficiency of the two refrigerants is better. In terms of energy efficiency, the COP of R1234yf and R513A are lower than that of R134a, while that of R513A is larger than that of R1234yf. The compressor discharger temperatures of R1234yf and R513A are lower than that of R134a.

Table 1. Simulative performance of three refrigerants under working mode

Mode	Performance parameter	R1234yf	R513A	R134a
Heating	Volumetric heating capacity [kJm^{-3}]	1553.41	1565.21	1572.27
	Mass flow rate [kgh^{-1}]	58.21	52.60	46.56
	Pressure ratio	3.53	3.67	3.84
	heating capacity [W]	2563.12	2582.59	2594.25
	Power consumption [W]	499.07	496.23	494.07
	COP	5.14	5.20	5.25
	Compressor discharge temperature [℃]	39.54	43.76	49.74

Experiment

The layout of the experimental device is shown in fig. 1. The performance of automotive air conditioning systems is tested in multi-functional simulation environment test system. The temperature and humidity can be adjusted by using the environment control box composed of cooling coil, heater, humidifier and fan. The enthalpy of air can be obtained by measuring the temperature of wet and dry balls before and after the heat exchanger. Air flowing through the heat exchanger is driven by a blower. At the same time, the volumetric flow rate of the air is measured and calculated by a nozzle flowmeter. The air-side heat exchanger capacity is calculated according to the enthalpy difference and volumetric flow rate before and after the heat exchanger.

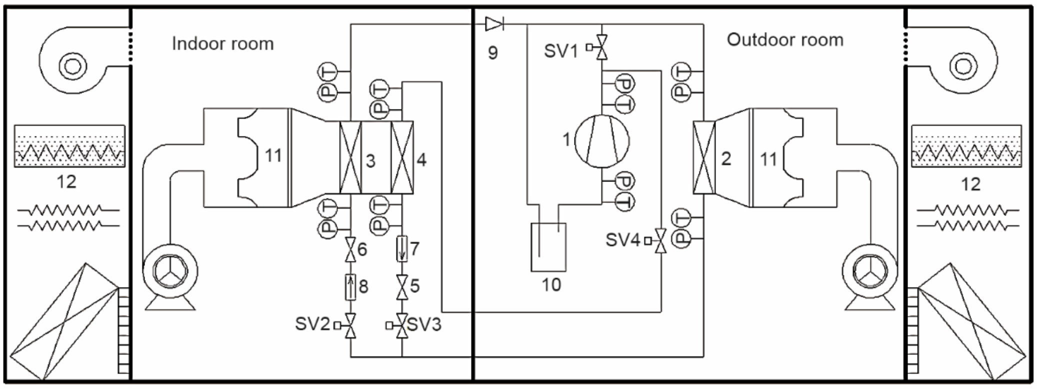

Figure 1. Layout of automotive air conditioning systems; *1 – compressor, 2 – out-car heat exchanger, 3 – in-car evaporator, 4 – in-car condenser, 5,6 – electronic expansion valve, 7, 8 – mass flowmeter, 9 – one-way valve, 10 – gas liquid separator, 11 – air measuring device, and 12 – air handling unit*

The automotive air conditioning systems are mainly composed of a compressor, two in-car micro-channel heat exchangers, an out-car micro-channel heat exchanger, two electronic expansion valves, two mass flowmeters and several solenoid valves. The main component parameters are shown in tab. 2. In the working mode, the refrigerant flow direction moves from the compressor outlet, to the in-car condenser, to the mass flowmeter, to the electronic expansion valve, to the out-car heat exchanger, to the gas-liquid separator, and finally back to the compressor inlet. The gas-liquid separator is set at the inlet of the compressor. To calculate the refrigerant side heat transfer capacity and compressor operating parameters, temperature and pressure measurement points are installed at the inlet and outlet of the compressor, the inlet and outlet of the out-car heat exchanger, the inlet and outlet of the in-car condenser and the evaporator.

Table 2. Specifications of the experimental set-up

Components	Specifications
Out-car heat exchanger	507.8 W × 393 H × 16 D Micro-channel parallel flow structure
In-car condenser	252 W × 250 H × 40 D Micro-channel parallel flow structure
In-car evaporator	223.6 W × 159.8 H × 24 D Micro-channel parallel flow structure
Compressor	Swash plate type, V_{dis} = 33cc/rev

The measurement and control system is composed of an agilent data acquisition instrument, PLC and computer. The computer can control the opening of electronic expansion valves, the opening and closing of solenoid valves and the speed of compressors through instructions issued by PLC. Temperature, pressure, mass-flow and compressor power consumption data can be recorded. When the system is stable, the enthalpy of each point is obtained according to the measured temperature and pressure parameters. According to the experimental data processing formula from [15], the system running performance parameters of the refrigerant side are calculated. The effective experimental data are recorded by regulating the steps of the electronic expansion valve to attain the best COP of the system. During the test period, the total energy balance between the refrigerant side and the air side is approximately 5%.

Table 3. Operating conditions in working mode

Working temperature conditions	Condition number	[rpm]	Indoor room		Outdoor room	
			Dry bulb temperature [°C]	Air mass flow rate [kg per minute]	Dry bulb temperature [°C]	Air mass flow rate [kg per minute]
High	1	2000	10	5	10	19
	2/3	3000/4000	10	8	10	40
Moderate	4	2000	5	5	0	19
	5/6	3000/4000	5	8	0	40
Low	7	2000	–5	5	–5	19
	8/9	3000/4000	–5	8	–5	40

The working mode is divided into nine conditions, as shown in tab. 3. The control parameters include the compressor speed, inlet air temperature, relative humidity and air mass flow rate. The tests in the working mode simulate the three working temperature conditions.

Results and discussion

The compressor power consumptions of R1234yf, R513A, and R134a in automotive air conditioning systems are shown in fig. 2(a). According to the figure, the compressor power consumption of the R513A is 2%, 4%, and 9%, and the R1234yf is 4%, 9%, and 16% higher than that of R134a at high, moderate and low temperature conditions, respectively. With decreasing ambient temperature, the compressor power consumption deviation between R513A, and R134a increases. As shown in fig. 3(a), the compression ratio deviation between R513A, and R134a decreases with decreasing ambient temperature, which leads to a decrease in the compression specific work deviation between R513A, and R134a. Due to the higher mass flow rate of R513A, the compressor power consumption deviation between R513A, and R134a is higher under low temperature conditions. The comparison of compressor power consumption between R1234yf and R134a can be explained in the same way.

The heating capacities of R1234yf, R513A, and R134a in automotive air conditioning systems are shown in fig. 2(b). The heating capacity of R513A is 1.5%, 2%, and 2.5%, and the R1234yf is 3%, 4%, and 6% lower than that of R134a under high, moderate and low temperature conditions, respectively. The mass-flow rates of R1234yf and R513A are higher, however, the latent heat of R1234yf and R513A in the condenser is lower, which leads to a lower heating capacity. In terms of heating capacity, R1234yf and R513A can replace R134a in automotive air conditioning systems.

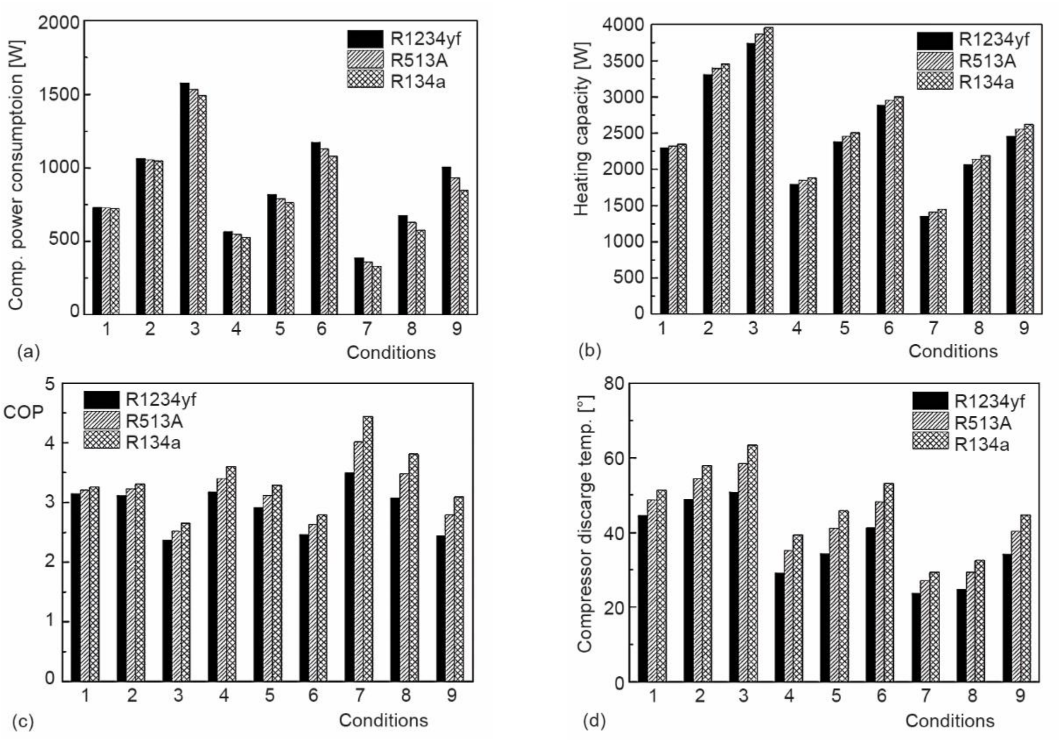

Figure 2. Experimental energy performance parameters under different working temperature conditions; (a) compressor power consumption (b) heating capacity, (c) COP, and (d) compressor discharge temperature

The COP of R1234yf, R513A, and R134a in automotive air conditioning systems are shown in fig. 2(c). The figure shows that the COP of R513A is 3%, 5%, and 9%, and the R1234yf is 6%, 10%, and 19% lower than that of R134a under high, moderate and low temperature conditions, respectively. Because the heating capacities of R1234yf and R513A are lower than that of R134a and the compressor power consumptions of R1234yf and R513A is higher than that of R134a, the COP of R1234yf and R513A are lower than that of R134a. The COP deviation increases with decreasing ambient temperature because the compressor power consumption deviation increases with decreasing ambient temperature. Compared with the theoretical calculations, the COP deviations between R134a, R1234yf, and R513A are larger in actual operation. This occurs because the compressor global efficiency is not taken into account. Moreover, the flow condensation heat transfer coefficients of R1234yf and R513A in the tube are lower than that of R134a. When applied to the same heat exchanger, the heat transfer efficiencies of R1234yf and R513A in the condenser are lower than that of R134a.

The compressor discharge temperatures of R513A, and R134a in automotive air conditioning systems are shown in fig. 2(d). The average compressor discharge temperatures of R1234yf and R513A are 8 °C and 4 °C lower than that of R134a under high, moderate and low temperature conditions, respectively. A lower compressor discharge temperature can increase the service life of the compressor.

The compression ratios of R1234yf, R513A, and R134a in automotive air conditioning systems are shown in fig. 3(a). The compression ratio of R134a is higher than those of R1234yf and R513A by 8% and 6% under all conditions, respectively. The compression ratio deviations of R1234yf, R513A, and R134a are smallest at low temperature conditions and largest at high temperature conditions. This occurs because the thermodynamic properties show that under low temperature, the saturation pressures of R1234yf and R513A are larger than that of R134a, and under high temperature, the saturation pressures of R1234yf and R513A are lower than that of R134a. Under moderate temperature conditions, both refrigerants operate at a high compression ratio. This occurs because the indoor temperature and outdoor temperature difference is larger, resulting in a larger difference between the condensation pressure and the evaporation pressure.

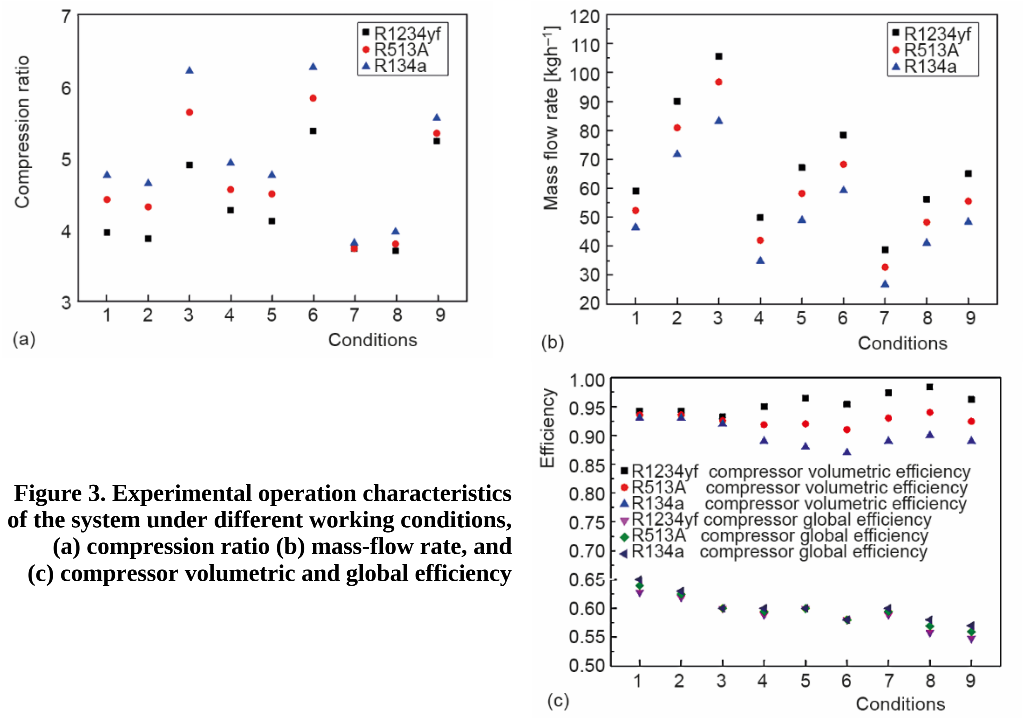

Figure 3. Experimental operation characteristics of the system under different working conditions, (a) compression ratio (b) mass-flow rate, and (c) compressor volumetric and global efficiency

The mass-flow rates comparison of R1234yf, R513A, and R134a in automotive air conditioning systems are shown in fig. 3(b). The mass-flow rates of R1234yf and R513A are 30% and 16% higher than that of R134a on average, respectively. The mass-flow rate decreases with decreasing outdoor temperature. This occurs because the evaporation pressure is determined by the outdoor environmental temperature. Low outdoor environmental temperature leads to low evaporation pressure, thus causing low suction density at the compressor inlet.

The compressor volumetric efficiencies and global efficiencies of R1234yf, R513A, and R134a in automotive air conditioning systems are compared, as shown in Figure 3(c). Comparing and analyzing working conditions 2, 3, 5, 6, and 8, 9, it is obtained that the compressor volumetric efficiency has reached or exceeded the optimum value at 3000 rpm, so when the compressor speed reaches 4000 rpm, the compressor volumetric efficiency shows a downward trend. The figure shows that the compressor volumetric efficiencies of R1234yf and R513A are 6% and 3% higher than that of R134a. This occurs because the compression ratios of R1234yf and R513A are lower than that of R134a under the same working conditions. Figure 3(c) shows that the compressor global efficiency decreases with decreasing ambient temperature. This occurs because the suction temperature of the compressor decreases with decreasing ambient temperature. The lower suction temperature of the refrigerant causes an increase in the viscosity of the lubricating oil. Lubricating oil with a high viscosity leads to poor mobility and large friction resistance between components. As a result, the global efficiency drops. The compressor global efficiencies of the three refrigerants are similar. Therefore, when R1234yf and R513A directly replace R134a in automotive air conditioning systems, it has little effect on the compressor global efficiency. A compressor with R134a is also suitable for R1234yf and R513A.

Comparison with R513A and R1234yf in automotive air conditioning systems

For automotive air conditioning systems, especially for electric vehicle air conditioning, energy conservation can directly affect the mileage of the vehicle. The heating capacity of R1234yf and R513A basically meet the requirements for replacing R134a. In terms of environmental protection, R1234yf has a GWP < 1, which is the refrigerant of automotive air conditioning systems. However, the COP of R1234yf is relatively low, with a maximum difference 19% in winter. To replace R134a with R1234yf, it is necessary to study the improvement of its energy conservation, such as by optimizing the heat exchanger and increasing the international heat exchanger. For R513A, the COP difference with R134a is small in winter, and R513A can directly replace R134a. The R513A has a GWP of 572 and can be used as transition product of low GWP refrigerants for automotive air conditioning systems.

Discussion and conclusions

Though there are many experimental methods to study thermal performance of an air conditioning system [19, 20], it is important to control the temperature in the working condition, and various terminal sliding mode (TSM) controllers [21-25] and optimal control theory [26-28] can be used to adjust and optimize the temperature to a desired value in the heat exchanger system.

In this paper, a new type of performance test bench for automotive air conditioning systems was built, and comparative experiments of R1234yf, R513A, and R134a in winter were carried out. Based on the test results, the following conclusions can be drawn:

The average heating capacities of R1234yf and R513A are lower than that of R134a by approximately 4% and 2%, respectively. The COP of R1234yf and R513A are lower than that of R134a by 6-19% and 3-9%, respectively. The average compressor discharge temperatures using R1234yf and R513A are lower than that using R134a by approximately 8 °C and 4 °C, respectively. The average volumetric efficiencies of R1234yf and R513A are higher than that of R134a by approximately 6% and 4%, respectively. The global efficiencies of the three refrigerants are similar.

The energy conservation R1234yf, with GWP < 1, needs to be improved for it to be considered as an alternative to R134a in automotive air conditioning systems. The performance of R513A is similar to that of R134a, however, the GWP of R513A is 572. The R513A can be used as a transition product to replace R134a in automotive air conditioning systems.

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