Environmental and Physicochemical Properties of Gaseous Dielectrics Alternatives to SF₆

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Received/Geliş: 25.05.2020 Accepted/Kabul: 07.07.2020

Abstract: Research on alternative dielectric gases to eliminate the disadvantages of SF₆, which is widely used in GIS and switching systems in the power system engineering, has been an important study topic in the literature for nearly 40 years. Because of environmental priorities defined by international agreements such as the Kyoto Protocol and Doha Amendment, the restrictions on the use of SF₆ make these studies an obligation. Although the number of alternative dielectric gases studied for this purpose is quite high, these gases can be classified under the titles of non-synthetics, hydrocarbons (HCs), fluorocarbons (FCs), hydrofluorocarbons (HFCs), fluoronitriles (FNs), fluoroketones (FKs) and other synthetic gases. In this study, the gases classified under these titles are compared using the dielectric constant relative to SF₆. Global Warming Potential (GWP), atmospheric lifetime, boiling point and toxicity parameters used in the comparison of dielectric gases. When compared with these parameters, non-synthetic air, CO₂ and N₂, C₂F₅CN from FNs, and C₃F₇O and C₄F₉O from FKs stand out among alternative gases to SF₆. These alternatives are used in some innovative power system industry applications and have a widespread use potential in the insulating gas industry instead of SF₆.

Keywords: Gaseous dielectrics, sulfur hexafluoride (SF₆), global warming potential, dielectric strength

SF₆ Alternatifleri Yalıtkan Gazların Çevresel ve Fizyokimyasal Özellikleri

Oz: Güç sistem mühendisliğinde GIS ve anahtarlama sistemlerinde yaygın olarak kullanılan SF₆’nun dezavantajları nedeniyle alternatif yalıtkan gaz araştırma, yaklaşık 40 yıldır literatürde önemli araştırmada konuludur. Kyoto Protokolü ve Doha Değişikliği gibi uluslararası anlaşmalarla tanımlanan çevresel düzensizlikler, yasağın bir zorunluluk haline gelmiştir. Alternatiflerdeki alternatif gazlarla ilgili çalışmaların sayısı, özellikle fizyokimyasal ve çevresel parametreler kullanılarak analiz edilmiştir. CO₂ ve N₂, C₂F₅CN, C₃F₇O ve C₄F₉O gibi alternatif gazlar, çevresel ve fizyokimyasal özellikler açısından önemlidir. Bu çalışmanın amacı, SF₆’ya alternatif gazların çevresel ve fizyokimyasal özelliklerini analiz etmek ve alternatif gazların yerine kullanılması yoluyla çevresel ve fizyokimyasal değerlendirilmesidir.

Anahtar Kelimeler: Gaz yalıtkanları, küükrt hezaflorür (SF₆), küükrt insma potansiyeli, yalıtkanlık kuvveti

How to cite this article
Duzkaya, H., Tezcan, S.S., Acartürk, A., Yilmaz, M., “Environmental and Physicochemical Properties of Gaseous Dielectrics Alternatives to SF₆”, El-Cezeri Journal of Science and Engineering, 2020, 7 (3); 1460-1470.

Bu makaleye atıf yapmak için
Duzkaya, H., Tezcan, S.S., Acartürk, A., Yilmaz, M., “SF₆ Alternatifleri Yalıtkan Gazların Çevresel ve Fizyokimyasal Özellikleri”, El-Cezeri Journal of Science and Engineering, 2020, 7(3), 1460-1470.
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1. Introduction

The distance between the points where electricity is produced and consumed and the regional energy demand that changes rapidly throughout the day make it an imperative to establish an integrated transmission and distribution system on a global scale [1]. Competitive design and production of the circuit components used during the transportation of the voltage increased by transformers in transmission and distribution systems, depending on the cost and size criteria, is an important research area in power systems [2-4].

Sulfur hexafluoride, SF$_6$ is non-toxic, odorless, nonflammable and chemically stable. In addition to its chemical stability, it is also an effective absorber in heat and light source energy emissions [5-7]. SF$_6$, which is an electronegative gas with high dielectric constant since the electron attachment cross section is larger than the total ionization cross section even in high electric fields, is widely used in power system transmission and distribution equipment since the 1950s [5]. Owing to these properties, the breakdown voltage is three times higher compared to air at the unit distance provided that the product of the pressure and electrode gap remains constant, approximately 89 kV/cm [8]. SF$_6$ gas is used in almost 80% of gas-insulated applications in transmission and distribution systems such as circuit breakers, disconnectors, busbars and transformers [9]. In addition to this extensive use in power systems, it also has a wide range of industrial uses such as laser and semiconductor technology, plasma physics, magnesium and aluminum casting [10-11]. With the use in the power system industry, the size of switching elements such as circuit breakers and sectionalizers is reduced, the areas required for substations are reduced and supply processes such as transportation and installation are simplified [12]. In addition to these advantages of SF$_6$, its major disadvantages can be listed as follows,

- Disruption of discharge characteristics for high pressure and wide electrode gaps in non-homogeneous electric field configurations [9],
- Partial liquefaction depending on the high pressure in cold climatic conditions [9],
- The occurrence of corrosive and toxic decomposition products as a result of partial discharge and breakdown mechanisms [13, 14],
- Since it is a synthetic gas, its relatively high cost [9], and
- As it is an important greenhouse gas, its use causes important environmental problems [15].

Global Warming Potential (GWP) value, which is one of the greenhouse gas indicators, is 23.500 times of CO$_2$ for 100-year period [16]. The use of SF$_6$, which has one of the highest GWP among the synthetic gases used for industrial purposes, is recommended to be limited to the countries that are parties to the United Nations Framework Convention on Climate Change (UNFCCC) with the 1997 Kyoto Protocol and the 2012 Doha Amendment to the Kyoto Protocol agreements [17, 18]. The atmospheric lifetime of SF$_6$ is about 3200 years, making these environmental effects more important [19, 20]. Despite these agreements that recommend restricting the use of SF$_6$, its proportion in the atmosphere continues to increase. While the rate in the atmosphere was 3.94 ppt (parts-per-trillion) in 1997 when the Kyoto Protocol was signed, this rate increased to 8.61 ppt in 2015 [15]. The concentration of SF$_6$ in the atmosphere has more than doubled in 20 years.

Considering these disadvantages, producing switching and substation equipment with alternative gases to SF$_6$ in the power system industry becomes an economic and environmental requirement [4]. Since alternative gases to SF$_6$ have been the subject of significant discussion in the literature for nearly forty years, the number of alternative gases is quite high. These alternative gases are examined in the study by classification in non-synthetics, hydrocarbons (HCs), fluorocarbons (FCs), hydrofluorocarbons (HFCs), fluoronitriles (FNs), fluoroketones (FKs), and other synthetics [19; 21, 22].
SF₆ and other gaseous dielectrics are used in the power system industry to meet economic, safety and size constraints and to minimize faults caused by electrical breakdowns, partial discharges, coronas etc. Within the scope of this study, gas insulator alternatives used in power system transmission and distribution systems, especially in switching equipment, are examined in detail in terms of their environmental and physicochemical properties. These properties examined during the evaluation of these alternatives are GWP and lifetime in terms of environmental effects, and dielectric strength, boiling point and toxicity in terms of their physicochemical properties.

2. Alternative Gaseous Dielectrics

2.1. Non-Synthetics

Stable molecules and noble gases in the atmosphere are often used as pure or gas mixtures in search of an alternative to SF₆ due to their almost no greenhouse effects, they can be used in cold climates without risk of liquefaction independent of pressure and low costs [23-25]. The relative dielectric coefficient of dry air, N₂, N₂O, CO₂, O₂, H₂, Ar, He and Ne gases, which are frequently used in the literature among non-synthetic gases, varies between 0.37-0.40, 0.34-0.43, 0.44-0.50, 0.33-0.37, 0.20-0.22, 0.04-0.10, 0.02-0.06 and 0.01-0.02 ranges, respectively, see Table 1. Although the dielectric strength of these gases is significantly less compared to SF₆, the prominent advantages of these non-synthetic alternatives are the lower GWP values, boiling temperatures, costs and non-toxicity except CO. In order to increase the dielectric strength of these alternatives, binary or ternary mixtures with different gases, especially SF₆, can be used [2, 7]. This feature can also be improved by applying a magnetic field in the perpendicular direction to the electric field that causes the breakdown [23, 26]. Dry air, N₂ and CO₂ insulating medium switching and Gas Isolated System (GIS) designs are used by important manufacturers in the industry as transmission and distribution system equipment [2, 4, 25, 27]. In applications where these gases are used in GIS and circuit breakers, important technical parameters such as rated voltage, rated normal current, short circuit breaking current and rated filling pressure range between 24-175 kV, 800-3150 A, 16-40 kA and 1.3-7.7 bar, respectively [4].

Table 1. Main properties of non-synthetic alternative gaseous

| Gaseous | Dielectric constant relative to SF₆ | GWP (Years) | Atmospheric Lifetime (Years) | Boiling point (⁰C) | Toxicity |
|---------|-----------------------------------|-------------|-----------------------------|-------------------|----------|
| SF₆     | 1.00                              | 23500 [16]  | 3200 [19, 20]               | -64.0 [19, 22]    | >50000 ppm for LC₅₀ 4h [20] |
| Air (Dry)| 0.37-0.4 [19, 25]                 | 0 [4, 26]   | ∞ [26]                      | -194.0 [4]        | Non-toxic [19] |
| N₂      | 0.34-0.43 [19, 22]                | 0 [4, 26]   | ∞ [26]                      | -196.0 [4, 19]    | Non-toxic [19, 27] |
| N₂O     | 0.50 [19]                        | 320 [19]    | 120 [26, 29]                | -89.0 [19, 27]    | Non-toxic [19] |
| CO₂     | 0.32-0.37 [19, 22]               | 1           | 30-95 [19]                  | -79.0 [19, 22]    | >300000 for LC₅₀ 4h [19] |
| CO      | 0.40 [19, 30]                     | 1-3 [19]    | 0.08-0.25 [31]              | -192.0 [27, 28]   | 1807 ppm for LC₅₀ 4h [4, 19] |
| O₂      | 0.33-0.37 [28]                   | 0.33 [30]   | 0 [4]                       | -182.0 [4]        | Hyperoxia [27] |
| H₂      | 0.20 [19]                        | 0.22 [28]   | 0 [4]                       | -253.0 [19, 27]   | Non-toxic [19, 27] |
| Ar      | 0.04-0.10 [19]                   | 0.07 [26]   | ∞ [26]                      | -186.0 [19, 27]   | Non-toxic [19, 27] |
| He      | 0.02-0.06 [19]                   | 0 [26]      | ∞ [26]                      | -269.0 [19]       | Non-toxic [19] |
| Ne      | 0.01-0.02 [19]                   | 0.006 [26]  | ∞ [26]                      | -246.0 [19, 27]   | Non-toxic [19, 27] |
2.2. Hydrocarbons (HCs)

Hydrocarbons, where carbon and hydrogen atoms combine with different geometrical sequences and the number of bonds, are a rich variety of organic compounds. When the literature on insulating gases is examined, it is seen that among the commonly used hydrocarbons are CH₄ and C₂H₂ [34, 35]. The relative dielectric coefficient of CH₄ relative to SF₆ is 0.43, its GWP is 23 times its CO₂ equivalent in a 100-year period, its atmospheric lifetime is about 10 years and its boiling point is -163.0 °C, see Table 2. Through these features, it can be preferred for high pressure applications in cold climates, and it is known to be more suitable than N₂ and Ar for design in electron-beam controlled on/off switches [41]. Although the relative dielectric strength of C₂H₂ is almost at the same level as CH₄, the high boiling point compared to CH₄ is a disadvantage, see Table 2. There is diffuse discharge switching applications using ternary gas mixtures including C₂H₂ [35]. It is an advantage in terms of power system applications that these gases and possible decomposition products are non-toxic.

Table 2. Main properties of HCs, FCs, and HFCs

| Gaseous | Dielectric constant relative to SF₆ | GWP | Atmospheric Lifetime (Years) | Boiling point (°C) | Toxicity |
|---------|------------------------------------|-----|-----------------------------|-------------------|----------|
| Hydrocarbons (HCs) | | | | | |
| CH₄ | 0.43 [27, 28] | 23 [31] | 8.4-12 [31] | -163.0 [28] | Non-toxic [36] |
| C₂H₂ | 0.42 [27] | | -84.8 [27] | | Non-toxic [36] |
| CF₄ | 0.42 [28] | 6300 [37, 38] | 50000 [19, 22] | -128.0 [4, 19] | 40000 ppm for LC₅₀ 4h [37] |
| C₂F₄ | 0.50 [21] | 0 [20] | 1.9 days [20] | -76.3 [20] | 40000 ppm for LC₅₀ 4h [20] |
| C₂F₆ | 0.78-0.79 [20, 38] | 12200 [4, 22] | 10000 [19, 22] | -78.0 [19, 38] | Non-toxic [19] |
| C₃F₆ | 0.90-1.00 [4] | 100 [4] | <10 [20, 38] | -28.0 [20, 38] | 750 ppm for LC₅₀ 4h [20, 37] |
| C₃F₈ | 0.97-1.12 [37] | 8830 [22, 39] | 2600 [19, 39] | -37.0 [28, 38] | 750 ppm for LC₅₀ 4h [20] |
| C₄F₆ | 1.71 [30] | | -25.4 [27] | -25.0 [40] | 82 ppm for LC₅₀ 4h [4, 19] |
| C₄F₈ | 1.32 [30] | 8700 [19] | 3200 [31] | -16.0/22.0 [21] | 0.5 ppm for LC₅₀ 4h [4, 19] |
| C₅F₁₀ | 1.25-1.31 [38] | 8860 [4] | 2600 [31, 38] | -2.0 [28, 38] | |
| C₆F₁₂ | 1.75 [30, 40] | 8900 [31] | 4100 [31] | 28.0 [38] | |
| C₇F₁₄ | 2.26 [40] | 9000 [31] | 3200 [29, 31] | 52.0 [40] | |
| C₄F₈₋₆C₂F₄ | 1.25-1.31 [26] | 8700 [19, 22] | 3200 [19, 22] | -6.0 [19, 20] | Non-toxic [19] |
| n-C₅F₁₀ | 1.32-1.36 [26] | 7000 [26] | 2600 [26] | -2.0 [26] | |

Fluorocarbons (FCs)

| Hydrofluorocarbons (HFCs) | | | | | |
| CH₃F | 0.28 [29] | 97 [31] | 2.6 [31] | -74.0 [28] | Non-toxic [36] |
| CH₂F₂ | 0.27 [28] | 0.50 [21] | 550 [31] | 5 [31] | -52.0 [28] | 520000 ppm for LC₅₀ 4h [36] |
| CHF₃ | 0.38 [38] | 11700 [26] | 264 [26] | -83.0 [27, 28] | 663000 ppm for LC₅₀ 4h [36] |
2.3. Fluorocarbons (FCs)

Fluorocarbons are highly stable due to the carbon-fluorine bond, which is considered one of the strongest bonds in organic chemistry. Due to the partial ionic character of the fluorine(s), the molecules on which these bonds are formed also have an electronegative property. As the number of carbons that forms the body of the molecule increases in fluorocarbons, the stability of the molecule increases with the effect of fluorine atoms. In other words, fluorocarbons are more stable than other organic compounds such as hydrocarbons [19]. Because of these properties, fluorocarbons are an important alternative in gas insulating applications in the power system industry.

Prominent alternatives among FCs compounds in the literature are CF₄, C₂F₆, C₃F₆, C₄F₆, C₄F₈, C₄F₁₀, C₂F₁₂, C₆F₁₄, n-C₂F₁₀, and c-C₄F₈, see Table 2. The dielectric constant of these gases relative to SF₆ tends to increase with the increase in the number of carbon and fluorine in its compound. This is one of the consequences of increased stability due to the growth of the molecule.

While this relative dielectric coefficient is 0.42 for CF₄ [28], it increases to 2.26 for C₆F₁₄ [40]. One of the characteristic features of fluorocarbons is that they are among the gases proposed to be restricted by the Kyoto Protocol and Doha Amendment [17, 18]. Fluorocarbons other than C₂F₄ and C₄F₆, which are alternatives to dielectric gas, have the potential to cause significant environmental problems with their high GWP value and long atmospheric lifetimes, such as SF₆, see Table 2. Another negative feature of these gases is the high boiling point, depending on the molecular size. Boiling points of fluorocarbons such as C₃F₆ and C₃F₈ with dielectric strength close to SF₆ are -28 °C and -37 °C, respectively. High boiling points make these alternatives inefficient in high pressure and/or cold climate applications.

LC₅₀, a unit of toxicity, indicates that half of all living things exposed to a gas over a certain concentration and time interval are killed. When FCs are examined for toxicity, C₃F₆, C₃F₈, C₄F₆ and C₄F₈ are toxic and their use in high amounts in industrial applications should be avoided [19, 20]. FCs are used in GIS and switching equipment in double or triple gas mixtures [42]. In these mixtures, gases such as SF₆, N₂ and Ar are used in different concentrations and their breakdown characteristics are examined in different electrical discharges [43]. The ratio of FCs in these gas mixtures ranges from 20% to 80% [44-45]. These rates are determined by the environmental and electrical limitations of power system equipment application.

2.4. Hydrofluorocarbons (HFCs)

Hydrofluorocarbons, which contain carbon, hydrogen and fluorine atoms in their compounds, are recommended to limit their use for industrial purposes due to their greenhouse gas effects, just like SF₆ and FCs [17, 18]. Although there are studies on different molecular structures such as CHF₃, CH₂F₂, CH₂F, C₂H₂F₃, C₂H₂F₄ and C₄H₂F₆, the HFCs frequently recommended as an alternative to SF₆ are CHF₃, CH₂F₂, and CH₃F, see Table 2 [21, 28].

The stability and dielectric constants of HFCs increase in relation to the increase in the number of carbon and fluorine in the molecular structure, similar to FCs [28, 46]. In the literature, CHF₃ has been frequently studied due to its nontoxicity, low boiling point, relatively low cost, and high electronegativity from fluorine atoms [47]. However, this gas cannot meet environmental priorities due to its high GWP [26].

2.5. Fluoronitriles (FNs)

The low dielectric coefficient of non-synthetic gases relative to SF₆ and the limitation of the use of FCs and HFCs due to their high GWP values make FNs and FKs prominent in the search for
alternative dielectric gases. Due to their high dielectric strengths and low GWPs, these gases have recently become an important alternative in high power transmission and distribution system equipment.

FNs contain carbon, fluorine and nitrogen atoms. Unlike FCs, the nitrogen atom makes a double or triple bond with a carbon in the molecule. FNs commonly used in alternative dielectric gas studies include CF₃CN, C₂F₅CN, C₃F₇N, and C₂F₇CN (C₂F₇N) [37, 46]. The relative dielectric strengths of these alternatives increase due to the increase in the number of carbon and fluorine in the structure and vary between 1.46-2.70, see Table 3. Despite these high dielectric strengths and relatively low GWPs compared to SF₆, it is an important disadvantage that FNs other than C₂F₇CN are acute toxic [19, 37]. Considering the dimensions of power system equipment, it is an obligation to take precautions for human and environmental health in the use of these alternatives.

**Table 3. Main properties of FNs and FKs**

| Gaseous | Dielectric constant relative to SF₆ | GWP | Atmospheric Lifetime (Years) | Boiling point (°C) | Toxicity |
|---------|-----------------------------------|-----|-------------------------------|--------------------|----------|
| Fluoronitriles (FNs) | | | | | |
| CF₃CN | 1.46 [37, 46] | 1.46 [37, 46] | -62.0 [19, 40] | 360 ppm for LC₅₀ 4h [37] |
| C₂F₅CN | 1.80-1.85 [19] | 2.00 [28] | -32.0 [19, 40] | High [19] |
| C₂F₇N | 2.20-2.35 [19] | 2.20 [4] | -2.0 [19] | Toxic [19] |
| C₂F₇CN | 2.20 [4] | 2.74 [30, 46] | 2100 [46] | 22 [22] | -4.7 [46] | 10000-15000 ppm for LC₅₀ 4h [19, 37] |
| Fluoroketones (FKs) | | | | | |
| C₂F₄O | 1.60 [4] | 4100 [4] | 0 [4] | 200 ppm for LC₅₀ [19] |
| C₂F₁₀O | 2.00 [4, 30] | 1 [19, 22] | 0.044 [22] | 24.0 [19] | Non-toxic [19] |
| C₄F₁₂O | 2.70 [22, 38] | 1 [22, 38] | 0.014 [38] | 49.0 [22, 38] | Non-toxic [19] |

Alternative dielectric gas studies are concentrated on the C₂F₇CN molecule, which is nontoxic among nitriles and has a relative dielectric strength in the range of 2.20-2.70 [4, 48]. However, due to the high boiling point of C₂F₇CN such as -4.7 °C, there is a risk of liquefaction in outdoor applications. In order to overcome this problem, binary mixtures with alternative non-synthetic dry air, N₂ and CO₂ gases are recommended [4, 49]. Due to partial discharges, arcs and breakdowns naturally occurring in power system equipment, decomposition products emerge depending on the molecular structure of the insulating gas. Decomposition products formed by the binary mixtures of C₂F₇CN with different gases and the effects of impurities such as H₂O and O₂, which are inevitably present in the environment, have been studied in detail recently [46, 48]. These main stable decomposition products include FKs such as C₂F₅CN, CF₃CN, and CH₂FCN, FCs such as CF₄, C₂F₆, C₃F₇, and C₄F₁₀, and HFCs such as CHF₃ [46, 48]. The electronegativity of these decomposition products is close to C₂F₇CN and therefore the insulation performance is not damaged. However, decomposition products such as COF₂, C₂F₇H, and HF are toxic and/or corrosive [46]. These decomposition products threaten the internal structure of the equipment and the safety of maintenance personnel, so they should be detected during service periods.

2.6. Fluoroketones (FKs)

Fluoroketones, which have similar properties with FNs, have an oxygen molecule in the molecular structure instead of a nitrogen molecule. Among the fluoroketones, C₄F₉O is more disadvantageous than C₂F₁₀O and C₆F₁₂O due to its 4100 equivalent CO₂ GWP value and highly toxic, see Table 3. The main disadvantages of C₂F₁₀O and C₆F₁₂O, which have optimum data on almost all properties
in the search for alternative dielectric gas, are the boiling points of 24.0 °C and 49.0 °C, respectively. This disadvantage is tried to be eliminated by mixing these gases with different gases and not using them in high pressure equipment [30, 50]. After the FKs are subjected to electrical discharges, decomposition products consisting of fluorocarbons are formed, such as CF₄, C₂F₆, C₃F₈, C₄F₁₀ and C₅F₁₂ [38]. These products can be varied depending on the buffer gases and the concentration of impurities in the medium. These by-products may have undesirable properties in terms of GWP and toxicity parameters.

2.7. Other Synthetics

Other synthetic alternatives include chlorocarbon, bromocarbon and iodide-carbons molecules using chlorine, bromine, and iodine from 7A elements instead of fluorine.

The chlorocarbons commonly used in the literature are CF₃Cl, C₂H₃Cl, CH₂FCl, CHF₂Cl, C₂F₃Cl, C₂F₅Cl, CF₂Cl₂, CHFCl₂, C₂HF₂Cl₂, C₂F₆Cl₂, C₃F₇Cl₃, CHCl₃, CFCI₃, and CCl₄. The relative dielectric coefficient of these molecules ranges from 0.30-1.80 [28, 40, 51]. These molecules generally have undesirable properties in terms of environment and human health, such as high GWPs and toxicity [36]. However, some molecular structures, such as CF₃CHCl₂, are proposed as an alternative in switching designs [51].

Bromocarbons studied in the gas dielectric literature are CH₃Br and CF₃Br. The relative dielectric coefficient of these gases is only 0.45 and 0.76, respectively [28, 30]. The boiling point of CH₃Br at 2.7 °C and the GWP value of CF₃Br at 5600 equivalents CO₂ restrict their use in the dielectric industry [27, 29].

c-CIF₃, CF₃I and CH₃I are important iodide-carbons. The relative dielectric coefficients of these molecules are 0.47-0.58, 1.27 and 1.15, respectively [19, 27]. Although CF₃I is the most widely used literature among these gases, its acute toxic feature prevents its use for industrial purposes. In order to reduce this toxic effect of CF₃I, double and triple gas mixtures with gases such as N₂, CO₂, CF₄ and Ar have been proposed in different studies [52-53]. In these studies, the ratio of CF₃I in these mixtures is kept in amounts not exceeding 10%. Despite this low rate, it significantly increases the dielectric strength of the mixture.

3. Conclusions and Perspectives

This study, in which alternative dielectric gases are examined in different parameters, focuses on the selection of the most suitable gas or gases in terms of environmental and physicochemical properties that can be used instead of SF₆ in the power system industry.

The environmental effect that causes the use of SF₆ to be limited is evaluated by examining the GWP and atmospheric lifetime properties of alternative gases, see Figure 1. In terms of these features, a better alternative gas is expected to have a low GWP and long atmospheric lifetime due to the nature of power system equipment. When Figure 1 is examined in terms of these requirements, it can be seen that non-synthetics, CH₄, C₃F₇CN and FKs may be alternative, and FCs and HFCs are not environmentally suitable due to their high GWP value. In terms of toxicity, another parameter in terms of human and environmental health, FCs, HFCs and FNs other than C₃F₇CN pose a threat and are not recommended for large-scale industrial use.

The dielectric characteristics of these alternatives are examined in terms of dielectric constants relative to SF₆ and boiling points, see Figure 2. It is desired that the dielectric coefficient of the gas dielectric material should be as big as possible due to reasons such as reduction in size, security and
cost in power system equipment. On the other hand, boiling point should be as low as possible to avoid liquefaction since these equipment operate outdoors under cold climate conditions.

![Figure 1](image1.png)

**Figure 1.** GWP and atmospheric lifetimes of alternatives to SF$_6$

According to Figure 2, HFCs, FNs and FKs stand out in terms of dielectric strength. However, the boiling points of these gases are quite high, and they are present as liquid in cold climate working conditions. To eliminate this disadvantage, these gases are mixed with non-synthetic gases such as air, N$_2$ and CO$_2$, where boiling points are considerably low.

![Figure 2](image2.png)

**Figure 2.** Dielectric constants relative to SF$_6$ and boiling points of alternatives

Among the gases that meet the requirements in terms of both environmental and electrical properties, non-synthetics, C$_3$F$_7$CN and FKs stand out. These gases are recently used by the leading companies of the power system industry sector in GIS and Circuit Breaker (CB) applications [4, 33, 49]. Non-synthetic gases in medium voltage equipment are preferred with high pressure
applications to increase the insulating level of the system [4]. In applications where C$_3$F$_7$CN and fluoroketones are used, double or triple gas mixtures of non-synthetic gases such as air, N$_2$, CO$_2$, and O$_2$ are used to prevent liquefaction in the gas dielectric environment [49, 54]. These application examples and scientific studies, which have become widespread recently, show that a new era has started in the SF$_6$ alternative gas industry and applications will continue to increase.

Acknowledgments

This work is supported by Dicle Electricity Distribution Company, under SF6-Free Gas Isolated Circuit Breaker Research Project, which is supervised by the Energy Market Regulatory Authority. This work is also supported by the BSTB-062883 R&D project between Gazi Technology Inc. and Dicle Dicle Electricity Distribution Company.

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