Computer Applications in Electrical Engineering
Vol. 12 *2014*

Sulphur hexafluoride as a high-voltage insulation – selected problems

Władysław Opydo, Zdzisław Juszczyk, Jerzy Stawicki
Poznań University of Technology
60-965 Poznań, ul. Piotrowo 3a, e-mail: Wladyslaw.Opydo@put.poznan.pl

Justyna Opydo-Szymaczek
Poznań University of Medical Science
Department of Pediatric Dentistry
60-812 Poznań, ul. Bukowska 50, e-mail: jopydo@ump.edu.pl

The paper presents some selected properties of sulphur hexafluoride (SF_6) a medium used for high-voltage insulation and electric arc suppression purposes. The results are presented of the studies aimed at determining the effect of the electrode material type, temperature, gas density and interelectrode gap on the SF_6 electric strength. The considered systems had both flat electrodes or one flat and the other (cathode) having the form of a rod of 3 mm or 30 mm diameter, ended with a hemisphere. The electrodes have been made of stainless steel or aluminum. The results were mathematically processed with the use of the Statistica [11] computer software.

It was found that SF_6 temperature changes in the range from 243 K to 293 K with constant SF_6 density did not cause variation of electric strength of the gas. Moreover, the effect of the electrode material type on electric strength of SF_6 was observed only in the systems distinguished by macroscopic uniformity of the electric field and in case of the gas density exceeding 15 kg/m^3, corresponding to SF_6 pressure amounting about to $2.5 \cdot 10^5$ Pa in the temperature 293 K. Physical interpretation of the study results is proposed and formulated.

Additionally, the paper discusses the hazards arising from the use of SF_6 for the health of the persons operating the equipment and for the environment.

KEYWORDS: high-voltage insulation, electric strength, sulphur hexafluoride (SF_6), toxic byproducts

1. Introduction

Sulphur hexafluoride (SF_6) is more and more commonly used as a medium assisting the electric arc suppression in the high-voltage circuit-breakers and as a high-voltage insulator in electrostatic generators, X-ray equipment, capacitors of measuring devices in the high and extra high voltage systems, electric power buses, shielded high-voltage switchboards [9] and transformers (inflammable and inexplosives). It is an electro-negative gas, that leads to considerably higher SF_6 electric strength as compared to that of the air and other gases. Investigation of electric properties of SF_6 electric insulation systems has shown that the type of electrode material of the system affects the SF_6 electric strength, e.g. [2, 10, 12, 13, 15]. It was found that the set of the electrode materials arranged with respect to growing value of the breakdown voltage in the SF_6 − including systems is equal to the one arranged with respect to growing values of the electron work function from the electrode materials of these systems [10, 15]. This gives evidence that breakdown initiation in an SF_6 system may be affected by field emission of electrons from the electrode of negative polarity – the cathode. The electron field emission presumably assists the classical mechanisms of breakdown initiation in the systems of Townsend mechanism or a streamer-type of the channel mechanism, according to the value of the product of pressure and interelectrode gap (p·d). In the authors' opinion the problem of the effect of field emission on the mechanism of breakdown initiation in SF_6 is not yet fully explained. Therefore, the present paper presents the study dealing with these problems. The intensity of electron field emission, apart from the electric field intensity in the vicinity of the electron emitting surface, depends also on the value of electron work function from the material of the emitting surface and on the surface temperature. Therefore, the influence of the following factors on the electric strength of SF_6 subject to direct voltage was investigated: the type of electrode material, temperature, gas pressure, interelectrode gap and the degree of nonuniformity of the macroscopic electric field near the cathode.

The meaning of SF_6 as a high-voltage insulating material and electric arc suppressor is already well established. Nevertheless, its use in the equipment gives rise to a certain hazard for the health of the people operating and repairing these devices. Another problem arises from the SF_6 effect on the environment. Therefore, the paper presents main problems resulting from the use of SF_6 for human health and the environment.

2. Description of the study stand and investigation method

The study was performed with the use of a cylindrical steel chamber, provided with double walls. The flux of methyl alcohol between the chamber walls, cooled in a cooler, allowed for cooling the SF_6 and the system of electrodes. Temperatures of the gas and electrodes were measured with the use of thermocouples connected to the recording voltmeters. Temperature 0ºC maintained in the mixture of distilled water and ice was assumed as a reference temperature level.

The SF_6 electric strength was investigated in the systems provided with both flat electrodes and the systems with one flat and the other one in the form of a rod with a hemispherical end. The flat electrodes had a form of a disk of 125 mm diameter, with their edges rounded according to the Rogowski`s formula.

On the other hand, the rod electrodes had 3 mm or 30 mm diameters. The electrodes were made of stainless steel or aluminum.

Before putting the electrodes into the chamber they were carefully ground and polished up to mirror finish. Afterwards, they were washed in an ultrasonic cleaner with acetone, distilled water, and ethyl alcohol. Structure of the chamber allowed smooth adjustment and measurement of the interelectrode gap.

Before filling the chamber with SF_6, it was emptied with a rotary oil vacuum pump down to the pressure about 1 Pa. Then SF_6 was introduced to the chamber through a column with silica gel.

The insulation system subject to the tests was then connected to a direct high-voltage source by a high-voltage cable, the capacitance of which, inclusive of the source internal capacitance, amounted to 1230 pF.

During the tests conducted with nonuniform electric field the rod-shaped electrode was connected to negative terminal of the high-voltage source.

During the measurement procedure the value of the voltage increase rate amounted around to 0.5 kV/s.

After installing new electrodes the system was conditioned by breakdowns, in order to stabilize the value of the breakdown voltage. The process consisted in causing ten conditioning breakdowns in the system with SF_6 under the pressure of 10^5 Pa and temperature 293 K, for every interelectrode gap varying by 1 mm in the range 1÷10 mm.

The electric strength was measured in three independent measurement series, using a new set of electrodes in each of the series. In each of the series the voltage values of 6 successive breakdowns were measured for a selected SF_6 pressure and temperature, and interelectrode gap.

The results were mathematically processed with the use of Statistica [11] computer software. Since it was found that multiple measurements of the breakdown voltage have normal distribution, an arithmetic average of the breakdown voltage values measured in three independent samples (six breakdowns in each sample) was considered as a representative electric strength level of a given system.

3. Measurement results and their discussion

Taking into account that electric strength of a gas does not depend directly on gas pressure but on its concentration and density [14], the results of SF_6 electric strength measurements are shown in the Figures versus the density. The Figures include also the data on SF_6 pressure and temperature, for which the considered result is obtained.

The relationships between the breakdown voltage in SF_6 and gas density in temperatures 243 K, 263 K, and 293 K, for the systems of electrodes made of stainless steel and aluminum separated at the distance d = 1, 5, 8, and 10 mm, are shown in Fig. 1. The electrode connected to negative terminal of the direct high-voltage source was a rod of 3 mm diameter, ended with a hemisphere, while the opposite electrode, connected to positive terminal of the source, had a form of a flat disk with rounded edges.

The measurement points in Fig. 1, showing the relationship between SF_6 electric strength and gas density, measured for various temperatures (243 K, 263 K, and 293 K) of the systems provided with stainless steel or aluminum electrodes, are situated basically at equal characteristic curves. Hence, it can be said that variation of the electrode materials (i.e. stainless steel or aluminum) as well as of the temperature values did not cause changes in electric strength of the tested systems for constant SF_6 density.

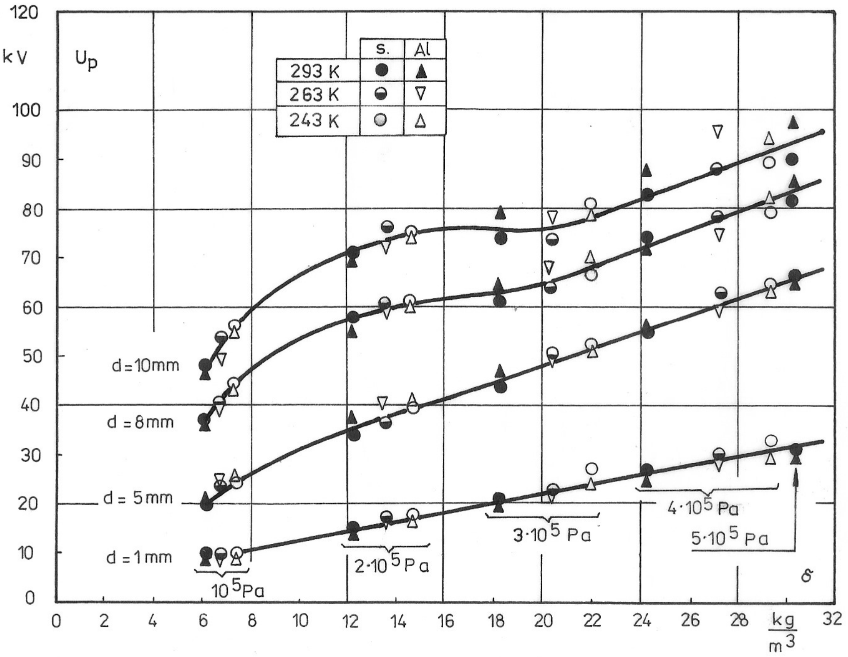

Fig. 1. The relationship between the breakdown voltage in SF_6 and gas density in temperatures 243 K, 263 K, and 293 K, for the systems with varying interelectrode gap (d); the considered systems were provided with stainless steel or aluminum electrodes, as the negative polarity electrode a rod of 3 mm diameter was used, ended with a hemisphere, while the positive polarity electrode had a form of a 125 mm diameter disk, with the edges rounded according to the Rogowski`s formula

Figure 2 presents the relationship between the SF_6 electric strength in temperature 293 K and the gas density for the insulation systems with stainless steel or aluminum electrodes spaced at d = 1, 3, 5, 8, or 10 mm. The electrode connected to negative terminal of the direct high-voltage source was a rod of 30 mm diameter, ended with a hemisphere. The opposite electrode, connected to positive terminal of the source, had a form of a flat disk with rounded edges.

Figure 2 gives evidence that the measurements of electric strength of SF_6 – containing systems with stainless steel electrodes are basically identical to the measurement results obtained in case of the systems with aluminum electrodes. Hence, it may be said that in the systems in which the degree of irregularity of the macroscopic electric field near the cathode is significantly reduced in result of enlarging the hemispherically ended rod electrode diameter from 3 mm to 30 mm, the electrode material also does not affect the SF_6 electric strength. At the same time, the reduced degree of irregularity of the electric field caused significant growth of electric strength of the system.

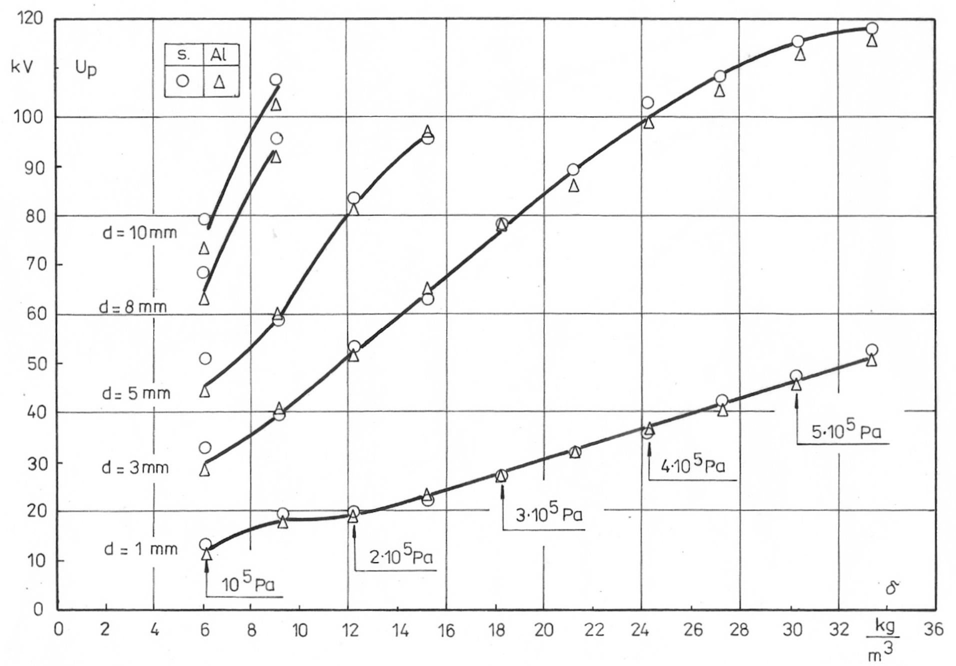

Fig. 2. The relationship between the breakdown voltage in SF_6 and gas density in temperature 293 K, for the systems with varying interelectrode gap (d); the considered systems were provided with stainless steel or aluminum electrodes, as the negative polarity electrode a rod of 30 mm diameter was used, ended with a hemisphere, while the positive polarity electrode had a form of a 125 mm diameter disk, with the edges rounded according to the Rogowski`s formula

Figure 3 presents the relationship between the SF_6 electric strength and gas density in temperatures 243 K, 263 K, and 293 K, for the systems provided with both electrodes flat, in the form of disks with rounded edges, made of stainless steel or aluminum. The interelectrode gap amounted to d = 1, 2, 3 or 5 mm.

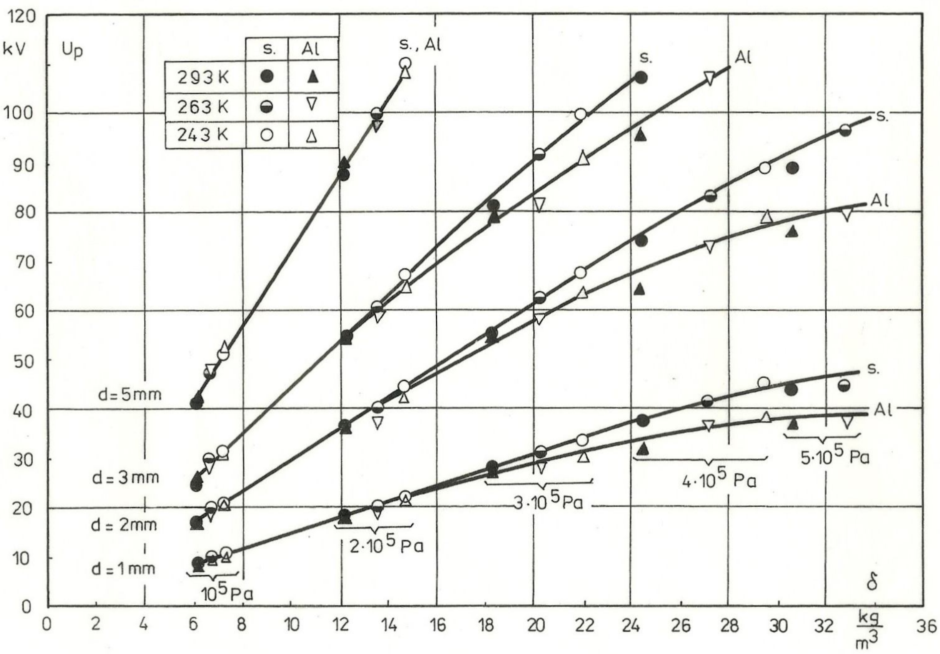

Fig. 3. The relationship between the breakdown voltage in SF_6 and gas density in temperatures 243 K, 263 K, and 293 K, for the systems with varying interelectrode gap (d); the considered systems were provided with flat electrodes in the form of a 125 mm diameter disk, with the edges rounded according to the Rogowski`s formula, made of stainless steel or aluminum

The measurement results shown in Fig. 3 give evidence that variation of SF_6 temperature in the range from 243 K to 293 K and constant gas density does not practically affect the electric strength of the systems provided with stainless steel and aluminum electrodes. Moreover, Figure 3 additionally shows that for SF_6 density above 15 kg/m^3 (corresponding to SF_6 pressure about $2.5 \cdot 10^5$ Pa at the temperature 293 K) the electrode material begins to affect the electric strength, and the effect is more intensive with further growth of the gas density. The electric strength of the insulation systems with stainless steel electrodes was higher than that of similar ones including the aluminum electrodes.

Comparison of the research results shown in Figs 1 and 2 to the ones of Fig. 3 allows to state that the electrode material affects the SF_6 electric strength only in the case of macroscopic uniformity of the electric field (Fig. 3). Even relatively insignificant growth of the degree of nonuniformity of the macroscopic electric field near the cathode led to the fading of the electrode material impact on the electric strength (Fig. 2). Moreover, higher degree of nonuniformity of the macroscopic electric field caused by replacing the flat cathode with a rod electrode of 30 mm diameter, ended with a hemisphere, did not practically reduce the electric strength of the system (Figs 2 and 3).

On the other hand, once the flat cathode is replaced for a rod electrode of 3 mm diameter ended with a hemisphere, the electric strength is lowered. The drop of electric strength is relatively (as a percentage) more significant with growing interelectrode gap (Figs 1 and 2, with Fig. 3 for comparison).

Physical interpretation of the result of the research is difficult. The problem begins e.g. from assumption of the mechanism of initiating the breakdown in the considered insulation systems. It is a consequence of the fact that the values of the product of pressure and interelectrode gap (p·d) calculated for the research conditions approximate 10^5 Pa·cm. At the same time, it is an upper limit for occurrence of the Townsend mechanism and the lower limit of the streamer channel mechanism [14, 22].

It seems that physical interpretation of the obtained results may be based on the assumption that the breakdown occurring in the considered systems of macroscopically uniform field is initiated just by the Townsend mechanism. According to the mechanism the free electrons present in the interelectrode space and accelerated by the electric field give rise to impact ionization of the gas molecules, thus creating the positive ions. Since SF_6 is an electronegative gas, intensity of the ionization is restricted by the phenomenon of binding (capture) of free electrons by the gas molecules and creating the negative ions.

The positive ions created and accelerated in the electric field, bombard the cathode and emit electrons from it in result of a secondary ion-electron emission. The bombardment gives also rise to local cathode temperature growth due to the change of at least a part of kinetic energy of the bombarding ions into heat. The temperature growth causes thermal stimulation of the metal electrons and activates field emission of the electrons from any of the heated cathode micro-points. Intensity of the field emission depends on the electron work function from the cathode surface material [13, 14]. It should be noticed that a material distinguished by lower electron work function causes, in equal conditions, emission of electron beam of higher density. The electrons emitted in result of the activated field emission boost the breakdown initiation.

Taking into account that the field emission of electrons requires a strong electric field, the field emission of electrons occurs in case of high intensity of the electric field. Therefore, the kind of the cathode material affects the SF_6 electric strength in case of the intensity of macroscopic electric field exceeding 20÷25 kV/mm. At the same time, a set of SF_6 insulation systems arranged according to increasing value of their electric strength complies with a similar set arranged according to growing values of the electron work function from the cathode surface materials.

In a system with macroscopically uniform field the electrons emitted from cathode in result of secondary ion-electron emission and field emission accelerate due to the electric field in the direction of the interelectrode space, from which came the positive ions bombarding the cathode. This is conducive to growing number of the electrons included in the electron avalanche and, in consequence, boosts the breakdown process.

On the other hand, in case of a macroscopically nonuniform field near the cathode (cathode in the form of a hemispherically ended rod – flat anode) the electrons emitted from the cathode in result of secondary ion-electron emission and field emission are very unlikely to flow into the interelectrode space, from which came the positive ions bombarding the cathode.

Hence, the electron avalanche arising in the macroscopically nonuniform field near the cathode is basically not supplied by the cathode electrons, as opposed to the avalanche arising in the system with macroscopically uniform electric field. This impedes the breakdown initiation by the Townsend mechanism and the breakdown occurs in result of the streamer channel mechanism. In case of the streamer channel mechanism the electrons emitted from the cathode do not play essential role in the breakdown initiation process. Therefore, in case of the systems with macroscopically nonuniform field the cathode material kind did not affect the electric strength.

The change in the breakdown initiation mechanism caused by change in the macroscopic distribution of the electric field – from uniform to moderately nonuniform one – explains why the strength of the systems with moderately macroscopically nonuniform field near the cathode does not depend on the cathode material (Fig. 2) and is nearly equal to electric strength of the systems with macroscopically uniform electric field (Fig. 3).

4. Staff health hazards and environmental issues

SF_6 is considered to be nontoxic and physiologically inert gas. It has been successfully used in medicine: as a contrast agent for ultrasound imaging and as a test gas in respiratory physiology [4, 18]. Other uses include its injection in vitreoretinal surgery for tamponade of retina [17]. Despite its inertness, by displacing oxygen in the lungs, it carries the risk of asphyxia, if too much is inhaled. Since it is heavier than air, if a substantial quantity of SF_6 is released, it settles in low-lying area and may pose a significant risk of asphyxiation if the area is entered. This is especially relevant to its use as an insulator in electrical equipment where workers may be in ducts or trenches below ground. Caution must be observed when working in confined areas and the atmosphere tested to ensure there is adequate oxygen. Symptoms of exposure include asphyxia: increase breathing rate, pulse rate; slight muscle incoordination, emotional upset; fatigue, nausea, vomiting [21].

Health hazards associated with SF_6 use, appear also when electrical discharges occur within SF_6-filled equipment and dangerous byproducts are produced. These compounds may cause the number of adverse health effects when workers come into contact with them [19, 21].

According to EPA (Environmental Protection Agency) the most important byproducts include: HF, SF_4, SOF_2, SOF_4, SiF_4, S_2F_{10}, SO_2F_2, SO_2. Additional byproducts that may be formed include SF_2, SOF_{10}, $S_2O_2F_{10}$, and H_2S, as well as a number of metal fluorides (e.g., CuF_2, AlF_3 WF_6, WO_3, FeF_3) [19]. Gaseous SF_6 byproducts such as SF_4, SiF_4, SO_2, SO_2F_2, and HF are extremely irritating to the eyes, nasal and pharyngeal mucosa. They may cause skin and eyes burns, nasal congestion, throat irritation, coughing, shortness of breath, pulmonary edema, and bronchitis [19]. S_2F_{10} is considered to be one of the most dangerous toxic byproducts because it does not produce lacrimation or skin irritation, providing little warning of exposure [8]. Solid byproducts such as AlF_3 and CuF_2 dusts irritate skin and eyes, nose, throat, and lungs when inhaled. While reaching the gastrointestinal tract, they may act as irritants causing salivation, nausea, vomiting, gastric pain, hemorrhagic gastritis, and diarrhea [19].

Safety precautions for solid or gaseous SF_6 decomposition products include the requirement for the staff to wear protective clothing, approved full-face respirator, disposable gloves and foot covering (where necessary), until the work area is determined to be clear of all decomposition products [19, 21].

With regard to environmental protection issues, SF_6 is the most potent greenhouse gas, with a global warming potential of 22 800 which means that 1 kg of SF_6 is equivalent to 22.8 tons of CO_2. It is extremely long-lived and has an estimated atmospheric lifetime of 800–3200 years [3, 5]. For this reason, although the SF_6 from electrical equipment represents a very small portion of the anthropic greenhouse gasses in the atmosphere, the electrical industry worldwide has undertaken many initiatives to reduce the SF_6 gas emissions [1, 6, 7, 20].

Theoretically, SF_6 should remain contained within equipment. However, in reality, the gas is emitted into the atmosphere as leaks develop during various stages of the equipment's lifecycle. SF_6 can be released at the time of equipment manufacture, installation, servicing, or disposal. Implementation of emission reduction strategies such as detecting, repairing or replacing problem equipment, innovative designs of gas-insulated constructions, as well as educating gas handlers on proper handling techniques of SF_6 gas minimize leaks to the atmosphere and health hazards [20].

The issue of SF_6 recycling has been described in details in "SF_6 Recycling Guide. Re-use of SF_6 Gas in Electrical Power Equipment and Final Disposal" [6]. International Council on Large Electric Systems recommends that at the end of life of SF_6 equipment, the gas will either have to be recycled, or reduced to environmentally compatible end products, using industrial waste treatment equipment [6]. Heated at above 1000°C, SF_6 starts to dissociate into reactive fragments, which interact with hydrogen and oxygen to form SO_2 and HF. The products of the reaction are removed by passing through a calcium hydroxide solution in order to neutralize the acids and to form solid sulfates and fluorides [1].

It must be remembered that SF_6, when properly managed, does not impose a greater risk to the users and environment. Polish regulations on safe handling of SF_6 [16] are a direct translation of International Electrotechnical Commission's Technical Raport [7].

5. Conclusions

The paper enables formulating the following conclusions that are important for designers and operators of SF_6 using electrical equipment:

1. The changes in SF_6 temperature in the range from 243 K to 293 K and constant SF_6 density do not basically affect the variations of the gas electric strength.
2. The effect of the electrode material kind on the SF_6 electric strength occurred only in the systems with macroscopically uniform electric field. It emerged for the gas density exceeding 15 kg/m^3 (corresponding to SF_6 pressure about $2.5 \cdot 10^5$ Pa at the temperature 293 K), for breakdown strength value above 20 kV/mm and became more intense with growing SF_6 density. At the same time, the electric strength of the insulation systems with stainless steel electrodes exceeded the one of those with aluminum electrodes.
3. Even relatively small change in macroscopic distribution of the electric field near the cathode, from uniform to moderately nonuniform one, i.e. consisting in replacing the flat cathode with an electrode in the form of a 30 mm diameter hemispherically ended rod, was conducive to reduction of impact of electrode material on the SF_6 electric strength. At the same time, the change practically did not reduce the electric strength.
4. Because of its unique dielectric properties, SF_6 is widely used in high voltage electrical equipment. Strategies assuring safe use of SF_6 include reduction of this greenhouse emission and precautions against toxic byproducts.

References

[1] Bessede J. L., Huet I., Montillet G., Barbier E. Micozzi J., Implementation of treatment & recovery of the SF_6 gas containing a high amount of decomposition products due to high voltage electrical interruptions, 3rd International Conference on SF_6 and the Environment, 2004, Scottsdale, Arizona.

[2] Cookson A. H., Electrical breakdown for uniform fields in compressed gases, Proc. IEE, 1970, 117, 269.

[3] Deux J. M., SF_6 end-of-life recycling for medium and high voltage equipment, Schneider Electric White Paper 2013.

[4] Gustafsson P. M., Ljungberg H. K., Kjellman B., Peripheral airway involvement in asthma assessed by single-breath SF_6 and He washout, Eur. Respir. J., 2003, 21, 1033.

[5] Intergovernmental Panel on Climate Change, Working Group 1, Climate Change 2007, Chapter 2.10.2.
[6] International Council on Large Electric Systems, SF_6 recycling guide. Re-use of SF_6 gas in electrical power equipment and final disposal, Publication number 117, Task Force 23. 10. 01, August 1997.
[7] International Electrotechnical Commission, Technical Raport − Type 2, IEC 1634: 1995, High-voltage switchgear and controlgear − Use and handing of sulphur hexafluoride (SF_6) in high-voltage switchgear and controlgear.
[8] Johnston H., A Bridge not Attacked: Chemical Warfare Civilian Research During World War II. World Scientific, 2003.
[9] Knothe S., Rozdzielnice wysokonapięciowe izolowane, Wydawnictwa Naukowo-Techniczne, Warszawa 1976.
[10] Kuffel E., Opydo W., Wpływ materiału elektrod i temperatury na wytrzymałość elektryczną sześciofluorku siarki w polu jednostajnym, Archiwum Elektrotechniki, 1980, 29, 841.
[11] Lesińska E., Statistica Pl, StatSoft Polska, Kraków 1997.
[12] Luxa G., Opperman G., Vigreux J., Paschen curve for sulhur hexafluoride, Electra, CIGRE, 1974, 32, 75.
[13] Opydo W., Problemy wysokonapięciowej izolacji próżniowej, Wydawnictwo Politechniki Poznańskiej, Poznań 1997.
[14] Opydo W., Właściwości gazowych i próżniowych wysokonapięciowych układów izolacyjnych, Wydawnictwo Politechniki Poznańskiej, Poznań 2008.
[15] Opydo W., Opydo J., Porównanie właściwości elektroizolacyjnych próżni i sześcifluorku siarki, Archiwum Elektrotechniki, 1994, 43, 403.
[16] Polski Komitet Normalizacyjny, Polska Norma PN-E-06115, Wysokonapięciowa aparatura rozdzielcza i sterownicza − Użytkowanie i postępowanie z sześciofluorkiem siarki (SF_6) w wysokonapięciowej aparaturze rozdzielczej i sterowniczej.
[17] Ryan S. J., Schachat A. P., Retina, Elsevier Mosby, Philadelphia, PA, 2005.
[18] Schneider M., Arditi M., Barrau M.B., Brochot J., Broillet A., Ventrone R., Yan F., BR1: a new ultrasonographic contrast agent based on sulfur hexafluoride-filled microbubbles, Invest Radiol, 1995, 30, 451.
[19] The U.S. Environmental Protection Agency, Byproducts of sulfur hexafluoride (SF_6) use in the electric power industry, Washington, DC, 2002, available at: http://www.epa.gov/electricpower-sf6/documents/sf6_byproducts.pdf.
[20] The U.S. Environmental Protection Agency, Climate Change Division, SF_6 emission reduction partnership for electric power systems, December 2011, available at: http://www.epa.gov/electricpower-sf6/documents/sf6_2010_ ann_report.pdf.
[21] UNIPEDE Group of Experts NORM SF_6, Guide to the safe use of SF_6 in gas insulated electrical equipment. June 1998, Brussels.
[22] Wieland A., Gasdurchlagmechanismen in elektronegtiven Gasen (SF_6) und in Gasgemischen, Elektrotechnischen Zeituschrift, 1973, A. 94, 7, 370.