Evaluation of Odorizing Refrigerant R-290 to Improve Leak Detection-System Performance and Compatibility

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Abstract

R-290 (propane) is a flammable refrigerant having an A3 classification according to the ASHRAE Standard 34. Because of its extremely low Global Warming Potential (GWP), several regions around the world use or consider using it for air-conditioning and refrigeration applications. On the other hand, its high flammability and safety implications limited its broader application. Odorizing R-290 would make its leak easier to detect by humans. The ability to smell a leak would not only benefit the consumer but would also prompt timely repair and create a safer working environment for the HVACR manufacturer and field service personnel. However, applying the odorant in R-290 systems with unknown compatibility with the compressor lubricant and construction materials may result in premature chemical or electrical failure and the degradation of the system efficiency.

The Air-Conditioning, Heating, and Refrigeration Technology Institute (AHRTI) undertook a research project to conduct experimental testing to evaluate odorants impact on system performance and odorants compatibility with refrigerant R-290, lubricants and other materials commonly used in HVACR equipment. This paper provides an overview of the testing effort and summarizes the test results of R-290 and odorant in a mini-split heat pump and a commercial refrigerated display case (reach-in cooler). A brief summary of compatibility testing results of R-290 with two odorants, three lubricants and other system materials will be presented as well.

Keywords: R-290; Odorants; Heat Pumps ;

1. Introduction

Odorizing refrigerants can make leaks easier to detect, improving safety for consumers, manufacturers, and service personnel—especially as the industry shifts to flammable, low global warming potential (GWP) refrigerants. However, compatibility issues between odorants, refrigerants, lubricants, and system materials may cause system failures and efficiency loss. Research efforts sponsored by ASHRAE [1, 2] and the U.S. Consumer Product Safety Commission [3] have narrowed potential odorants options and evaluated how odorants distribute and their effectiveness over time inside running HVACR systems. AHRTI conducted a follow-on project to evaluate odorants' impact on system performance and odorants' compatibility with refrigerants, lubricants and other materials [4]. It further builds the knowledge base and prior research to implement odorants, low GWP refrigerants in HVACR products. The work consists of equipment performance testing with odorized R-290 and compatibility testing with R-290, odorants, and common materials inside refrigeration systems. The performance testing was conducted by OTS R&D, and the compatibility evaluation was done by Spauschus Associates, Inc. This paper is a high-level summary of the research work, and more detailed information is contained in the project final report [4].

2. Technical Approach

The equipment tested in this study includes a mini-split heat pump (not sold in the US market) and a refrigerated display case merchandiser. They were tested using pure R-290 and R-290 odorized with 150 ppm of dimethyl sulfide (DMS). The units were slightly modified with instrumentation for performance measurement and fitted with charging ports.

Material compatibility tests were conducted with R-290 refrigerant and odorants such as DMS and methyl ethyl sulfide (MES) at 150 ppm. The lubricants used in the tests were POE (RL32-3MAF), PAG (RFL 68EP), and Mineral Oil (Trane Oil 22). The materials commonly used in these systems were also evaluated for compatibility.

2.1. Mini-split heat pump test setup

The heat pump is rated for a capacity of 2.6-3.5 kW (9–12 kBtu/hr) and utilizes 310 grams of R-290 as its refrigerant. It is important to note that this unit is not equipped with a filter-drier. Figure 1 below illustrates the arrangement of the pressure sensors, thermocouples, wattmeter, mass flow meter, and relative humidity sensor within the system. Capacity calculations are performed using the refrigerant enthalpy method, which incorporates data from mass flow, pressure, and surface temperature measurements.

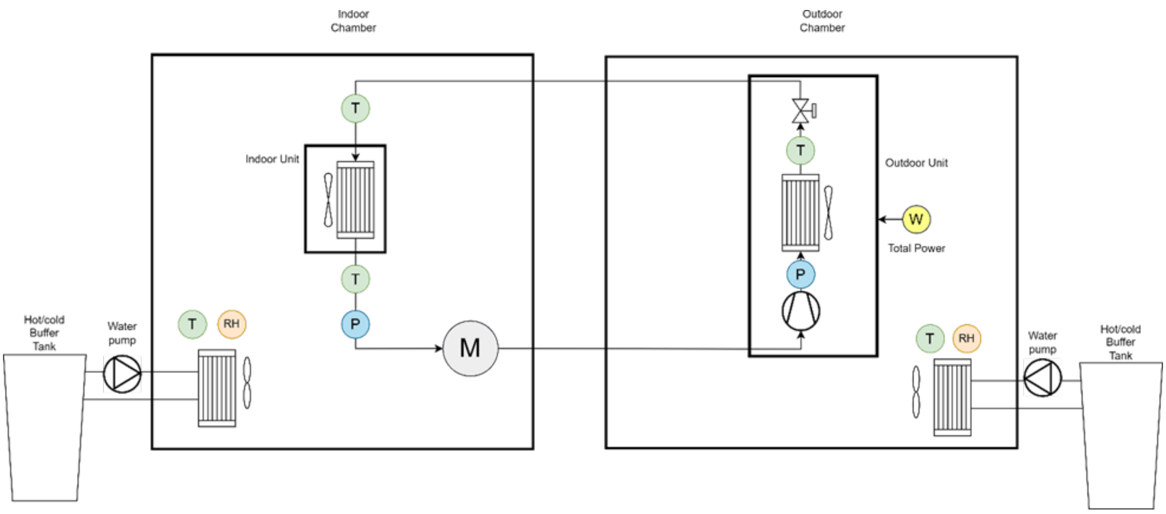

Figure 1. Schematic of the Mini-Split Heat Pump Test Setup

The schematic does not show piping for the reversing valve. The mass flow meter is placed on the vapor line set (suction in cooling and discharge in heating mode). Installing the mass flow meter on the liquid line is impractical due to the unit's tight spacing, which could disrupt airflow or affect charging procedures. Three thermocouples are positioned at the inlets of both outdoor and indoor units. A stable power supply provides 230V / 50Hz power to the unit.

The heat pump was evaluated under five conditions in accordance with AHRI Standard 210/240 [5], employing the methodologies outlined in ASHRAE Standard 37 [6]. The test conditions are shown in Table 1. Despite featuring an inverter-driven compressor, all tests were conducted at maximum compressor speed to ensure repeatable results. A single replicate test was performed to confirm repeatability. After the initial test, the system was evacuated and recharged with an identical quantity of refrigerant, following which the second test served as verification. All subsequent tests were then executed with the same recharged refrigerant. Tests performed at a 1.7°C (35°F) ambient temperature corresponded to defrost test conditions, which are transient conditions where the data is taken from the end of a defrost to the end of the next defrost. This will result in relatively larger uncertainties for these tests.

Table 1. Mini-split heat pump test matrix

Refrigerant	AHRI Condition	Air DB/WB °C (°F)	Compressor speed
Baseline R-290	AFull	35/23.8 (95/75)	Full
Baseline R-290	AFull (replicate, recharge)	35/23.8 (95/75)	Full
Baseline R-290	BFull	27.8/18.3 (82/65)	Full
Baseline R-290	H1Full	8.3/6.1 (47/43)	Full
Baseline R-290	H2Full	1.7/0.6 (35/33)	Full
Baseline R-290	H3Full	-8.3/-9.4 (17/15)	Full
Odorized R-290	AFull	35/23.8 (95/75)	Full
Odorized R-290	BFull	27.8/18.3 (82/65)	Full
Odorized R-290	H1Full	8.3/6.1 (47/43)	Full
Odorized R-290	H2Full	1.7/0.6 (35/33)	Full
Odorized R-290	H3Full	-8.3/-9.4 (17/15)	Full

2.2. Reach-in cooler test setup

A two-door, self-contained reach-in merchandiser was selected for testing in accordance with ASHRAE Standard 72 [7] and AHRI Standard 1200 [8]. The unit contains 150 grams R-290. The equipment was placed within an environmental chamber equipped with appropriate instrumentation. Three watt meters were used: one to measure the total power consumption, another dedicated to the compressor and condenser fan, and a third for the evaporator fans. This methodology allows for accurate determination of energy consumption attributable solely to the refrigeration system. Total power can then be subtracted from the refrigeration power to get the power for lighting/controls per the standard.

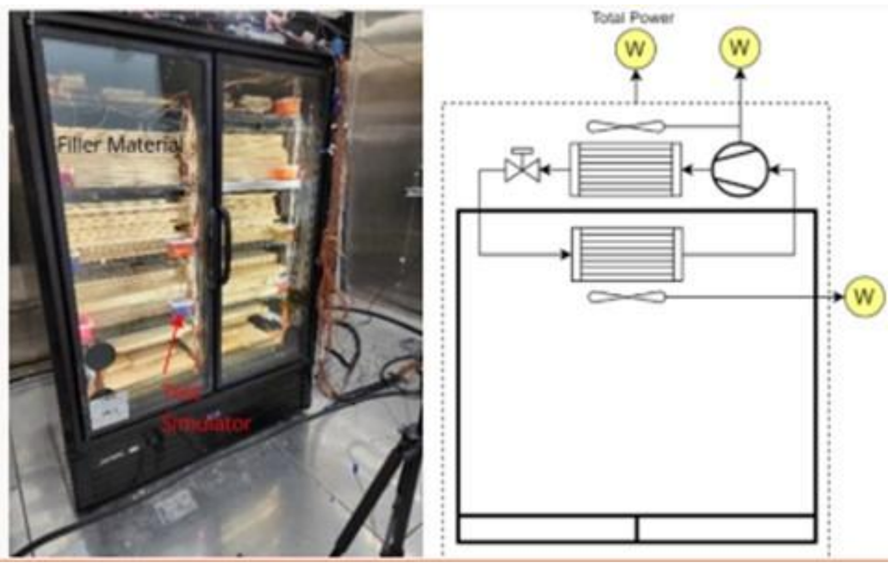

Figure 2. A Photo of the Reach-in Cooler and Schematic of the Reach-in Cooler Test Setup

Figure 2 shows a picture of the reach-in cooler in the test chamber and the schematic of the test setup. The refrigerator setpoint was set to -2.8°C (27°F) for all tests in accordance with the product manual. The key performance metric for this equipment is the Total Daily Energy Consumption (TDEC), which is calculated in units of kWh/day per AHRI Standard 1200. Table 2 illustrates all the tests done to the refrigerator.

The refrigerator uses very small quantities of refrigerant; deviations between the factory charge and the quantity charged during the testing per the nameplate could potentially impact system performance. After the initial test with the factory charge, the system was evacuated, recharged with pure R-290, and retested. The testing showed very good repeatability between the two tests, confirming that the charging procedure used in the testing can produce repeatable results and does not affect equipment performance significantly. A third test involved recharging with odorized refrigerant and repeating the same performance test. Test 4 was performed while operating the refrigerator in an indoor space (outside environmental chamber controls) for 6 months in order to determine if long-term operation of a system with odorized refrigerant affects performance potentially from degradation of materials, breakdown of fluids, or formation of reaction products that affect the cycle thermodynamics. During this period of operation, the space was continuously monitored for leaks since a loss of refrigerant could dramatically alter performance. The fifth and final test reevaluated the odorized system after the 6-month period to determine if there was any change in performance.

Table 2. Reach-in cooler test matrix

Test	System	Description
1	Baseline	Measure TDEC of unaltered system per AHRI Standard 1200
2	Baseline – recharged	Evacuate and recharge baseline with refrigerant-grade R-290 to quantify sensitivity to charging procedure. Repeat AHRI Standard 1200 test of TDEC.
3	Odorized	Evacuate and recharge baseline with odorized refrigerant. Measure TDEC.
4	Odorized	Install refrigerator outside of environmental chamber and allow to operate for 6 months.
5	Odorized	Install refrigerator in chamber and remeasure TDEC per AHRI Standard 1200.

2.3. Material compatibility tests

The effects of odorants on system materials, including plastics, elastomers, gaskets, and motor materials were investigated by testing material compatibilities in pressure vessels according to ASHRAE Guideline 38 "Guideline for Using Metal Pressure Vessels to Test Materials Used in Refrigeration Systems" [9]. The use of pressure vessels allows for the testing of a variety of materials, regulation of the pressure of the test and use of larger sample size.

Thirty materials were tested in R-290 and three different lubricants (Trane Oil 22 (MO), RL32-3MAF (POE), and RFL 68EP (PAG)) as shown in Table 3. The materials consist of seven types of elastomers, three different gaskets, nine types of polymers, and eleven various motor materials. Two odorants including Dimethyl Sulfide (DMS) and Methyl Ethyl Sulfide (MES) were tested along with control samples (without odorant) for comparison.

Table 3. Odorants, Materials, and Lubricants Compatibility Test Matrix

Material Number	Refrigerant/Lubricant	Odorant
1 to 30	R-290/Trane Oil 22 (mineral oil: MO)	Control (no odorant)
1 to 30	R-290/Trane Oil 22 (MO)	Dimethyl Sulfide (DMS)
1 to 30	R-290/Trane Oil 22 (MO)	Methyl Ethyl Sulfide (EMS)
1 to 30	R-290/RL32-3MAF (Polyolester: POE)	Control (no odorant)
1 to 30	R-290/RL32-3MAF (POE)	Dimethyl Sulfide (DMS)
1 to 30	R-290/RL32-3MAF (POE)	Methyl Ethyl Sulfide (EMS)
1 to 30	R-290/RFL 68 EP (Poly Alkylene Glycol: PAG)	Control (no odorant)
1 to 30	R-290/RFL 68 EP (PAG)	Dimethyl Sulfide (DMS)
1 to 30	R-290/RFL 68 EP (PAG)	Methyl Ethyl Sulfide (EMS)

Test materials were cut, weighed, and measured for dimensions, density, and hardness. Two samples per material were placed in test tubes that are filled to 80% of their volume with lubricant containing 150 ppm odorant by weight; controls without odorant were also prepared for comparison. Tubes were visually inspected and photographed before aging. Eight tubes were aged in one pressure vessel under a 20/80 refrigerant/lubricant ratio at 127°C for 21 days. Once the aging process was complete, the pressure vessels were taken out of the oven, cooled, and opened. Tubes were extracted from each vessel and checked for changes such as lubricant color change, cloudiness, formation of floc or particulates, and test materials appearance change. Pictures were taken to document the tubes after aging. Each test sample was gently removed and dried with a paper towel to soak up extra oil. The samples' weights were measured wet and dry or out-gassed. Wet samples were weighed within thirty minutes of being removed from the vessel, while out-gassed samples were measured after being left at room temperature for 24 hours. The properties of the out-gassed samples were determined, and the percentage changes in material property were calculated.

3. Test Results

The tested equipment performance with R-290 and odorized R-290 are measured and compared. The compatibility results are briefly summarized in this section.

3.1. Mini-Split heat pump test results

The mini-split heat pump was evaluated under five AHRI rating conditions using both virgin and odorized refrigerants. Figure 3 presents the capacity plots for these tests. The comparison between baseline and odorized refrigerant tests indicates a difference of less than 2.7% across all conditions. All observed differences are within the measurement uncertainties. The COP plots are displayed in Figure 4 below. When comparing the baseline and odorized tests, the difference between odorized and baseline systems is less than 2.9% under all conditions. All observed differences in COP are smaller than the measurement uncertainties for COP.

There was no statistically significant difference found between the baseline and the odorized heat pump system performance. The test results showed no evidence that adding odorant had any immediate effect on how the heat pump unit performed.

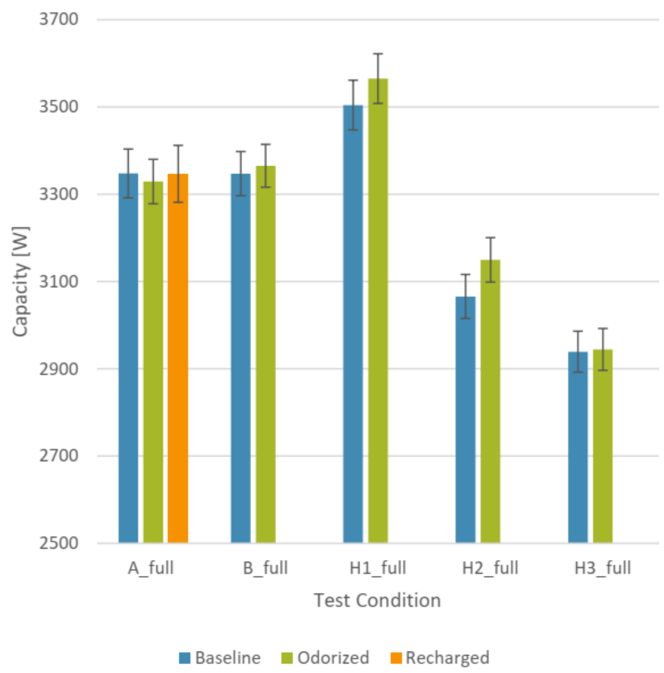

Figure 3. Mini-split Heat Pump Cooling and Heating Capacities under Standard Rating Conditions.

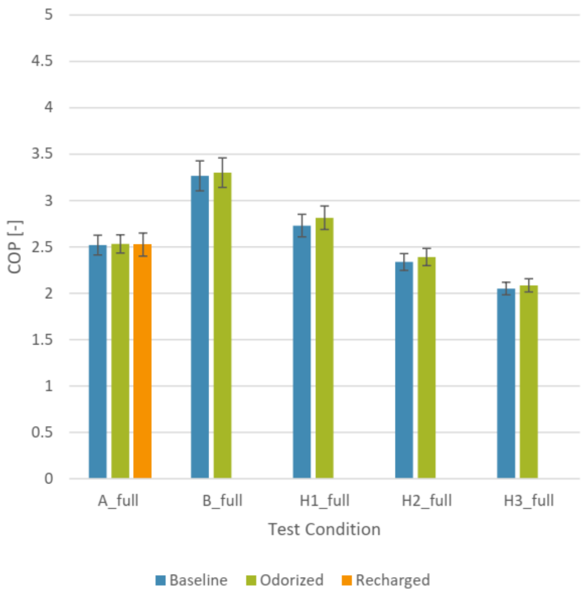

Figure 4. Mini-split Heat Pump Cooling and Heating COPs under Standard Rating Conditions.

3.2. Reach-in cooler test results

The main performance measure for this equipment is TDEC, expressed in kWh/day. Figure 5 below illustrates that the five tests defined in Table 2 have very similar energy use, with differences falling within the calculated uncertainty range, which accounts for both systematic and random errors. The test conducted after six months showed a slightly higher compressor power draw, but this increase remained within the limits of measurement uncertainty.

During the six months testing period, only a small amount of data was collected. Figure 6 illustrates recorded temperatures over the six months of steady operation of the refrigerator filled with odorized refrigerant. These measurements aimed to verify that the unit's performance remained consistent throughout the testing period. The test unit stayed inside an environmental chamber, which was generally left uncontrolled except for a few occasions when other projects required temperature adjustments—these can be seen as peaks where higher temperatures were set. Despite these changes, the unit consistently maintained refrigerated temperatures for the entire duration. There was a brief gap in data around March due to sensor connectivity loss, but the unit's operation continued unchanged. These tests indicate that the presence of odorant (DMS at 152 ppm-mass) does not have a measurable impact on the refrigerator's energy consumption or its ability to control temperature.

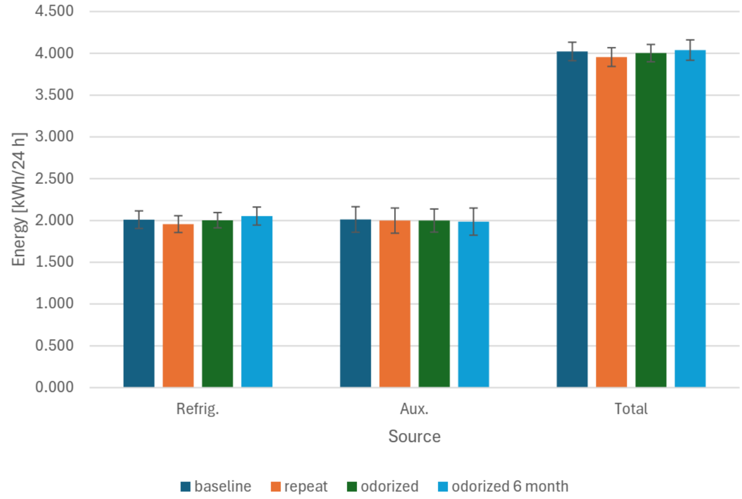

Figure 5. Reach-in Cooler Energy Consumption under Standard Rating Condition.

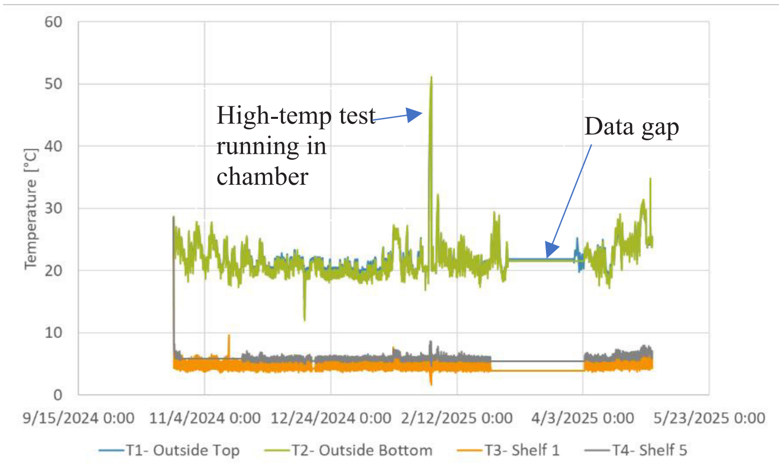

Figure 6. Logged Refrigerator Temperatures during 6-Month Running Period with Odorized Refrigerant.

3.3. Material compatibility test results

Post aging analyses of the materials included visual observations and measurements of weight, density, hardness, and dimensions. Changes in material properties, including the changes due to aging and changes due to the presence of the odorants, were determined. The changes due to aging were assessed by comparing the post-aging material properties to the pre-aging properties. The changes due to the presence of the odorants were evaluated by comparing the control samples to the odorant-containing samples. The data set is extensive, and only a subset of it is presented in this paper. Readers are encouraged to read the project report.

3.3.1. Weight changes due to odorants

In general, weight losses in materials are indicative of leaching, degradation, or volatilization of additives, while weight gains are likely due to absorption of refrigerant/lubricant into the bulk material. The comparison between the weight changes of the samples aged in the presence of odorants versus the weight changes of the controls was made. The individual weights of the two replicate samples (Sample 1 and Sample 2), depicting the degree of variation or spread between them, are measured and compared. In cases where the spreads between control and odorant data overlapped, the odorant is interpreted to have no measurable effect. When the odorant data fell below the control values (i.e., lower weight change with no overlap), it indicates a positive effect, suggesting reduced absorption, leaching, or chemical interaction. Conversely, when the odorant data were greater than the control values (showing higher weight change without overlap), the odorant is considered to have a negative effect, implying a slight increase in material interaction or instability. The designation ‘inconclusive’ was applied when the duplicate sample results did not exhibit a consistent trend (for example, one showing a weight gain and the other a weight loss), or when the odorized samples demonstrated a trend opposite to that of the corresponding control (for example, a control indicating a weight gain while the odorized sample indicated a weight loss, or vice versa).This approach allows a clear, directional assessment of odorant impact: lower values signify improved compatibility, while higher values denote potential adverse influence relative to the baseline control condition.

As shown in Tables 4 and 5, based on all 30 materials, in the R-290/Trane Oil 22 mixture, DMS exhibited predominantly neutral or positive responses (60%) and fewer negative outcomes (33%) than MES, which showed a higher proportion of negative results (47%). In the POE system, both odorants displayed similar distributions, though DMS again had a slightly lower fraction of negative effects. In the more polar PAG system, both odorants demonstrated strong compatibility, with 80–90% of responses classified as positive or neutral.

Table 4. Effects of Odorants on Materials Weight Change

Effects of Odorants on Weight Changes of Materials						
	R-290/Trane Oil 22		R-290/RL32-3MAF (POE)		R-290/RFL 68 EP (PAG)	
Material	Odorant		Odorant		Odorant	
	DMS	MES	DMS	MES	DMS	MES
1.Neoprene 1 C0873	Negative	Negative	Negative	Negative	Positive	No effect
2.Neoprene 2 C1276	Negative	Negative	Positive	No effect	No effect	Negative
3.HNBR N1173	Negative	No effect	Negative	Negative	Positive	Positive
4.NBR NA151	Negative	Positive	Negative	Negative	Positive	Positive
5.Fluorocarbon VA075	Negative	Negative	No effect	Positive	Positive	Positive
6.Epichlorohydrin YB-146	Negative	Negative	Negative	Positive	Positive	Negative
7.Butyl Rubber B0612	No effect	No effect	Negative	Negative	Positive	Positive
8.Garlock 3300	No effect	Negative	Positive	Positive	No effect	No effect
9.Armstrong N-8092	No effect	Negative	No effect	Positive	No effect	No effect
10.Klingersil C-4401	No effect	No effect	No effect	No effect	No effect	Positive
11.Polyester PBT Unfilled	No effect	No effect	No effect	No effect	No effect	No effect
12.Nylon 66 Unfilled	Negative	Positive	Positive	Positive	Positive	Positive
13.PEEK Unfilled	Inconclusive	Inconclusive	Positive	Positive	Negative	No effect
14.PPS Filled	No effect	Negative	No effect	Negative	No effect	Negative
15.PAI Unfilled	No effect	Positive	Positive	No effect	No effect	Positive
16.PEI $_2$	No effect	Inconclusive	No effect	No effect	No effect	Negative
17.Phenolic$_2$	Negative	Negative	Positive	Negative	No effect	No effect
18.PBT$_2$	Negative	Positive	No effect	Negative	No effect	Positive
19.PTFE Unfilled	No effect	Negative	Negative	Negative	Positive	Negative
20.Mylar MO21	Positive	Positive	Positive	Positive	No effect	No effect
21.Melinex 238	No effect	No effect	Inconclusive	Inconclusive	Positive	Positive
22.Nomex 410	No effect	No effect	No effect	No effect	Negative	No effect
23.Mica Glass Cloth	Inconclusive	Inconclusive	Positive	Positive	Negative	Negative
24.Polyester Tie Cord	No effect	No effect	Positive	No effect	No effect	No effect
25.Solvent-Based Varnish	Positive	No effect	No effect	No effect	No effect	No effect
26.Water-Borne Varnish	Positive	Negative	Negative	Negative	Positive	Positive
27.Film Insulated Round Magnet Wire	Negative	Negative	Inconclusive	Inconclusive	Positive	Positive
28.Fibrous Covered Round Magnet Wire with Solvent-based Varnish	No effect	Negative	Negative	Negative	Positive	Positive
29.Film Insulated Round Magnet Wire	No effect	Negative	Negative	No effect	No effect	Positive
30.Fibrous Covered Round Magnet Wire with Water-Borne Varnish	No effect	Negative	Negative	Negative	Positive	Positive

Table 5. Quantitative Summary of Odorants Effects on Materials Weight Change

Quantitative Summary of Odorant Effects on Material Weight Change					
Refrigerant/Lubricant	Odorant	Positive Effect	No Effect	Negative Effect	Inconclusive
R-290/Trane Oil 22 (MO)	DMS	10%	50%	33%	7%
	MES	17%	27%	47%	9%
R-290/RL32-3MAF (POE)	DMS	30%	30%	33%	7%
	MES	27%	30%	37%	6%
R-290/RFL 68 EP (PAG)	DMS	43%	47%	10%	0%
	MES	47%	33%	20%	0%

3.3.2. Hardness changes due to odorants

In general, a decrease in hardness indicates softening of the material, typically associated with absorption of refrigerant or lubricant and the resulting loss of mechanical integrity. Conversely, an increase in hardness suggests embrittlement, which may result from plasticizer leaching, cross-linking, or surface oxidation. The individual hardness of the two replicate samples (Sample 1 and Sample 2), depicting the degree of variation or spread between them, were compared. In cases where the spreads between control and odorant data overlapped, the odorant is interpreted to have no measurable effect. When the odorant data showed smaller hardness change than the control with no overlap, it indicates a positive effect, suggesting that limited interaction between the odorants and polymer matrix may have helped stabilize the polymer network. Conversely, when the odorant data showed larger hardness change than the control without overlap, the odorant is considered to have a negative effect, implying localized degradation or softening of the polymer due to odorant absorption or chemical incompatibility. The designation ‘inconclusive’ was applied when the duplicate sample results did not exhibit a consistent trend (for example, one showing a hardness increase and the other a hardness decrease), or when the odorized samples demonstrated a trend opposite to that of the corresponding control (for example, a control indicating a hardness increase while the odorized sample indicated a hardness decrease, or vice versa).

As shown in Tables 6 and 7, both DMS and MES exhibit either no effect or a positive effect on most materials tested in the R-290/Trane Oil 22 (MO) mixture—86% with DMS and 81% with MES. In contrast, the R-290/POE and especially the R-290/PAG mixtures show greater variability, with the PAG system displaying the highest proportion of hardness changes, particularly under MES exposure.

Table 6. Effects of Odorants on Materials Hardness Change

Effects of Odorants on Hardness Changes of Materials						
	R-290/Trane Oil 22		R-290/RL32-3MAF (POE)		R-290/RFL 68 EP (PAG)	
Material	Odorant		Odorant		Odorant	
	DMS	MES	DMS	MES	DMS	MES
1.Neoprene 1 C0873	No effect	No effect	No effect	No effect	No effect	Negative
2.Neoprene 2 C1276	Negative	Positive	No effect	No effect	Positive	Positive
3.HNBR N1173	No effect	No effect	Negative	No effect	Positive	Positive
4.NBR NA151	Negative	No effect	No effect	Positive	No effect	Positive
5.Fluorocarbon VA075	No effect	Negative	No effect	No effect	No effect	No effect
6.Epichlorohydrin YB-146	No effect	No effect	No effect	Negative	Inconclusive	Negative
7.Butyl Rubber B0612	No effect	Positive	Inconclusive	Negative	Inconclusive	Negative
8.Garlock 3300	No effect	No effect	No effect	No effect	No effect	No effect
9.Armstrong N-8092	No effect	No effect	No effect	Positive	No effect	No effect
10.Klingersil C-4401	No effect	No effect	Positive	No effect	Positive	Positive
11.Polyester PBT Unfilled	N/A	N/A	No effect	No effect	Inconclusive	Positive
12.Nylon 66 Unfilled	No effect	Negative	No effect	No effect	No effect	No effect
13.PEEK Unfilled	No effect	No effect	No effect	Inconclusive	Negative	Inconclusive
14.PPS Filled	No effect	Inconclusive	Inconclusive	Positive	Positive	Positive
15.PAI Unfilled	No effect	No effect	Inconclusive	Inconclusive	No effect	Positive
16.PEI $_2$	Positive	No effect b	No effect	No effect	Inconclusive	No effect
17.Phenolic$_2$	No effect	Positive	Positive	No effect	Positive	Positive
18.PBT$_2$	No effect	No effect	Inconclusive	No effect	Negative	Negative
19.PTFE Unfilled	No effect	No effect	Inconclusive	No effect	Positive	Positive
20.Mylar MO21	N/A	N/A	N/A	N/A	N/A	N/A
21.Melinex 238	No effect	Inconclusive	Positive	No effect	No effect	No effect
22.Nomex 410	No effect	No effect	Inconclusive	Inconclusive	Inconclusive	No effect
23.Mica Glass Cloth	Inconclusive	No effect	Negative	No effect	No effect	No effect
Note: Hardness data not available for material 20 because it was brittle and broke upon handling, for material 24 because it is a string, for materials 25 and 26 because they are varnish pucks, and for materials 27 to 30 because they are magnet wires; hardness data not available for material 11 in R-290/Trane Oil 22 because it became brittle after aging and broke upon handling.						

Table 7. Quantitative Summary of Odorants Effects on Materials Hardness Change

Quantitative Summary of Odorant Effects on Material Hardness Change					
Refrigerant/Lubricant	Odorant	Positive Effect	No Effect	Negative Effect	Inconclusive
R-290/Trane Oil 22 (MO)	DMS	5%	81%	9%	5%
	MES	14%	67%	9%	10%
R-290/RL32-3MAF (POE)	DMS	14%	50%	9%	27%
	MES	13%	64%	9%	14%
R-290/RFL 68EP (PAG)	DMS	27%	41%	9%	23%
	MES	41%	36%	18%	5%
Note: The percentages for samples aged in R-290/Trane Oil 22 (MO) were calculated based on a total of 21 samples, while the percentages for samples aged in R-290/RL32-3MAF(POE) and R-290/RFL 68EP (PAG) were calculated based on a total of 22 samples.					

4. Conclusions

The study found that adding DMS odorant to propane refrigerant at 150 ppm-mass did not significantly impact system performance in either a heat pump or refrigerator, even after six months of operation. Due to the resource constraint, the testing period is limited to six months; however, longer term evaluation or under accelerated conditions is needed to further assess the odorant impact to the product performance. Odorant levels remained detectable at the end of the six-months testing period as confirmed by gas chromatography and technician observation. The compatibility testing indicates some potential incompatibility signs among R-290, odorants, lubricants and system materials. While these results suggest technical feasibility for using odorants in R-290, more research is needed. Key future work includes examining how odorants distribute between refrigerant phases, testing their interaction with system filters, conducting long-term system tests, evaluating more odorants options and compatibility assessment.

Acknowledgements

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