Hot Surface Ignition Testing of Low GWP 2L Refrigerants

Mary Koban*, Barb Minor, Patrick Coughlan, Nina Gray

[1]The Chemours Company
Wilmington, DE, USA
Mary.e.koban@Chemours.com

* Corresponding Author

ABSTRACT

The demand for environmentally sustainable substances is high. The number of low global warming (GWP) refrigerants entering the market is rapidly increasing to meet environmental needs. Many of the new low GWP refrigerants are "mildly flammable" or "2L" as classified by ISO 817 and ANSI/ASHRAE Standard 34 (ISO 2014, ASHRAE 2008). The new refrigerant flammability class provides the heating/air-conditioning/refrigeration industry more options to meet environmental regulations with equipment designed for low flammability refrigerants. Mildly flammable refrigerants are defined as refrigerants which have burning velocity (BV) less than 10 cm/sec and heat of combustion (HOC) less than 19,000 kJ/kg. Therefore, while these refrigerants are flammable, they are harder to ignite and potential events are less severe than class 2 or class 3 refrigerants. Understanding viable ignition sources are paramount in equipment design.

A hot surface, which can be found in air conditioning auxiliary heaters and other refrigeration systems, is a relatively unexplored potential ignition source. Maximum hot surface temperatures are specified in various equipment standards. Recently, work was conducted to review potential ignition/non-ignition for seven different 2L refrigerants which were released onto a hot surface. Tests were designed to simulate a 2L refrigerant leak onto a hot surface within a piece of equipment or ductwork. In particular, individual refrigerants were released onto a round heated metal surface, and potential ignition was observed for a set period after the refrigerant was released. This study builds upon previous work where refrigerants were released onto hot surfaces at 800°C. In addition to ignition phenomena at higher elevated temperatures (825°C and 850°C), temperature profiles were recorded along with hot surface recovery time to better understand each refrigerant's "impingement cooling capacity".

1. INTRODUCTION

Due to increasing global environmental pressures, the HVAC industry is facing many challenges. Currently available non-flammable refrigerants (class 1) do not exhibit flame propagation but have undesirable GWP ranging from >1000 GWP up to several thousand GWP. Reducing the GWP while keeping refrigerant performance attributes is therefore quite desirable. As GWP is reduced, refrigerant stability is also reduced and hence refrigerants become flammable. Class 3 refrigerants, which are typically hydrocarbons, have low GWP but undesirable flammability characteristics. Class 3 refrigerants are easily ignitable with potential resulting ignition events being quite severe. Therefore, 2L refrigerants are of interest to the HVAC industry. 2L refrigerants have the benefit of low GWP and exhibit reduced flammability characteristics compared to class 3 counterparts. In additional to low BV and low HOC, these refrigerants exhibit high minimum ignition energy (MIE), implying that they are difficult to ignite. Typical MIE values for 2L refrigerants are two to four orders of magnitude greater than class 3 refrigerants. The 2L flammability properties are desirable for original equipment manufacturers (OEMs) designing HVAC equipment.

Most equipment and area standards focus on lower flammability limit (LFL) and autoignition temperature (AIT) as the basis for safety design (ASHRAE 15-2013, UL 1995, UL 60335-2-40, IEC 60335-2-40). If all refrigerant classes required similar ignition energies or if the leak events were similar to AIT conditions this could be an appropriate approach. However, data from the past 10-15 years has shown that not all refrigerants are as easily ignited due to differences in MIE. Due to the higher MIE value versus class 2 or 3 flammable refrigerants, 2L refrigerants are typically tough to ignite.

Also, AIT testing is not entirely representative of the type of leak events encountered in heating/air-conditioning/refrigeration industry. The autoignition temperature (AIT) of a gas mixture is the minimum temperature at which a gas mixture spontaneously ignites without an external ignition source. Static testing, autoignition phenomena is a balance between the heat production and heat loss. If the rate of heat production is higher than the rate of heat loss, the temperature of the gas mixture will increase, and auto-ignition will occur. AIT is not an intrinsic property of a mixture, but rather dependent upon system volume, pressure, boundary conditions for heat transfer, and time of contact (induction time) between the hot environment and gas mixture.

AIT is typically determined at atmospheric pressure, using small test vessels open to the atmosphere where gas is quickly injected into the test vessel and heated for a pre-determined time observing ignition or non-ignition (ASTM E659-15). Therefore, AIT is often not directly applicable to real-world heating/ventilation/air-conditioning (HVAC) situations where potential ignitions due to refrigerant leaking onto the hot surface are in an open, unconstrained environment. The phenomena where a flammable substance impinges on a hot surface and ignites is known as "hot surface ignition" and the resulting temperature is called the "hot surface ignition temperature" or HSIT.

Hot surface ignitions were extensively investigated in the automotive, aviation and petroleum and natural gas fields for decades (Zabetakis 1965, Lewis 1987). Colwell and Rezza conducted statistical evaluations of hot oil ignitions on a flat plate (Colwell and Rezza 2005). Similarly, Davis et al., performed combustible liquid hot surface ignitions (Davis 2006). Independently, Monforte and Olson each conducted studies in the automotive industry to understand potential hot surface ignition temperature of HFO-1234yf (Montforte 2009, Olson 2012). These studies provide confirmation that HSIT is expected to be well above the AIT. Also, the American Petroleum Institute (API) notes that hot surface ignition is projected to be at least 200°C (392°F) above the AIT (API 1991).

Recently, work was conducted to review potential ignition/non-ignition for seven different 2L refrigerants which were released onto a hot surface. Tests were designed to simulate a 2L refrigerant leak onto a hot surface within a piece of equipment or ductwork. In particular, individual refrigerants were released onto a round heated metal surface, and potential ignition was observed for a set period after the refrigerant was released. This current work builds upon previous work where refrigerants were released onto hot surfaces. In addition to ignition phenomena, temperature profiles were recorded along with hot surface recovery time to better understand each refrigerant's "impingement cooling capacity".

2. EXPERIMENTAL SETUP

As was mentioned in the previous work (Koban and Coughlan, 2016), the experimental set-up was designed to simulate a sudden, catastrophic leak of liquid refrigerant onto an exposed heating element. Therefore, the test apparatus consisted of a thermally stable hot impingement surface and a refrigerant spray system both contained within a non-heated, static enclosure. The enclosure replicates refrigerant leaking into a small crawl space, closet or possibly ductwork where the refrigerant would expand within the entire volume.

2.1 Hot Surface Apparatus

The heated surface portion of the test apparatus consisted of a 35.6 cm by 35 cm (14 in by 14 in) ceramic heating element (MHI HP220-HIGHBO-1250) with a 5 cm (2 in) 316 stainless steel round planchet placed on top of the ceramic heating element. While the ceramic heating element has a 22.9 cm by 22.9 cm (9 in by 9 in) metal surface and can theoretically reach temperatures up to 1250°C (2280°F), it is hard to keep this vast area at a constant temperature during the testing. Therefore, the ceramic heating element was used to provide uniform heat to the much smaller 5 cm (2in) round metal planchet which was in contact with the ceramic plate. Gemcolite® ASM FG30-165050 ceramic insulation board covered the hot plate except for the area cutout for the planchet.

Hence, the metal planchet served as the hot surface where refrigerant was released on the surface (see Figure 1). K-type thermocouples were attached to opposite sides of the top of the planchet to record the surface temperature. A data logger was attached to the thermocouples to continuously capture the temperature output. Data was recorded before, during and at least two minutes after, each refrigerant was released.

2.2 Refrigerant Spray System

The refrigerant spray system consisted of a -0.3175 cm (0.125 in) stainless steel cylindrical tube with an opening at the release end connected to refrigerant containing cylinder. The tubing had the following dimensions:

Length:	152 mm ± 5.0 mm	(6.0 in ± 0.20 in)
Outer dimension:	3.2 mm ± 0.2 mm	(0.125 in ± 0.01 in)
Inner dimension:	1.6 mm ± 0.1 mm	(0.06 in ± 0.005 in)

An opening was cut at the end of the tubing to create a refrigerant release point. The tubing was cut perpendicular to the axis making a right angle cut. The tip of the refrigerant spray system was maintained 38 mm ± 13 mm (0.15 in ± 0.5 in) above the hot planchet and was directed at the center of the hot planchet. The angle of the refrigerant spray tubing was at an angle of 45 degrees +/- 5 degrees with respect to the planchet surface. The distance from the end of the tubing to the planchet was kept constant for all testing.

2.3 Testing Enclosure

Testing was performed in a modified enclosure contained within a laboratory fume hood. Ventilation was off during the testing. Dimensions of the enclosure were 94 cm (37 in) in length by 122 cm (48 in) in depth with a height of 142 cm (56 in). The enclosure was completely sealed except the opening to the back of the hood to facilitate venting.

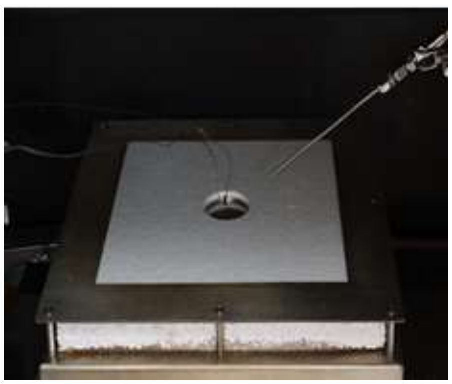


Figure 1 The picture on the left shows the ceramic hot plate with the attached planchet. The refrigerant spray line can also be seen. The picture on the right shows the complete enclosure which is contained within the fume hood. It should be noted that before turning on the hot plate, the enclosure varied in temperature between 18-20 °C (64.4- 68 °F) and was draft-free as measured by an anemometer.

2.3 Test Method

As was mentioned earlier, this work is an extension of previous work done by Chemours. In the earlier work (Koban and Coughlan, 2016), testing was limited to 800 °C. In this study, the testing was conducted at 825 °C and 850°C. For 825 °C testing, the planchet was heated until a steady test temperature of 825 °C (1517 °F) with +/- 10 °C (+/-18 °F) is maintained for 5 minutes. Approximately five grams of liquid refrigerant at room temperature was discharged directly onto an 825 °C (1517 °F) hot planchet which was contained within the static enclosure (i.e. the hood ventilation is off). The hot planchet surface was observed for an initial refrigerant (liquid) hot surface ignition. It was also noted for an additional two minutes for possible refrigerant vapor ignition. If the sample did not show visible ignitions (immediately or during the 2 minute observation time), the ventilation was turned on to clear the enclosure of refrigerant vapors. A corresponding “NO GO” result was also recorded for this refrigerant release. If the refrigerant ignited during any part of this test, the hood ventilation was immediately turned on, and a “GO” result was recorded. Ignition testing was done at a temperature of 825 °C (1517 °F) with +/- 10 °C (+/-18 °F) for a pass/fail response. Each refrigerant sample was tested five times to ensure that results were robust.

2.4 Refrigerants Tested

Again, building upon previous, several 2L refrigerants and blends containing 2L refrigerants were evaluated for hot surface ignition temperature. The following is a table (Table 1) of the 2L refrigerants and refrigerant blends that were tested using this apparatus and the associated flammability data if known.

Table 1: Flammability Properties for Refrigerants included in Study

Refrigerant	Blend Composition	AIT, °C (°F)	BV, cm/sec (in/sec)	LFL, vol %	MIE, mJ (ft-lb)	ASHRAE Std 34 Class
R-32	N/A	648 (1198)	6.7 (2.64)	14.4	30-100 (0.02 -0.07)	A2L
R-1234ze	N/A	375 (707)	1.2 (0.47) *	7.0 **	61,000-64,000 (45 - 47)	A2L
R-1234yf	N/A	405 (761)	1.5 (0.59)	6.2	5,000-10,000 (3.7 - 7.4)	A2L
R-452B Pending	R-32/125/1234yf (67/7/26)	N/A	4.2	7.5	est 100-300	Expected A2L
R-454A	R-32/1234yf (35/65)	N/A	2.4	6.3	est 300-1000	A2L
R-454C Pending	R-32/1234yf (21.5/78.5)	N/A	<4* (2.5)	6.2	est 300-1000	Expected A2L
Not Submitted to ASHRAE	R-32/R-1234ze (21.5/78.5)	N/A	<4*	~ 7.0	est > 1000	Expected A2L

*Denotes BV and **ETFL per ASHRAE Standard 34. Two of the blends were recently submitted to ASHRAE for safety classification and are pending classification. Therefore, they are marked as R-pending. One blend was tested, but it has not been submitted to ASHRAE.

3. RESULTS

Table 2 shows the testing results for refrigerants tested in the current test apparatus. Data indicates that all of the 2L refrigerants tested in this present study have HSIT that is at least 850°C (1562 °F), as none of the refrigerants tested had an ignition at the 850°C (1562 °F) mark. The 850°C (1562 °F), HSIT value is well above the reported AIT value for R-32, R-1234ze, and R-1234yf. It should be noted that since the neat 2L refrigerants (R-1234ze, R-1234yf, and R-32) did not ignite at 800°C. Therefore, the refrigerant blends which were composed of the same 2L flammable components were not tested at 800°C, but rather tested at 825°C (1517 °F)and 850°C (1562 °F).

Table 2 Results for the subject refrigerants tested in the current apparatus.

2L Substance	Rep Number	Test Temperature (800C)		Test Temperature (825C)		Test Temperature (850C)	
		Spot Ignition (liq on surface), Y/N	Two Min Ignition (vap above LFL), Y/N	Spot Ignition (liq on surface), Y/N	Two Min Ignition (vap above LFL), Y/N	Spot Ignition (liq on surface), Y/N	Two Min Ignition (vap above LFL), Y/N
R-1234zyf	1	N	N	N	N	N	N
	2	N	N	N	N	N	N
	3	N	N	N	N	N	N
	4	N	N	N	N	N	N
	5	N	N	N	N	N	N
R-1234ze	1	N	N	N	N	N	N
	2	N	N	N	N	N	N
	3	N	N	N	N	N	N
	4	N	N	N	N	N	N
	5	N	N	N	N	N	N
R-32	1	N	N	N	N	N	N
	2	N	N	N	N	N	N
	3	N	N	N	N	N	N
	4	N	N	N	N	N	N
	5	N	N	N	N	N	N
R-452B Pending R-32/125/1234yf (67/7/26)	1	-	-	N	N	N	N
	2	-	-	N	N	N	N
	3	-	-	N	N	N	N
	4	-	-	N	N	N	N
	5	-	-	N	N	N	N
R-454A R-32/1234yf (35/65)	1	-	-	N	N	N	N
	2	-	-	N	N	N	N
	3	-	-	N	N	N	N
	4	-	-	N	N	N	N
	5	-	-	N	N	N	N
R-454C Pending R-32/1234yf (21.5/78.5)	1	-	-	N	N	N	N
	2	-	-	N	N	N	N
	3	-	-	N	N	N	N
	4	-	-	N	N	N	N
	5	-	-	N	N	N	N
R-32/R-1234ze (21.5/78.5) Not Submitted to ASHRAE	1	-	-	N	N	N	N
	2	-	-	N	N	N	N
	3	-	-	N	N	N	N
	4	-	-	N	N	N	N
	5	-	-	N	N	N	N

3.1 HSIT Profile

As an additional part of this work, the HIST profile versus time was recorded. A data logger was used to collect temperature data for each refrigerant, listed in **Table 2**, during the five test runs. This information was subsequently averaged in a unique profile for each refrigerant and is shown below in **Figure 2**. The refrigerants are not listed in any particular order and are generically coded refrigerant #1 through #7. What is important to note is that during the refrigerant release, the surface is cooled significantly within the first five seconds after the release. Depending on the refrigerant, the surface is cooled anywhere from 50°C to as much as 100°C. The surface temperature decrease after refrigerant impingement is noted as "refrigerant surface-impingement cooling capacity" in **Figure 2** below. Results show that the surface cooling can be quite significant due to the amount of liquid refrigerant impinging on the surface. The surface temperature rebounds back to the initial surface temperature and is noted as "surface temperature time lag" in **Figure 2**. It takes approximately 30 seconds for the hot surface to come back to temperature and plateau

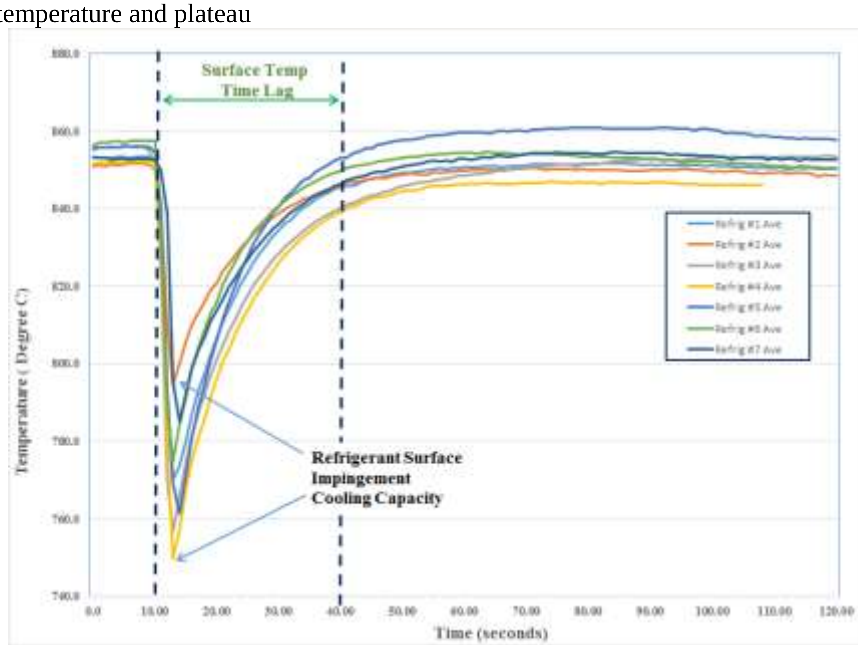

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Figure 2 HSI Profile vs Time for 2L Refrigerants tested at 850°C.

3.2 Impingement Cooling Capacity

In further analysis, it seems that not all refrigerants have similar "surface impingement cooling capacity". Some refrigerants appear to be able to provide more cooling capacity. In reviewing the data, it was apparent that refrigerant #2 had the least cooling capacity while refrigerant #4 had the greatest cooling capacity, as seen in **Figure** 3 below. The differences between these two refrigerants are not trivial. It appears to be about 50°C averaged between the five different runs for each refrigerant. Therefore, it is important to understand how real this phenomenon is with regards to repeatability. During the testing, it was noted that some of the ceramic insulation appeared to decay. Therefore, boards were changed as needed throughout the testing process. Boards were replaced when they were deemed unsuitable for further testing. Hence, it is possible that there is some confounding effect of board replenishment on surface impingement cooling. This will be further investigated going forward and reported as information becomes available.

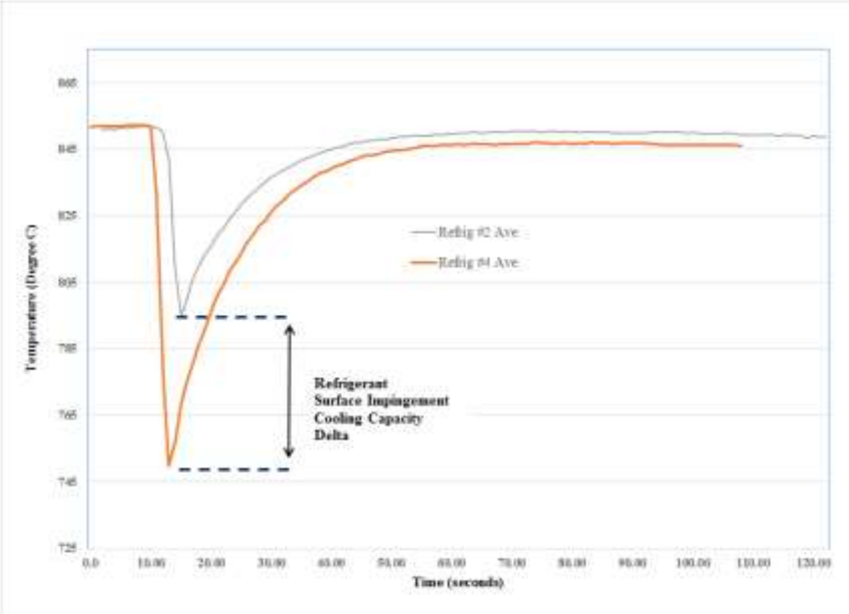

Figure 3 HSI Profile vs Time for Refrigerant #2 and Refigerant #4 tested at 850°C.

4. DISCUSSION

The data shows that 2L refrigerants tested did not ignite when impinged on hot surfaces with temperatures up to 850°C. In the previous work (Koban and Coughlan, 2016) refrigerants were released onto the hot surface and "GO" or "NO GO" was noted at a testing temperature of 800C Refrigerant ignition information is useful to OEMs in designing HVAC equipment. Hot surface testing results can be more descriptive regarding refrigerant surface cooling capacity. Therefore, a data logger was attached to the surface thermocouples to continuously capture the hot surface temperature output. Data was recorded before, during and after each refrigerant was released, for a period up to two minutes after the refrigerant was released.

As noted in the previous work, the test method described here is satisfactory for gathering data regarding hot surface ignitions, but it does have some limitations. The ceramic insulation can be easily moved and also eroded by the force of the refrigerant spray causing refrigerant to get trapped under the ceramic insulation temporarily creating similar conditions to AIT tests. When the insulation was errored it was easy to note during testing as the ceramic insulation lifted slightly. When this displacement occurred, the testing was stopped, and readings were not taken as the temperature of the ceramic hot plate was 1250°C (2282 °F) well exceeding the pass/fail test limit. Another limitation was that the boards could be less stiff after refrigerant release (i.e., not insulate the corresponding surface as well) and impact the refrigerant surface cooling capacity. Therefore, it is possible that some of the deviations in cooling capacity can be related to board affects. The potential implications insulation board variability has on the test will be investigated. And, as was previously discussed, a refined planchet design may also be a possible equipment modification in future studies to eliminate refrigerant getting trapped under the insulation. Both of these changes will be investigated further.

The HSIT values noted here are several hundred degrees C higher than AIT values. (It should be pointed out that AIT values were not available for all of the refrigerants.) The shift in temperature for HSIT vs. AIT has been discussed in various industries. Zabekis and Colwell and Rezza made note of the shift in temperature for HSIT. They note that as ignition events become less than ideal (non-forced), the ignition temperature shifts to the right (increases). Therefore, HSIT values are greater than AIT values due to the uncontrolled loss of vapor and heat after the refrigerant impinges upon the surface.

5. CONCLUSIONS

A previously investigated test method was used to evaluate seven 2L refrigerants in a pass/fail type HSIT test. While the pass/fail temperature already studied was 800 °C (1472 °F), testing in this study was done at 825°C (1517 °F) and 850C (1562 °F). All of the 2L refrigerants evaluated passed the test with no ignitions in any of the five replicates. The 2L refrigerants had HSIT well above the AIT literature values. This result was expected. As the ignition events become less than ideal (non-forced), the ignition temperature shifts to the right (increases). Therefore, HSIT values are greater than AIT values due to the uncontrolled loss of vapor and heat after the refrigerant impinges upon the surface.

A data logger was used to collect temperature data for each refrigerant during the release event. In further analysis, it seems that not all refrigerants have similar "surface impingement cooling capacity". Some refrigerants appear to be able to provide more cooling capacity. It is important to note that during the refrigerant release, the hot surface is cooled significantly within the first five seconds after the release. Depending on the refrigerant, the hot surface is cooled anywhere from 50°C to as much as 100°C. This is noted as "refrigerant surface-impingement cooling capacity." The hot surface temperature rebounds back to the initial surface temperature and the time it takes the surface to rebound is noted as "surface temperature time lag."

NOMENCLATURE

AIT = Auto-Ignition temperature
ASHRAE= American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM= ASTM International (formerly American Society for Testing and Materials)
BV = Burning Velocity
HSIT = Hot Surface Ignition Temperature
GWP = Global Warming Potential
IEC = International Electrotechnical Commission
ISO = International Organization for Standardization
LFL = Lower Flammability Limit
MIE = Minimum Ignition Energy

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