THE INFLUENCE OF THE MANUFACTURING PROCESS ON THE ELECTRIC BREAKDOWN STRENGTH OF SILICONE GEL-INSULATIONS

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Abstract: Silicone gels belong to the RTV-2 silicone rubbers, which are room temperature vulcanizable materials consisting of two components. They are soft and conformable materials having certain tackiness. Due to these unique mechanical properties silicone gels are interesting materials for the use in electrical insulation technology. In order to ensure a constantly high quality level of a silicone gel-insulation a consolidated knowledge of the key-parameters of the manufacturing process and the influencing factors is mandatory. The work presented, identifies the manufacturing parameters, the main influencing factors and describes their influence on the electric breakdown strength of a model silicone gel-insulation. The results provide practical information for the handling of the material and for the manufacturing of silicone gel-insulations.

1 INTRODUCTION

Silicone gels are widely accepted for a variety of applications in the telecommunications, electronics, and automotive markets. The reason for this is found in the unique combination of mechanical and electrical properties of this material. It combines the advantages of the electrical and chemical properties of silicones with the mechanical properties of gels. From the mechanical point of view, the characteristics of softness, deformability and tackiness are the dominating properties of the material.

Over the last years, some applications where silicone gels are used as an insulation material for higher field strengths have entered the market. They are used as an embedding compound for power electronic circuits [1,2] or as an insulation material for power cable joints up to 1 kV [3,4]. The attempt to expand these kinds of application to higher voltages and to use silicone gel as an insulation material in long-term stable and reliable high and medium voltage insulations requires a comprehensive and consolidated knowledge of its electric breakdown performance.

The results of fundamental phenomenological investigations on the electric breakdown performance of silicone gel under various environmental stress conditions are presented in [5,6,7]. Above that, the electric breakdown behavior of the material used at electrically stressed interfaces is presented in [8].

To provide comprehensive knowledge on the electric breakdown behavior of the material, the key-parameters of the manufacturing process and influencing factors on the electric breakdown strength of silicone gel-insulations have to be investigated. A confirmed knowledge on this point is mandatory to maintain a consistent and constant quality level of such a product. Above that, this knowledge is also needed for the evaluation of results obtained from investigations using prototypes of silicone gel-insulations manufactured in laboratory-scale. In this connection the information about the comparability of test results, e. g. obtained from prototypes prepared with material taken from different batches, is a point of interest.

The purpose of the work presented is to increase the basic knowledge on the influence of the manufacturing parameters and other specific factors on the electric breakdown strength of a model silicone gel-insulation. The aspects are under consideration are the following:

- preparation method of the electrode surface
- used electrode material (steel, brass, aluminum)
- degassing parameters (pressure and time)
- curing parameters (temperature and time)
- storage time of the gel-components
- humidity
- mechanical pressure on the insulation material

The results presented, provide practical information for the handling of the material and the manufacturing of silicone gel-insulations.

2 DESCRIPTION OF THE MATERIAL

Silicone gel belongs to the group of RTV-2 silicone rubbers, which are Room-Temperature-Vulcanizable materials consisting of two components. It consists of a chemically cross-linked polymer network which is swollen with silicone extender fluid that is compatible with the network. A model of the gel structure is shown in figure 1. The network gives the silicone gel its electrometric characteristics and provides a framework to retain the extender fluid. Therefore, silicone gel is much softer and more deformable than silicone rubber. The low modulus of silicone gel results from its low cross-link density and the high contingent of extender fluid. This low cross-link density also causes the material to have a high tensile strength and a high stress relaxation [2]. More details about the material structure and a quantitative characterization of the mechanical properties of the silicone gel under investigation are given in [7,8,9].

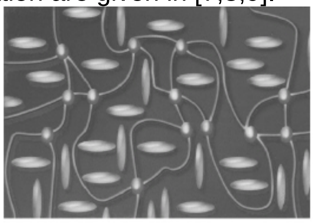

Figure 1. Structure of silicone – cross-linked polymer network (represented by the structure consisting of dots and lines) swollen with silicone fluid (represented by the ellipses).

3 EXPERIMENTAL PROCEDURES

This section describes the model silicone gel-insulation under investigation, the used test procedure and the method for the statistical evaluation.

3.1 Model silicone gel-insulation

For the determination of the electric breakdown performance of the silicone gel a test-cell with two sphere electrodes is used (fig. 2).

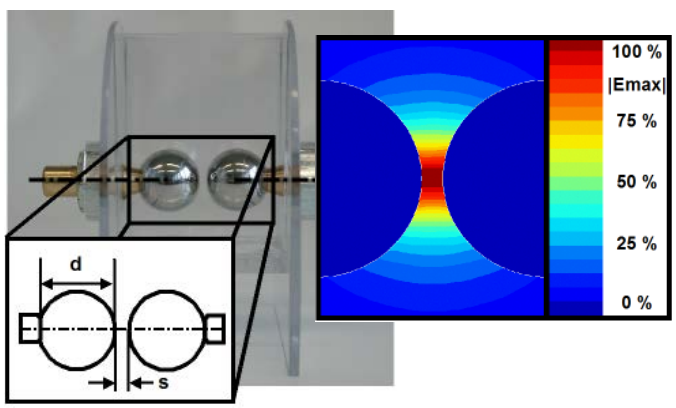

Figure 2. Test-cell with sphere electrodes.

As the default, a sphere diameter of d = 20 mm and a gap distance of s = 2 mm is chosen. The field distribution (see fig. 2), which is generated in the area between the electrodes, can be characterized by the utilization factor η (Schwaiger) of the electrode geometry. The utilization factor for the used sphere-sphere configuration is calculated to $\eta = 0.94$.

Figure 3 displays the steps of the manufacturing process of the model silicone gel-insulation. In the first process step, both components of the silicone gel are mixed in a fixed proportion of 1 : 1 (volumetric content). For that, an air-driven static mixer is used to ensure defined mixing condition. After pouring the mixture into the test-cell containing the electrodes, a vacuum is applied to remove air-filled bubbles that might have formed inside the gel during the processing. The parameters for this process step are the degassing pressure and the degassing time. After the degassing process, the curing process with the parameters time and the temperature follows. The storage under ambient conditions (22°C and a relative humidity of less than 35 %) completes the preparing process of the model insulation.

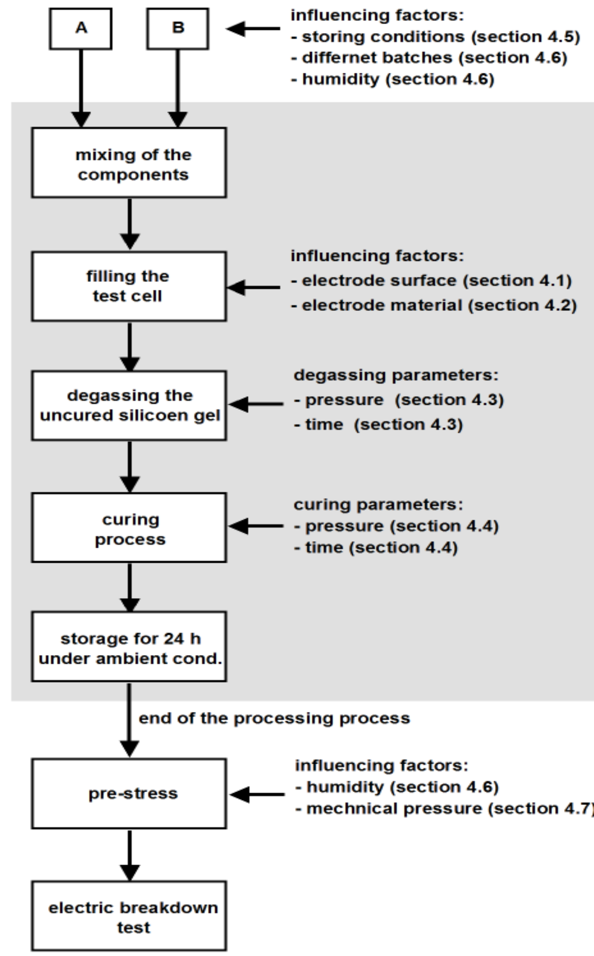

Figure 3. Sequence of operation diagram for the manufacturing and testing of the model silicone gel-insulation.

3.2 Breakdown Tests

The electric breakdown tests are carried out with AC voltage and a continuous increase in voltage at a rate of rise of 1 kV/s. During the breakdown test the sample was placed in sulphur hexafluoride (SF_6) to prevent external flashovers.

4 INVESTIATIONS AND RESULTS

This section describes the phenomenological investigations on the influence of the manufacturing conditions and other influencing factors on the electric breakdown strength of the model silicone gel-insulation. The results provide practical information for the material handling, i. e. the identification of the key-parameters and the parameter sensitivity respectively the robustness of the manufacturing process.

4.1 Preparation of the Electrode Surface

Impurity layers on the electrode surface can cause a reduction of the adherence of the silicone gel to the surface. In this case an interface delamination between the silicone gel and the electrode surface can occur. Such voids and also the presence of particles on the electrode surface are generally considered as weak points of insulation. This is because such voids are preferred starting points and propagation paths for electric discharges. Above this, specific substances in contact with the uncured silicone gel can interfere the cross-linking of the silicone gel. All these conditions can lead to a decrease in the quality of the interface, which can result in a decrease of the electric breakdown strength of the whole insulation.

To assess the significance of the influence of the preparing of the electrode surface on the electric breakdown strength of the model silicone gel-insulation, electrodes consisting of polished brass are used. The electrode surfaces of one test series are cleaned with Isopropanol alcohol using nonabrasive, low-linting and low-extractable wipers before the molding them with the silicone gel. For a second test series electrodes in the delivery condition without cleaning of their surfaces are used. In both cases, the visual inspection of the surface does not show any kind of impurities, e. g. oil or grease films, lint.

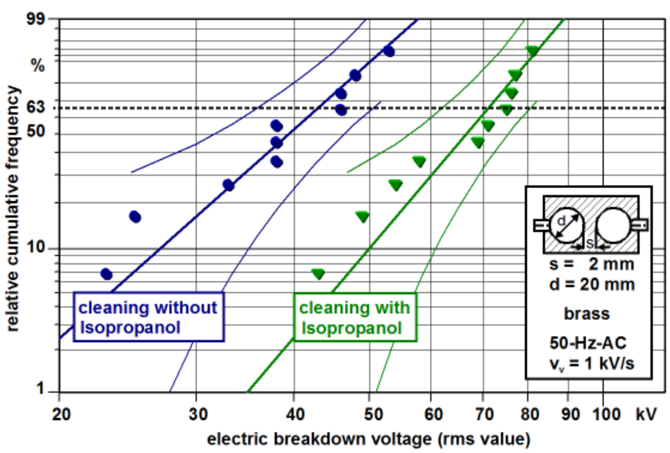

Figure 4. Influence of the electrode surface preparation before the molding them with the silicone gel.

Regarding the determined distribution functions, the estimated 63-%-quantile of the breakdown voltage U_{b63} increases from 42 kV up to 70 kV. Furthermore, a decrease of the scattering of the values takes place. This is described by the increase of the Weibull-exponent δ from 4.9 to 6.5. The results show clearly, that cleaning the electrodes enhances the electric breakdown strength of the model silicone gel-insulation significantly.

4.2 Electrode Material

Above the presence of impurities on the electrode surfaces, the used electrode material itself, can also affect the electric breakdown strength of an insulation. The adherence between the gel and the electrode surface depends on the material combination at the interface.

The used electrode materials are aluminium brass and steel (V2A). The surfaces of the electrodes are polished and a preparation of the electrode surface as described in section 4.1 takes place. The visual inspection of the surface does not show any kind of impurities. To increase the statistical confidence 20 samples instead of 10 for each test series are used. The results are shown in figure 5.

The confidence levels of the determined distribution function show a nearly total overlapping. Therefore, an influence of the electrode material on the electric breakdown voltage cannot be detected. From the practical view, the effect of impurities on the electrode surface – as described in section 4.1 – is more significant than the influences of the material itself.

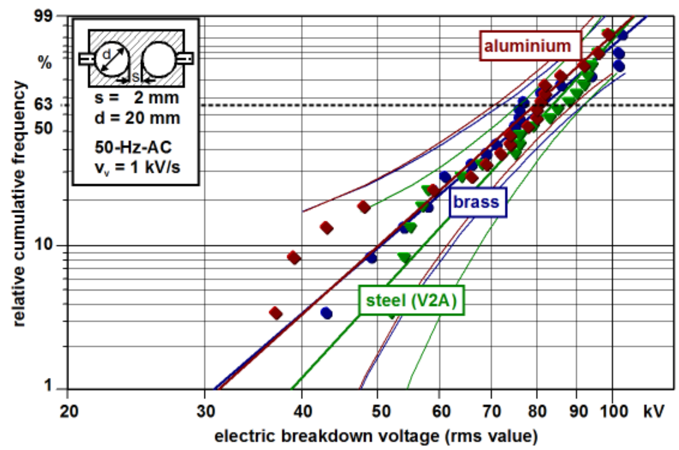

Figure 5. Influence of the electrode material on the electric breakdown voltage

4.3 Degassing Process

Air-filled voids inside an insulation material are generally considered as weak points which lead to a reduction of its electric breakdown strength. As described before, such voids are preferred starting points for discharges which can lead to a degradation of the material and finally to a breakdown of the whole insulation. To remove air-filled bubbles that might have been formed inside the gel, a vacuum has to be applied directly after mixing the components.

Figure 6 shows the used test-cell filled with un-cured silicone gel during several states of the degassing process. It can be seen, that a high amount of air enclosed in the mixture leads to a huge expansion of the un-cured silicone gel at the beginning of the degassing process.

The reason to decrease the pressure in two steps is founded in the fact that the high amount of air enclosed in the mixture can leads to a huge expansion of the uncured silicone gel at the beginning of the degassing process if the degassing pressure is extreme low.

Figure 7 shows the influence of the degassing process on the electric breakdown voltage of the model silicone gel-insulation.

Further investigations carried out with varied parameters shows that slight variations of the degassing parameters have no influence on the electric breakdown strength of the used model insulation. For example the use of 10 kPa over 30 min instead of the profile mentioned before, leads to statistically nearly identical results.

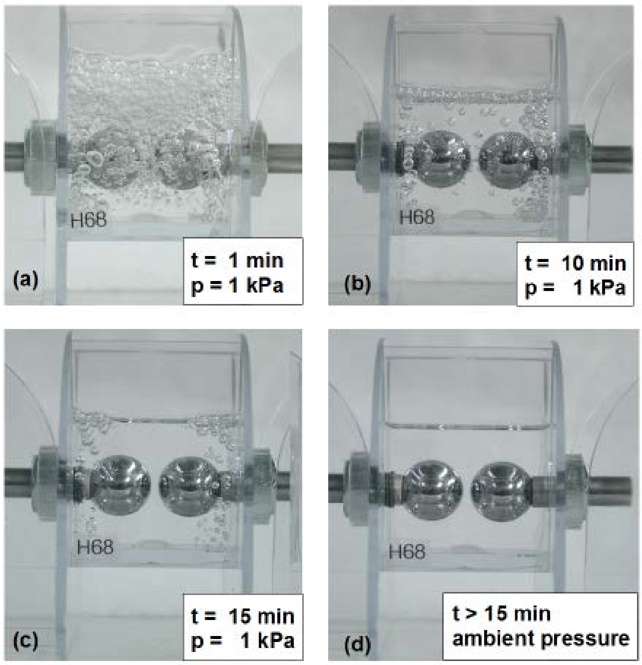

Figure 6. Degassing of the un-cured silicone gel.

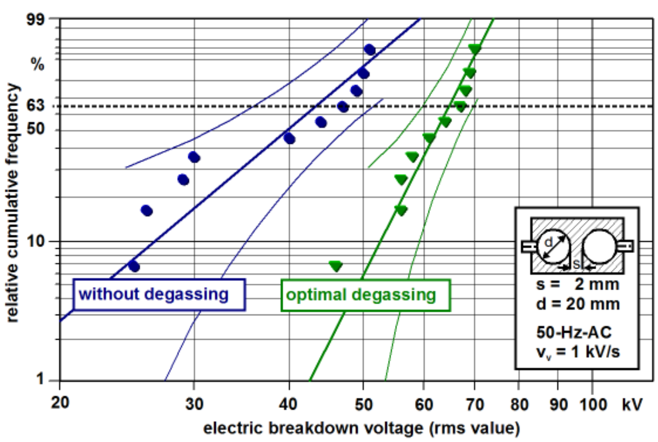

Figure 7. Influence of the degassing process

4.4 Curing Process

The reaction rate of the curing process increases with increasing the temperature. The knowledge of a potential influence of the curing temperature on the electric strength of the model silicone gel-insulation has a practical relevance. The increase of the processing speed in a series-production demands high curing temperatures. In doing so, a delamination between the silicone gel and the electrode surface due to thermo-mechanical stress on the insulation, which occurs during the cooling down to ambient temperature, could take place.

For the investigation, the curing of one test series takes place at 22 °C. The curing of the second series takes place at 90 °C over 2 hours.

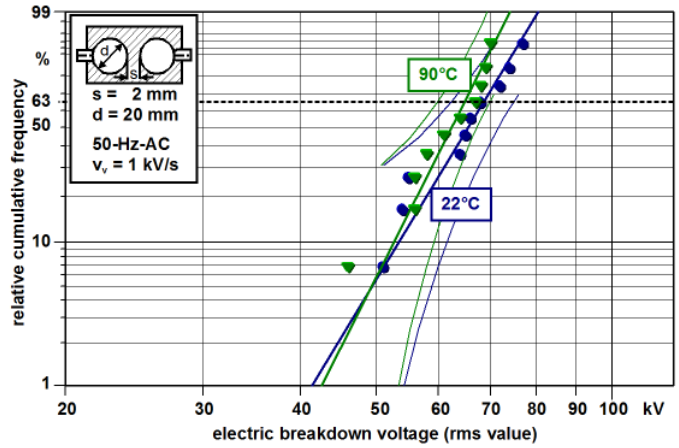

Figure 8. Influence of the curing temperature on the electric breakdown voltage of the model silicone gel-insulation.

As shown in figure 8, in the tested temperature range of 22 to 90°C an influence of the curing temperature on the electric breakdown strength of the silicone gel-insulation could not be detected. This result is confirmed by the results of investigations on the ageing performance of silicone gel, where the gel is stored over a period of 5000 h at 90 °C [12]. Even under these conditions, an influence of the thermal stress on the electric breakdown strength could not be detected. These results point out the high quality of the interface between the gel and the electrode. In the used configuration the silicone gel is able to compensate the thermo-mechanical stress mechanical even without an external pressure. Therefore, the parameters of the curing process used for this works are fixed to 2 h at 90°C.

4.5 Storage Conditions of the Components

This experiment has its focus on the influence of the storage time of the gel-components A and B before manufacturing the insulation on its electric breakdown strength. Besides the practical relevance for the handling of the material in a series-production, the knowledge about the comparability of test results, obtained from testing prototypes prepared with material from one batch but at different times, is important for the laboratory-work with the material. Specimens prepared with components in the delivery conditions are compared to ones prepared with the same components after the storage over three months in the sealed containers of the used static mixer. The results are shown in figure 9. It is found that the long-term storage of the single components A and B leads to a noticeable decrease of the electric breakdown voltage (13 %) and should be avoided. It can be assumed that moisture absorption (comp. section 4.6) and a separation of raw materials due to different specific weights which lead to an inhomogeneous material structure are effects that can lead the determined behaviour.

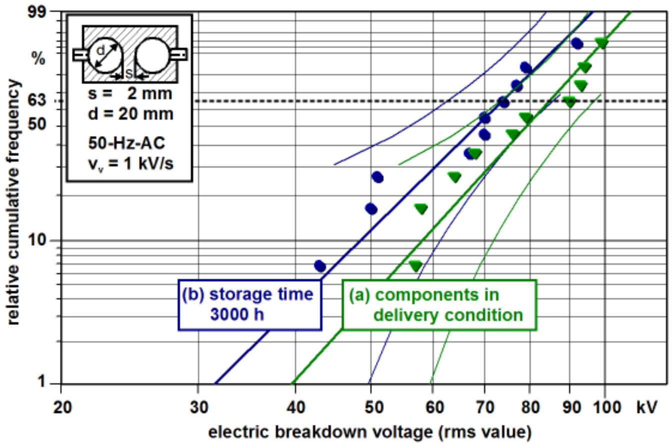

Figure 9. Influence of the storage time of the gel-components before manufacturing the model insulation on the electric breakdown voltage.

4.6 Influence of Humidity

The presence of outside influences, e. g. humidity, could lead to a change of the dielectric properties. In [5,6,7] is shown, that, humidity in contact with the silicone gel causes a decrease of approximately 50 % of the electric breakdown voltage compared to the gel stored under ambient conditions. A significant difference between the water storage and the storage in a humid atmosphere could not be detected. This effect is shown in figure 10. Such a significant effect of humidity on the electric breakdown strength is also known from most insulation fluids, e. g. transformer oil or silicone fluid.

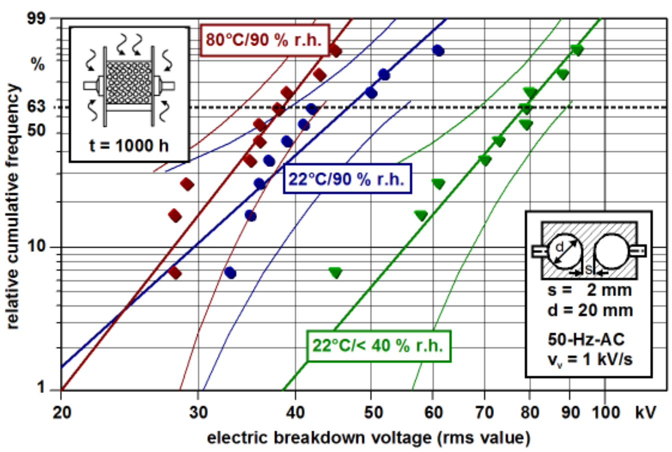

Figure 10. Distribution functions of the electric breakdown voltage of silicone gel influenced by humidity [7].

Regarding these results, it is anticipated that the effect of humidity on the electric breakdown strength covers all other possible effects and impacts. Therefore, only test results determined with samples prepared under the same condition and with the material taken of one and the same batch are directly comparable to each other. This fact is important for the laboratory-work with the material and the design of practical insulations.

4.7 Mechanical Pressure

To determine the influence of pressure on the electric breakdown strength of the model silicone gel-insulation a modified test setup is used. After the curing process through-holes with a diameter of 3 mm are bored in the housing of the test-cell to ensure also the contact to the environment. The pressure is generated by the use of a mass. The principle of pressure application by gravity has the advantage that a loss of silicone gel, e. g. through the holes, has not an effect on the pressure value inside the silicone gel between the electrodes.

The gel formulation used in this work is stable up to a pressure of 12.4 kPa [3]. If this level is increased, uncured silicone fluid will pour out of the gel and lead to a change in the mechanical characteristic of the gel. Details on the characteristic of fluid loss of the silicone gel under pressure are given in [3,8]. Regarding this effect, a pressure of 10 kPa and 20 kPa is used for the investigation.

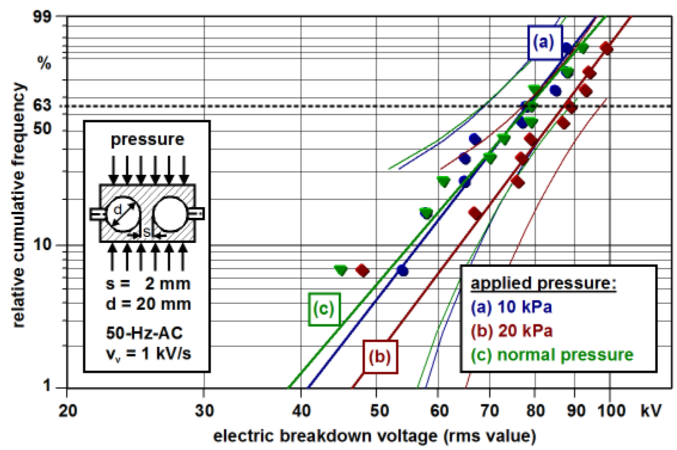

Figure 11. Distribution function of the electric breakdown strength of model silicone gel-insulations under the influence of mechanical pressure.

The results (figure 11) show that an applied over-pressure of 10 kPa has no influence on the electric breakdown strength of the model insulation. Neither an increase of the 63-%-quatile of the DBV, nor a reduction of the scattering of the measured values takes place. The use of an over-pressure of 20 kPa leads also not to a significant increase of the DBV. In this case the increase in the 63-%-qunatile of the DBV is 11 % compared to the one determined under ambient conditions. These facts point out the high electric breakdown strength of the bulk material and also the high quality of the interface layer between the electrode and the silicone gel under ambient pressure.

Nevertheless, this result should not suggest that the influence of mechanical pressure on a silicone gel-based-insulation is irrelevant. It should be taken in consideration that thermo-mechanical stress can lead to delaminations between the silicone gel and the electrode. To avoid such void, the mechanical pressure can have an important impact. Therefore the thermal expansion of the silicone gel [3,7,8], has to be considered in the design of an insulation using silicone gel. Furthermore, it is shown [8], that the application of mechanical pressure on silicone gel-interfaces leads to an effective removal of enclosed gas bubbles out of the interface layer due to the high value of the gas permeability coefficient of the SG.

5 CONCLUSION

The work presented has its focus on the influence of the manufacturing process and specific impacts on the electric breakdown strength of a model silicone gel-insulation. This knowledge, especially the identification of the key-parameters and the robustness of the processing process, has a high practical relevance for the material handling in the series-production. Also for the laboratory work with the material a consolidated knowledge on these points is mandatory, i. e. for the evaluation of results obtained from phenomenological investigations using prototypes of silicone gel-insulations manufactured in laboratory-scale under different conditions with materials taken from different batches. The main findings are:

Cleaning the electrodes enhances the electric breakdown strength of the model silicone gel-insulation significantly. Therefore a standardized preparation of the electrode surfaces is necessary to achieve consistent and reproducible test results.

An influence of the electrode material (brass, steel, aluminum) on the breakdown strength of a model silicone gel-insulation could not be detected.

Air-filled bubbles inside the silicone gel are weak points in the insulation which lead to a reduction of its electric breakdown strength. The degassing of the uncured silicone gel to remove these voids is a precondition to achieve high electric breakdown strength. Thereby, an adaptation of the degassing parameters to the specific shape of the mould is recommended.

In the invested temperature range between 22°C and 90°C an influence of the curing temperature on the electric breakdown strength of the model silicone gel insulation could not be detected. From the practical view, the thermal stability of the used mould is normally the parameter which limits the temperature. For the design of a practical insulation, the occurrence of thermo-mechanical stress on has to be considered. The use of mechanical pressure as a design parameter can avoid a delaminations at stressed interfaces between materials having different expansion coefficients.

A long-term storage of the gel-components before the processing can affect the electric breakdown strength of the material. It can be assumed, that a separation of raw materials due to different specific weights, which lead to an inhomogeneous material structure, is a possible effect which can lead to this behaviour. However, the absorption of humidity has a significant effect on the electric strength of the silicone gel. A small amount of humidity leads to a drastic decrease of the electric breakdown strength of the silicone gel in the range of 50 %. It can be assumed that most of the other impacts are covered by the effect of humidity. Also slight differences in the electric breakdown strength of silicone gel taken from different batches are detected.

Regarding these facts, a quality monitoring of the silicone gel in the series-production is recommended. Furthermore it is obvious that especially for phenomenological investigations on this material, only test results determined with specimens prepared under the same condition and with the material taken of one and the same batch are directly comparable to each other.

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