



## Effects of temperature and humidity on the flammability limits of several 2L refrigerants

Shigeo Kondo\*, Kenji Takizawa, Kazuaki Tokuhashi

National Institute of Advanced Industrial Science and Technology (AIST), Central 5, 1-1-1, Higashi, Tsukuba, Ibaraki 305-8565, Japan

### ARTICLE INFO

#### Article history:

Received 11 July 2012

Received in revised form 21 August 2012

Accepted 23 August 2012

Available online 30 August 2012

#### Keywords:

Flammability limits

Temperature and humidity dependence

2L refrigerants

HFO-1234yf

HFO-1234ze

### ABSTRACT

Flammability limits were measured in air for several compounds classified as 2L refrigerants by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). The compounds treated are ammonia,  $\text{CH}_2\text{F}_2$  (HFC-32),  $\text{CH}_3\text{CF}_3$  (HFC-143a),  $\text{CH}_2=\text{CF}_2$  (HFO-1234yf), and  $\text{CHF}=\text{CHCF}_3$  (HFO-1234ze). The measurements of flammability limits were made in a 12L spherical glass flask following ASHRAE method. The temperature range examined was from 5 to 100 °C, and the humidity was ranged from 0 to 90% corrected for 23 °C. The temperature dependences of flammability limits of ammonia, HFC-32, and HFC-143a were found basically explainable by White's rule. On the other hand, the temperature dependences of flammability limits of HFO-1234yf and HFO-1234ze are considerably larger than the predictions by White's rule. For ammonia, HFC-32, and HFC-143a, the flammability limits are not much affected by the humidity of air used. On the other hand, the flammable ranges of HFO-1234yf and HFO-1234ze whose molecules contain more F-atoms than H-atoms markedly depend on the humidity of air. In particular, HFO-1234ze is non-flammable if the humidity of air is equal to or less than 10% corrected for 23 °C.

© 2012 Elsevier B.V. All rights reserved.

### 1. Introduction

Recently, development of various new refrigerants is under way in order to cope with the environmental problem [1]. Since there are some combustible gases among them, flammable properties of refrigerant compounds are focused. In particular, those compounds classified as 2L refrigerants are highlighted due to the extremely weak combustibility [2]. Some of them are characterized by their molecular structure that the molecules contain more fluorine atoms than hydrogen atoms. Because of this, the flammability limits of those compounds are known to be affected by the humidity condition of air used for the measurements [3].

Apart from this, it is widely known that the experimental flammability limits depend on the experimental condition under which they are measured [4–7]. For example, they are dependent on the size and shape of the vessel used [5] and the ignition source as well [6,7]. Coward and Jones have reported numerous data of flammability limits measured under various conditions [4].

In order to clarify quantitative relationship between the experimental values of flammability limits and the measurement condition, we have recently done a temperature dependence study of flammability limits for a number of compounds [8]. We have

also done a pressure dependence study of flammability limits for a few compounds [9].

As for the temperature dependence, it is known that the flammable range becomes wide when the temperature is raised; the lower limit becomes lower and the upper limit becomes higher. The obtained data were successfully interpreted using White's rule that the limiting flame temperature is kept constant independently of the experimental temperature [10].

As to the humidity effect, it is known that the flammable ranges of compounds whose molecules having more fluorine atoms than hydrogen atoms are wider in moist air than in dry air [3]. Then, the question arises what is the relationship between the flammability limits and the humidity condition for this kind of compounds.

In this paper, we report the result of measurement and analysis of temperature and humidity dependence of the flammability limits for several gases classified as 2L refrigerants. The method of measurement proposed by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is suitable for the present purpose because it can detect relatively small shifts of flammability limits resulting from the changes in the temperature and/or humidity condition.

### 2. Experimental

In the present study, the measurements of flammability limits faithfully followed the ASHRAE method [1,11]. Fig. 1 shows a schematic diagram of the experimental setup. The explosion vessel

\* Corresponding author. Tel.: +81 29 861 4770; fax: +81 29 861 4770.  
E-mail address: [s.kondo@aist.go.jp](mailto:s.kondo@aist.go.jp) (S. Kondo).

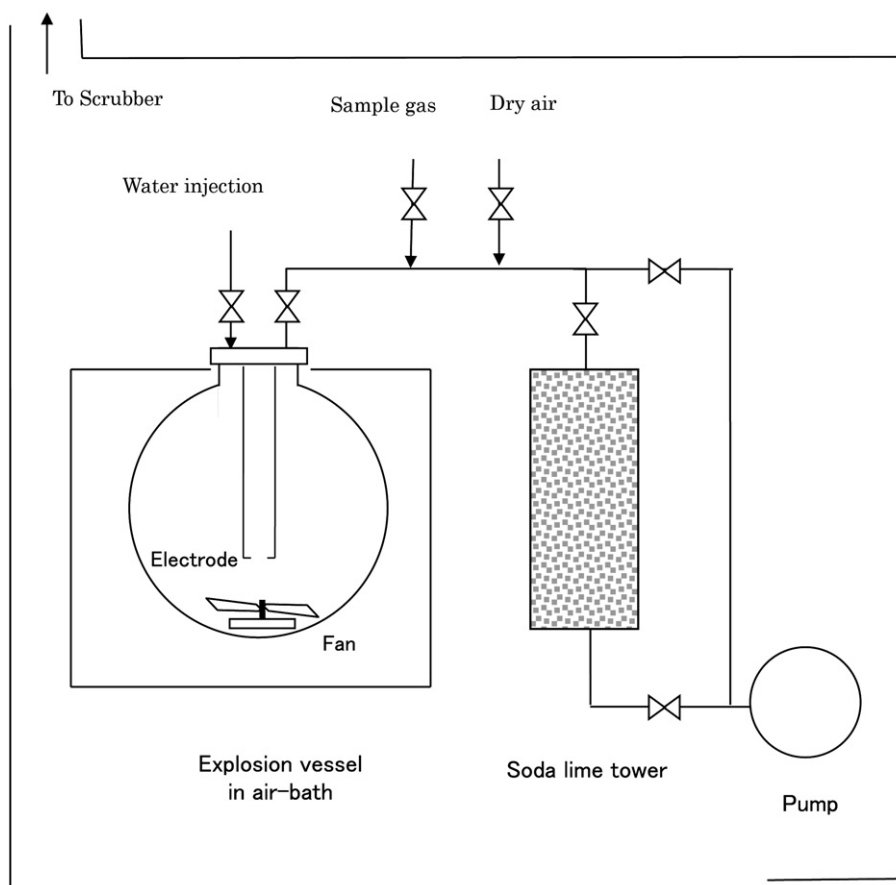


Fig. 1. Schematic diagram of explosion vessel and exhaust system.

is a 12-L spherical glass flask. The vessel flange is held on the top by spring-loaded clamps. The vessel is equipped with a pair of tungsten electrodes for AC electric discharge, whose ends were pointed and set 1/4 in. (0.63 cm) apart. The electrodes were positioned one-third from the bottom to the shoulder of the vessel.

The 12-L spherical glass flask was placed in an air-bath to be held at a certain temperature from 20 to 100 °C. The temperature of the head part of the vessel, which was out above the air-bath ceiling, was kept at the same levels of temperature using a ribbon heater. The air in the air-bath was circulated continuously to keep the temperature constant. In addition, the fan to stir the gas mixture in the vessel helped to secure the homogeneity of temperature inside the vessel. For the measurement at 5 °C, the flask was set in a cool water bath. We believe that the accuracy and homogeneity of temperature were controlled better than 2 °C.

For the measurement, gas mixtures were directly prepared in the explosion vessel by the partial pressure method. Two kinds of MKS baratrons, 100 and 1000 Torr heads, were used appropriately for the pressure measurement. Before introduction of gases, the vessel was evacuated to  $5 \times 10^{-2}$  Torr (1 Torr = 133.32 Pa). Fuel gas was first introduced into the vessel followed by dry air. A gas mixture was prepared in the vessel at a predetermined pressure which is about the same as the ambient pressure. In order to adjust the humidity condition of air, a certain amount of pure water was injected into the vessel by a syringe. In this case we waited 30 min to vaporize the water before ignition.

For ignition, an AC electric spark was initiated between the electrodes by a 15 kV neon transformer. The spark duration was 0.4 s. This corresponds to ignition energy of approximately 10 J. This was roughly estimated by recording the electric current and voltage between the electrodes during the discharge. The flame

propagation was observed visually in the dark and at the same time video pictures were taken. The mixture is determined to be flammable if the flame moves upward and outward from the point of ignition to reach an arc of the vessel wall subtending an angle of 90° as measured from the point of ignition. After each measurement, the exhaust gas was evacuated roughly through a soda lime tower 15 cm in diameter and 35 cm in height followed by filling with nitrogen and evacuation for two times, and finally the vessel was directly evacuated by a pump.

The measurements of flammability limits were done for ammonia, CH<sub>2</sub>F<sub>2</sub> (HFC-32), CH<sub>3</sub>CF<sub>3</sub> (HFC-143a), CH<sub>2</sub>=CFCF<sub>3</sub> (HFO-1234yf), and CHF=CHCF<sub>3</sub> (HFO-1234ze). The temperature dependence of flammability limits of ammonia was measured in a previous study, but was re-measured here because the measurement method in a previous study was a modified version of ASHRAE method. Sample gases were purchased from Chemical companies. Purities of sample gases were 99% or better. The compressed air used was extra-pure and dry. All sample materials were used without further purification.

### 3. Results and discussion

#### 3.1. Temperature dependence of flammability limits

The measurements of the temperature dependences of flammability limits of ammonia, HFC-32, and HFC-143a were done in dry air. On the other hand, the measurements of HFO-1234yf and HFO-1234ze were done both in dry air and in moist air, where the humidity of the moist air is 50% corrected for 23 °C. The measurements in dry air were done for a temperature range from 5 to 100 °C. However, since the saturated vapor pressure of water at

**Table 1**  
Observed values of flammability limits at various temperatures for several 2L compounds.

Compound	Temperature (°C)	L		U		G
		vol%	±	vol%	±	
Ammonia in dry air NH <sub>3</sub>	5	15.5	0.2	29.5	0.4	21.38
	20	15.6	0.2	29.8	0.6	21.56
	35	15.3	0.3	30.4	0.5	21.53
	50	15.2	0.4	30.7	0.5	21.60
	75	15.1	0.3	31.0	0.5	21.64
	100	14.7	0.5	31.5	0.5	21.52
HFC-32 in dry air CH <sub>2</sub> F <sub>2</sub>	5	13.65	0.10	27.10	0.30	19.23
	20	13.48	0.15	27.70	0.50	19.32
	35	13.50	0.15	28.00	0.50	19.44
	50	13.30	0.20	28.00	0.50	19.30
	75	13.20	0.20	28.00	0.50	19.22
	100	12.95	0.15	28.20	0.50	19.11
HFC-143a in dry air CH <sub>3</sub> CF <sub>3</sub>	5	7.50	0.10	17.60	0.40	11.49
	20	7.40	0.20	17.90	0.50	11.51
	35	7.30	0.15	17.90	0.50	11.43
	50	7.25	0.15	17.80	0.40	11.36
	75	7.12	0.15	18.30	0.50	11.41
	100	7.00	0.10	18.40	0.40	11.35
HFO-1234yf in dry air CH <sub>2</sub> =CF <sub>2</sub> CF <sub>3</sub>	5	7.05	0.15	11.70	0.50	9.08
	20	6.85	0.05	12.00	0.40	9.07
	35	6.70	0.20	12.00	0.60	8.97
	50	6.50	0.15	12.20	0.50	8.91
	75	6.10	0.10	12.50	0.50	8.73
	100	5.80	0.10	12.70	0.50	8.58
HFO-1234yf in moist air CH <sub>2</sub> =CF <sub>2</sub> CF <sub>3</sub>	20	5.45	0.05	13.30	0.50	8.51
	35	5.40	0.15	13.50	0.50	8.54
	50	5.35	0.10	13.70	0.50	8.56
	75	5.20	0.10	13.90	0.50	8.50
	100	5.10	0.10	14.10	0.50	8.48
HFO-1234ze in moist air CHF=CHCF <sub>3</sub>	20	6.25	0.2	12.4	0.4	8.80
	35	5.95	0.15	12.7	0.4	8.69
	50	5.85	0.15	13.3	0.5	8.82
	75	5.65	0.15	13.5	0.5	8.73
	100	5.35	0.1	13.8	0.5	8.59

5 °C does not reach 50% corrected for 23 °C, the measurements in the moist air were done only for a temperature range of 20–100 °C. The result of the measurements is summarized in Table 1. The numbers attached to the observed values are uncertainties estimated considering the stability and the gradient of the plot of maximum flame propagation angle versus fuel concentration in air.

As for the temperature dependences of the flammability limits of ammonia, HFC-32, and HFC-143a, the values of both upper and lower flammability limits have been found to change moderately

and almost linearly to temperature. As the temperature is raised the lower flammability limits shift to lower concentrations and the upper limits to higher concentrations. The linear regression analysis was made for each of the lower and upper flammability limits of these compounds. The result of the analysis is summarized in Table 2.

In a previous paper, we have found that in general the temperature dependence of lower flammability limits can be explained by a limiting flame temperature concept (White's rule) [10]. According to this rule, the lower flammability limit *L* at

**Table 2**  
Temperature dependence of flammability limits of several 2L compounds. Observed and predicted values.

Compound	Temperature (°C)	Regression analysis of observed values				Predicted coefficient (vol%/°C)	
		Intercept at 0 °C (vol%)		Coefficient (vol%/°C)		Pred	Obs/pred
(a) LFL							
Ammonia	5–100	15.63	±0.08	−0.0086	±0.0014	−0.0095	0.90
HFC-32	5–100	13.68	±0.04	−0.0070	±0.0007	−0.0064	1.09
HFC-143a	5–100	7.51	±0.01	−0.0051	±0.0002	−0.0038	1.36
HFO-1234yf (dry)	5–100	7.13	±0.02	−0.0133	±0.0004	−0.0029	4.57
HFO-1234yf (moist)	20–100	5.55	±0.02	−0.0045	±0.0003	−0.0028	1.61
HFO-1234ze (moist)	20–100	6.39	±0.06	−0.0104	±0.001	−0.0029	3.63
(b) UFL							
Ammonia	5–100	29.50	±0.11	0.0208	±0.0019	0.0189	1.10
HFC-32	5–100	27.40	±0.18	0.0091	±0.0032	0.0132	0.69
HFC-143a	5–100	17.60	±0.1	0.0080	±0.0017	0.0093	0.86
HFO-1234yf (dry)	5–100	11.70	±0.05	0.0102	±0.0008	0.0052	1.95
HFO-1234yf (moist)	20–100	13.15	±0.05	0.0098	±0.0008	0.0070	1.40
HFO-1234ze (moist)	20–100	12.17	±0.18	0.0174	±0.0029	0.0061	2.85

**Table 3**

Thermo-chemical data used to obtain the predicted values of temperature coefficients of flammability limits in Table 2 and the values of adiabatic flame temperatures in Figs. 11 and 12.

Compounds	Chemical formula	Heat of formation (kJ/mol)	Heat of combustion <sup>c</sup> (kJ/mol)	Heat capacity (J/(K mol))	Note
Nitrogen	N <sub>2</sub>	0.0	–	29.13	a
Oxygen	O <sub>2</sub>	0.0	–	29.36	a
Air	0.79N <sub>2</sub> + 0.21O <sub>2</sub>	0.0	–	29.17	–
Carbon dioxide	CO <sub>2</sub>	–393.5	–	37.11	a
Water (gas)	H <sub>2</sub> O	–241.8	–	33.58	a
Hydrogen fluoride	HF	–271.1	–	29.13	a
Carbonyl fluoride	F <sub>2</sub> CO	–634.7	–	46.82	a
Ammonia	NH <sub>3</sub>	–46.1	317	35.06	a
HFC-32	CH <sub>2</sub> F <sub>2</sub>	–446.9	489	42.89	a
HFC-143a	CH <sub>3</sub> CF <sub>3</sub>	–736.4	864	78.20	a
HFO-1234yf	CH <sub>2</sub> =CF CF <sub>3</sub>	–799.3	1165 (in dry air)	100.55	b
–	–	–	1224 (in moist air)	–	b
HFO-1234ze	CHF=CHCF <sub>3</sub>	–803.6	1160 (in dry air)	99.62	b
–	–	–	1220 (in moist air)	–	b

<sup>a</sup> Ref. [12].

<sup>b</sup> Present work. The values of heat of formation were obtained by AAC-G2 method [13].

<sup>c</sup> The values of heat of combustion were calculated from the heat of formation.

temperature  $t$  °C is expressed by the following equation [8].

$$L = L_{25} - \frac{100C_{p,L}}{Q}(t - 25) = L_{25} \left\{ 1 - \frac{100C_{p,L}}{L_{25} \cdot Q}(t - 25) \right\} \quad (1)$$

Here,  $L_{25}$  is the lower flammability limits (vol%) at 25 °C,  $C_{p,L}$  is the heat capacity of unburnt gas at lower flammability limit at 25 °C, and  $Q$  is the molar heat of combustion of the fuel gas.  $C_{p,L}$  and  $Q$  can be assumed to be constant in the present temperature range of 5–100 °C. The predicted values of temperature coefficient of the lower flammability limits of these compounds in Table 2 were obtained based on this equation, where the thermo-chemical data necessary for the calculation were obtained from the literature and the values are listed in Table 3. As shown in Table 2, agreement between the observed and predicted values of temperature coefficient is good. Figs. 2–4 show visual comparison of the predicted values with the observed ones, where open circles show the observed values and solid line shows the predicted values using Eq. (1).

As for the upper flammability limit region, a similar reasoning as for the lower limit region cannot be used since the heat of combustion per mole of fuel gas apparently decreases if the fuel concentration is increased. Instead, based on the assumption that the geometric mean  $G$  of both the upper and lower flammability limits of a compound is constant irrespective of temperature, the following equation is obtained for the temperature dependence of

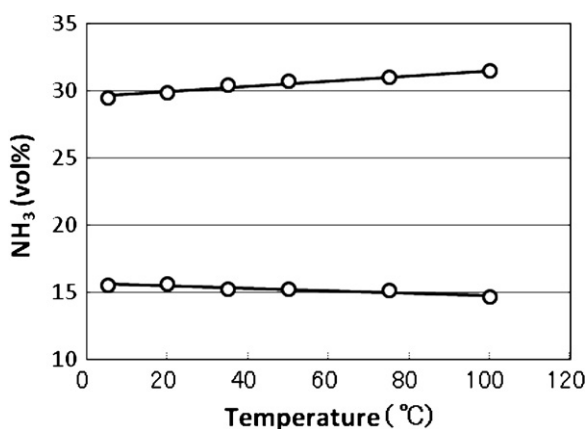
upper flammability limit  $U$  [8].

$$U = U_{25} \left\{ 1 + \frac{100C_{p,L}}{L_{25} \cdot Q}(t - 25) \right\} \quad (2)$$

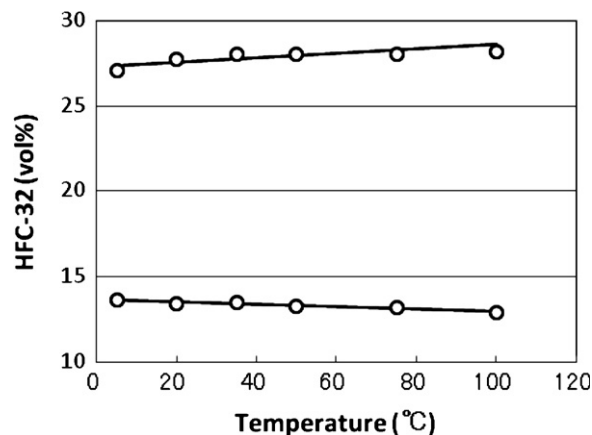
The predicted values of temperature coefficients for the upper flammability limits in Table 2 were obtained using this equation. In Figs. 2–4, the predicted values are visually compared with the observed ones, where open circles show the observed values and solid lines show the predicted values. Agreement between the observed and predicted values of upper flammability limits is also reasonably good.

On the other hand, the temperature dependences of the flammability limits of HFO-1234yf and HFO-1234ze are quite different from the respective predictions. In particular, the observed values of temperature coefficients for HFO-1234yf in dry air and those for HFO-1234ze in moist air are much larger than the respective predicted values, though the result for the HFO-1234yf in moist air is not so different from the prediction (see Figs. 5–7).

The combustion characteristics of HFO-1234yf and HFO-1234ze compared to the other three compounds are apparent in their extremely slow burning velocities. The slow burning velocity means that the burning reactions are weak and the flame front may easily suffer from heat loss to the surrounding. It is quite possible that the relatively large heat loss to the surrounding may play a



**Fig. 2.** Temperature dependence of flammability limits for ammonia in dry air. White circles represent the observed values and solid lines are predictions by Eqs. (1) and (2).



**Fig. 3.** Temperature dependence of flammability limits for HFC-32 in dry air. White circles represent the observed values and solid lines are predictions by Eqs. (1) and (2).

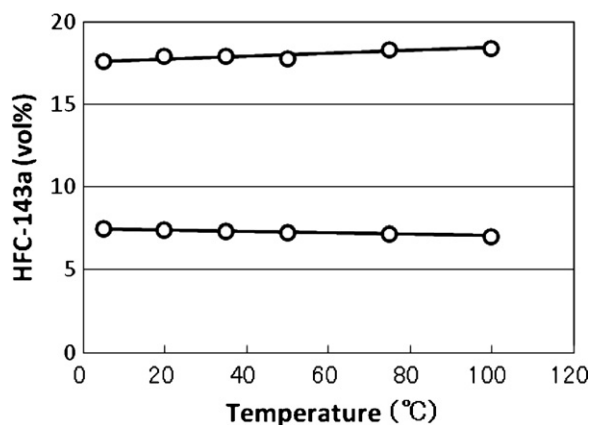


Fig. 4. Temperature dependence of flammability limits for HFC-143a in dry air. White circles represent the observed values and solid lines are predictions by Eqs. (1) and (2).

certain role to determine the temperature dependence of flammability limits. As the experimental temperature becomes low the heat loss may become large to narrow the flammable range, and vice versa. This effect may make the temperature coefficients of flammability limits larger than the values solely predicted from White's rule.

### 3.2. Effect of humidity on the flammability limits

Effect of humidity on the flammability limits has been measured for the same five compounds; i.e., ammonia, HFC-32, HFC-143a, HFO-1234yf, and HFO-1234ze. All measurements were done at 35 °C. As a result, it has been found that the flammability limits of ammonia, HFC-32, and HFC-143a remain almost constant irrespectively of the humidity condition (see Fig. 8). The humidity effect is small on these compounds. On the other hand, the flammability limits of both HFO-1234yf and HFO-1234ze have been found to be quite sensitive to the humidity condition, which is shown in Figs. 9 and 10. This is indeed expected because the number of hydrogen atoms is smaller than fluorine atoms in the molecules of these compounds and the existence of water vapor in air is expected to enhance the heat of combustion to yield wider flammable ranges for higher humidity [3]. In particular HFO-1234ze becomes flammable if the humidity in air becomes larger than 10% corrected for 23 °C, though it is non-flammable when the humidity is 10% or lower.

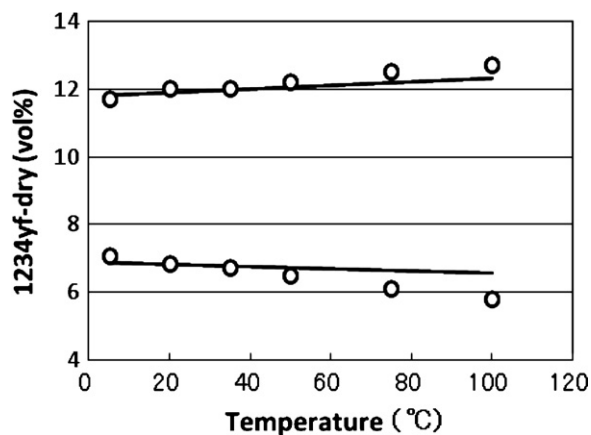


Fig. 5. Temperature dependence of flammability limits for HFO-1234yf in dry air. White circles represent the observed values and solid lines are predictions by Eqs. (1) and (2).

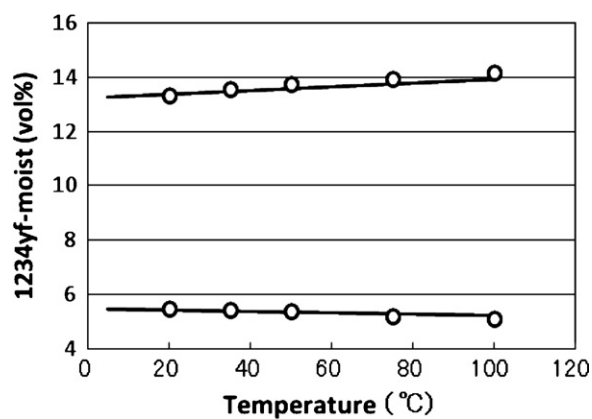


Fig. 6. Temperature dependence of flammability limits for HFO-1234yf in moist air, where white circles represent the observed values and solid lines are predictions by Eqs. (1) and (2).

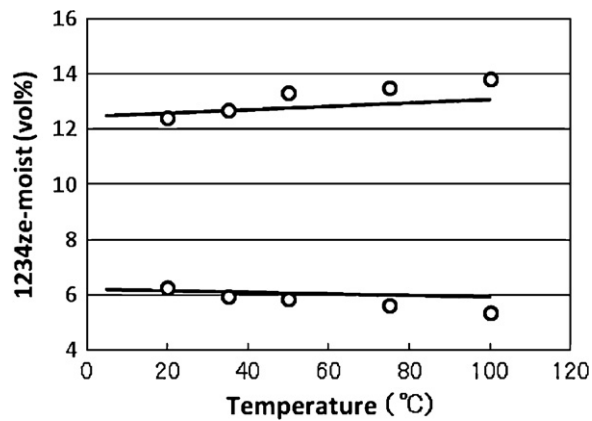


Fig. 7. Temperature dependence of flammability limits for HFC-1234ze in moist air. White circles represent the observed values and solid lines are predictions by Eqs. (1) and (2).

Considering the existence of nitrogen in air, the chemical equation for the complete combustion of these compounds in dry air can be written as follows.

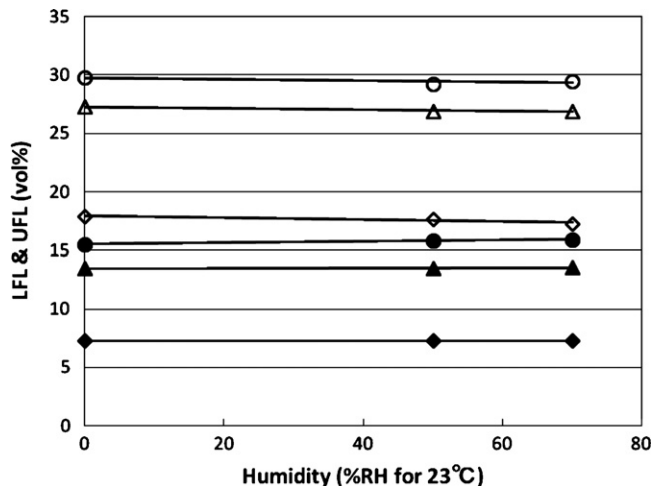
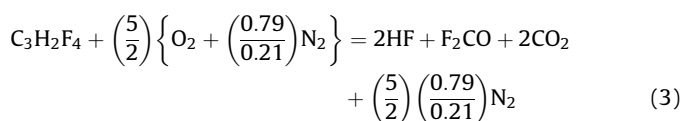


Fig. 8. Effect of humidity on the flammability limits of ammonia (○, ●), HFC-32 (△, ▲), and HFC-143a (◇, ◆). Humidity is the value corrected for 23 °C.

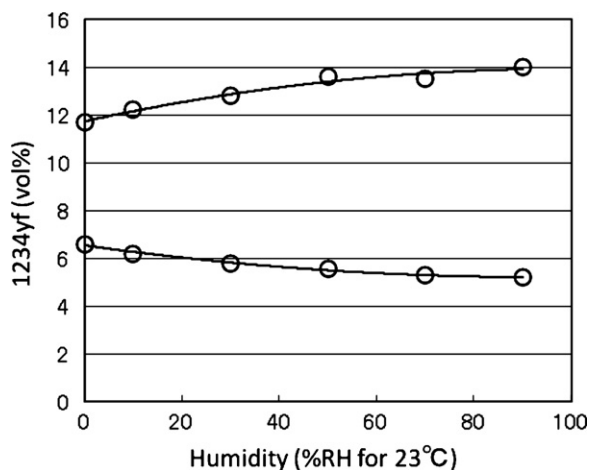
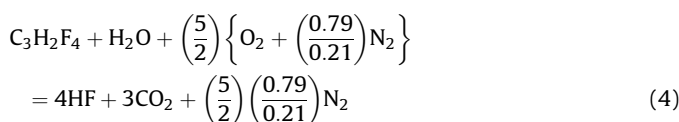


Fig. 9. Effect of humidity on the flammability limits of HFO-1234yf. Humidity is the value corrected for 23 °C.

Heat of reaction for this equation is 1165 kJ for HFO-1234yf and 1160 kJ for HFO-1234ze, and the total heat content for the compounds in the right side is 453.3 J/(mol K) at 298 K, where the thermo-chemical data in Table 3 were used. If there is enough water vapor, the combustion reaction may become as follows.



Then, the heat of reaction may become 1224 kJ for HFO-1234yf and 1220 kJ for HFO-1234ze, and the total heat content for the right side may become 501.8 J/(mol K) at 298 K. It is interesting that the relative increase of heat content at 298 K due to existence of water vapor is even larger than the increase of heat of reaction, in spite of the fact that the flammable range of these compounds are increased for higher humidity of air.

This result may indicate that the addition of water vapor changes the combustion reaction itself to lower the effective activation energy rather than the increase of heat of reaction. However, the more accurate discussion may require the knowledge of temperature dependence of heat content. In addition, certain portions of the molecules in the right side of these equations may be dissociated at high temperatures. In this connection, adiabatic flame temperatures were calculated using

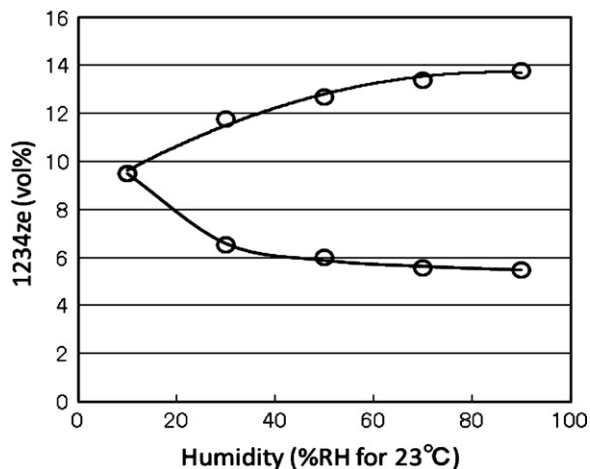


Fig. 10. Effect of humidity on the flammability limits of HFO-1234ze. Humidity is the value corrected for 23 °C.

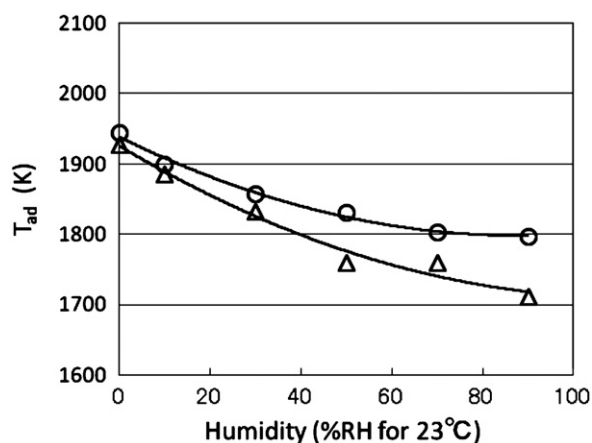


Fig. 11. Adiabatic flame temperatures at the flammability limits of HFO-1234yf as functions of humidity in air. Humidity is the value corrected for 23 °C.

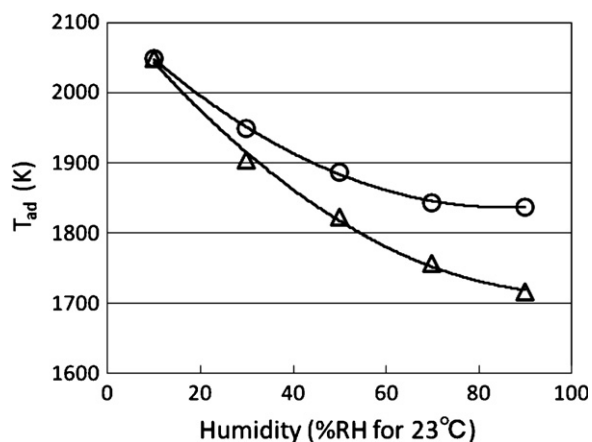


Fig. 12. Adiabatic flame temperature at the flammability limits of HFO-1234ze as functions of humidity in air. Humidity is the value corrected for 23 °C.

a computer code [14] for the flammability limits compositions of these compounds under various humidity conditions. The results are plotted against humidity in Figs. 11 and 12 for HFO-1234yf and HFO-1234ze, respectively. The adiabatic flame temperatures for the limiting flames markedly become lower as the humidity of air increases. In other words, the combustion reaction can be sustained under lower flame temperatures if water vapor is involved in the gas.

#### 4. Conclusion

The flammability limits were measured at various temperatures between 5 and 100 °C for ammonia, HFC-32, HFC-143a, HFO-1234yf, and HFO-1234ze. As a result, the linear temperature dependence of flammability limits has been confirmed for ammonia, HFC-32, and HFC-143a. For these compounds, the temperature dependence can adequately be predicted using a limiting flame temperature concept (White's rule) [10]. On the other hand, for compounds of HFO-1234yf and HFO-1234ze, the changes of flammability limits due to temperature changes are much larger than what are obtained from the limiting flame temperature concept. It seems to be that for compounds whose burning velocity is extremely small the heat loss from the flame front to the surrounding begins to play an important role to determine the temperature dependence of flammable limits. On the other hand, humidity does not affect much the flammability

limits of ammonia, HFC-32, and HFC-143a. However, the flammability limits of HFO-1234yf and HFO-1234ze does depend on humidity of air. In particular, HFO-1234ze which is non-flammable in dry air becomes flammable if humidity becomes larger than 10% corrected for 23 °C.

## References

- [1] American Society of Heating, Refrigerating and Air-conditioning Engineers, Number Designation and Safety Classification of Refrigerants. ANSI/ASHRAE Standard 34-2007, ASHRAE, Atlanta, GA, 2007.
- [2] ISO 817, Refrigerants: Designation and Safety Classification, Draft for Public Comment, March 2010.
- [3] S. Kondo, Y. Urano, K. Takizawa, A. Takahashi, K. Tokuhashi, A. Sekiya, *Fire Safety Journal* 41 (2006) 46–56.
- [4] H.F. Coward, G.W. Jones, *US Bureau of Mines Bulletin* 503 (1952).
- [5] A. Takahashi, Y. Urano, K. Tokuhashi, S. Kondo, *Journal of Hazardous Materials A105* (2003) 27–37.
- [6] S. Kondo, Y. Urano, A. Takahashi, K. Tokuhashi, *Combustion Science and Technology* 145 (1999) 1–15.
- [7] A. Takahashi, Y. Urano, K. Tokuhashi, H. Nagai, M. Kaise, S. Kondo, *Journal of Loss Prevention in the Process Industries* 11 (1998) 353–360.
- [8] S. Kondo, K. Takizawa, A. Takahashi, K. Tokuhashi, *Journal of Hazardous Materials* 187 (2011) 585–590.
- [9] S. Kondo, A. Takahashi, K. Takizawa, K. Tokuhashi, *Fire Safety Journal* 46 (2011) 289–293.
- [10] A.G. White, *Journal of the Chemical Society* 127 (1925) 672–684.
- [11] American Society of Testing and Materials, Standard Test Method for Concentration Limits of Flammability of Chemicals. Designation: E681-04, West Conshohocken, 2004.
- [12] D.D. Wagman, W.H. Evans, V.B. Parker, R.H. Shumm, I. Halow, S.M. Balley, K.L. Churney, R.L. Nuttall, The NBS tables of chemical thermodynamic properties. Selected values for inorganic and C1 and C2 organic substances in SI units, *Journal of Physical and Chemical Reference Data* 11 (Suppl. 2) (1982).
- [13] S. Kondo, A. Takahashi, K. Tokuhashi, *Journal of Hazardous Materials A94* (2002) 37–45.
- [14] S. Gordon, B.J. McBride, Computer program for calculation of complex chemical equilibrium compositions, rocket performance, incident and reflected shocks, and Chapman-Jouguet detonations, in: NASA SP-273, Washington, DC, 1971.