# How to Eliminate ESP Insulator Thermal Break Down and Insulation Aging

Long Tao, Xu Jian, Zhou Baoshan

*Nanjing Tailong Special Ceramics Co., Ltd.*
*East End of Shennong Road, Jixiang'an, Nanjing 210038*
*China*

## Abstract

High voltage electric field combining with high temperature may lead to ESP insulator failure. Particulates having a relatively lower breakdown voltage strength stick on the insulator surface can induce corona discharge and local temperature rise thereby speed insulator aging. Select insulator material with higher Te (the temperature when the resistivity lowers to 1MΩ·cm) and optimize design to even the field around insulator can effectively protect insulator from heat breakdown and aging.

## Introduction

Insulator is key component of ESP for high voltage operation. How to ensure its insulation capability on high voltage, high temperature and pollution working conditions is worth studying [1]. Arbitrary electric porcelain may not be competent at this job. Select suitable insulator material is important.

Now the worldwide evaluation index for insulator material is Te. It means the temperature at which material's volume resistivity lowered to 1 Mς-cm. Table 1 listed the main characteristics of some common used ceramics [2]

Yet in China, Te has not been used as a characteristic parameter in national standards whether for electrical ceramics (GB772), electronic ceramics (GB/T5593) or ESP ceramics (JB/T6746). Enough attention should be given to Te for insulator's material selection and shape design.

Nanjing Tailong Special Ceramics Co. has built a unique high temperature, high voltage (ultimate temperature and voltage reached 800□ and 200KV respectively) laboratory for ESP insulators. Enormous test data were attained for evaluation of insulator capabilities. These tests established a technical foundation of national standard revising in the future.

## ESP Insulator failures

Earlier days in China, ESP Insulators were commonly designed just like general electrical porcelain insulators, thus lead to a large number of insulator damages. Such as, a 300m$^2$ ESP just worked for 2 months, there were 14 porcelain rotating shaft, 5-6 big porcelain bushings broken. Other material such as macromolecular was also used. But In certain case, among the 42 macromolecular rapping rods, 18 macromolecular rapping rods of were broken within 8 months.

At the beginning, people regarded the ceramics as brittle material and mechanical failure is dominative. So, thicker walls, bigger size and higher compressive strength were pursued and macromolecular rapping rods replaced ceramic rods. But failure still occurred. In some cases, insulator looked maintaining well appearance but no high voltage was attained.
Through long term study and verification, the conclusion we have it is the thermal breakdown and insulation aging induced the insulation failure.

Table 1 Physical properties of some kinds of ceramics

| Class | Name | Porosity | Density | Bending strength | Average linear expansion coefficient |  | Heat conductivity | Te Value Min |
|---|---|---|---|---|---|---|---|---|
|  |  |  | Min $g/cm^{-3}$ | Min MPa | 20~100□ $\times10^{6}/K^{-1}$ | 20~600□ $\times10^{6}/K^{-1}$ | 20~100□ W $(m.K)^{-1}$ | Temp.at which volume resistivity equal to 1MΩ.cm □ |
| C110 | Silicon ceramic | 0 | 2.2 | 50 | 3~6 | 4~7 | 1~2.5 | 350 |
| C111 | Press ceramic | 3 | 2.2 | 40 | 3~5 | 4~7 | 1~2.5 | 350 |
| C120 | Alumina ceramic | 0 | 2.3 | 90 | 3~6 | 4~7 | 1~2.6 | 350 |
| C130 |  | 0 | 2.5 | 140 | 4~7 | 5~7 | 1.5~4 | 350 |
| C220 | Steatite | 0 | 2.6 | 120 | 7~9 | 7~9 | 2~3 | 530 |
| C221 | Low loss steatite | 0 | 2.7 | 140 | 6~8 | 7~9 | 2~3 | 800 |
| C230 | Porous steatite | 35 | 1.8 | 30 | 8~10 | 8~10 | 1.5~2 | 800 |
| C310 | TiO2 ceramic | 0 | 3.5 | 70 |  | 6~8 | 3~4 |  |
| C410 | Cordierite | 0.5 | 2.1 | 60 | 1~3 | 2~4 | 1.5~2.5 | 400 |
| C511 | Porous cordierite | 20 | 1.9 | 25 | 3~6 | 4~6 | 1.3~1.8 | 500 |
| C520 |  | 20 | 1.9 | 30 | 1.5~3.5 | 2~4 | 1.3~1.8 | 500 |
| C530 |  | 30 | 2.1 | 30 | 3.5~5 | 4~6 | 1.4~2 | 600 |
| C610 | Aluminum silicate ceramic | 0 | 2.6 | 120 | 5~6 | 5~7 | 2~6 | 600 |
| C620 |  | 0 | 2.8 | 150 | 5~6 | 5~7 | 5~15 | 600 |
| C780 | Alumina Ceramic | 0 | 3.2 | 200 | 5~7 | 6~8 | 10~16 | 700 |
| C786 |  | 0 | 3.4 | 250 | 5.5~7.5 | 6~8 | 14~24 | 800 |
| C795 |  | 0 | 3.5 | 280 | 5~7 | 6~8 | 16~28 | 800 |
| C799 |  | 0 | 3.7 | 300 | 5~7 | 7~8 | 19~30 | 800 |

## Thermal Breakdown

Solid dielectric medium breakdown normally conduct to molecular structure destruction, insulation capability disappear accompanying with continuous or discontinuous current peak. There are electronic, thermal and mechanical breakdown, which occur simultaneously or alternatively, hard to identify clearly.

The reason for thermal breakdown are: □ It is the external electric field destroys energy balance that causes intrinsic breakdown and avalanche breakdown, □It is the tunnel effect that electrons passing through valence band to conduction band causes Zener breakd.

High temperature working condition will cause insulator breakdown due to combined action from electrical and thermal. For example, one kind of electrical ceramic has a good insulation capability in normal temperature which means the energy “We” applying on ions by electric field is not enough to support ions pass through valence band to conduction band. While in an ESP, the heat “Q” from flue gas will apply extra energy “Wq” to the ions in crystal lattice. Even the field strength keep unchanged, the total energy in ions now is “We+Wq”. The more energy ions have from outside, the higher probability to pass through valence band to conduction band; the more ions in in the material with a wide forbidden band (the range between valence band and conduction band)[3].

The foundation of thermal breakdown is the heat balance between $We+Wg=Q_F$ (the energy applied to solid crystal lattice by electric field and temperature field, which raises the lattice temperature) and the heat dissipated from whole crystal lattice system. In the case of ionic conduction electric field energy is transmitted to crystal lattice directly, then dissipate to surrounding medium by heat exchange. The emitted heat Qs is briefly proportional to difference of t-$t_0$ (where “t” is heat access temperature, “$t_0$”is ambient temperature). Crystal temperature keeps rising to such a balance that $Q_F$=$Q_S$. In figure 1(a), where field U1 is lower, $Q_{F□U1}$ (energy to crystal lattice system) is also at a lower level. When temperature rises to the balance temperature $t_1$, $Q_{F□U1□}$intersect with $Q_S$ at zero point. At this point, even temperature has a surge occasionally, but due to $Q_{F□U1□}$□$Q_{S,}$ crystal lattice temperature still returns to $t_1$; the thermal balance is not broken. If temperature increased to $t_2$, where $Q_{F□U2□}$□$Q_S$, $Q_{F□U2□}$ is tangent to $Q_S$ at point A, which temperature is tm; when temperature is lower than tm, as $Q_{F□U2□}$□$Q_S$, raised temperature will bring back to balance point A. If temperature higher than tm, as $Q_{F□U2□}$□$Q_S$, so insulator temperature will keep rising till breakdown, for the lines we can tell that U2 is the lowest unbalance voltage, thermal breakdown voltage.

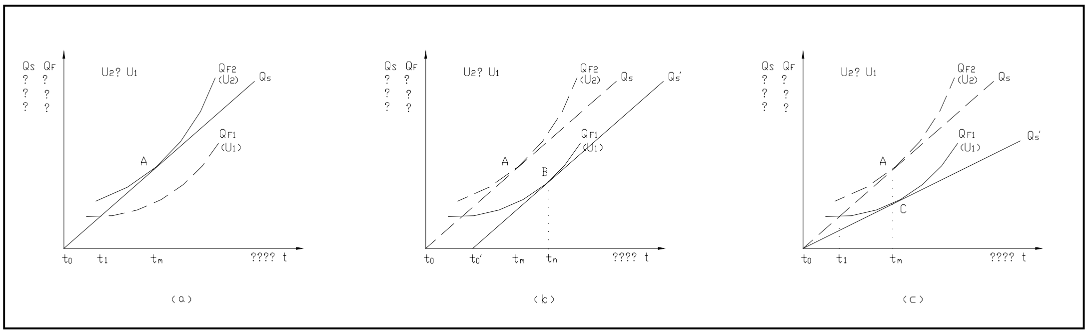

Fig. 1 Relation of Heat generation and Heat Loss with Temperature when breakdown

If heat emit condition is same as before, lower the voltage to $U_1$, ambient temperature $t_0$ rises $t_0^{'}$ , shown as Fig.1(b), line Qs move to $Qs^{'}$ and get tangent to $Q_{F□U1□}$ at point B. If temperature lower than $t_{n,}$ as $Q_{F□U1□}$□$Q_S$, temperature will rise to point B to keep balance. If occasionally temperature gets higher than $t_{n,}$, as $Q_{F□U1□}$□$Q_{S,}$ temperature keeps going up to breakdown. So $U_1$ is the lowest voltage where heat balance is to be broken in crystal lattice system, called thermal breakdown voltage $U_{1.}$

Similarly, if we keep the voltage and ambient temperature stable, just change heat emission condition, the slope of $Q_S$ will change subsequently. For a surrounding medium, if heat conductivity is low, heat dissipation is bad, the slop of Qs is getting to be smaller to certain extent so as tangent to $Q_{F□U1□}$ at point C, shown in 1(c), $U_j$ descends ,otherwise $U_j$ rises.

So we can see from above that it is not only field voltage that determines insulator’s thermal breakdown, but also ambient temperature and material properties, such as high temperature durability (lower Te, lower breakdown strength $E_j$), heat conductivity (lower conductivity, lower $E_j$ ),etc. Insulator thickness and high voltage duration (long duration lower $E_j$) also play their roles.

## Insulation aging

Gas breakdown induces local corona discharge, mass quantity of positive and negative ions impacting solid surface, causes aging of insulator. Arborization trace can be observed (Fig.2)

Fig. 2 Arborization trace on insulator surface

It is difficult to measure the ions impact energy, but it can be calculated from the average free path and discharge strength to be an average of 3.2 electron volts. Assume Maxwell distribution, quantity of ions with energy larger than 10 electron volts holds 4.2%. For macromolecule material, its ionization energy is about 10-11 electron volts, so it may be broken down to low molecule. Oxidizing reaction at surface causes corrosion and carbonization, thus lead to insulation ability gradually loses.

For ceramic material, if small hole exits, inside gas electric discharge will cause high temperature up to 170□(the highest temperature may reach 1000□), within an area of $5\times10^{-11}$cm$^{2}$, minor crack will appear once thermal expansion stress exceed its allowable tensile stress. The minor crack will continuous to expand under the electric, thermal and rapping forces. Insulation failed at last. So we can say that local discharging is the prime culprit for insulator aging.

In fact, for ESP insulators, all the defects mentioned above may occur simultaneously. For example, a wall bushing of:

- Rating voltage 72kV
- Working temperature not less than 2508C
- DC testing voltage 100kV
- Dimensions: Inner hole ϕ77mm, Outer umbrella ϕ130mm, Thickness 26.5mm, Totaql length 848mm, Lenth ratio of hot end and cold end 1.2
- Actual working voltage 32~35 V
- Temperature of CO+tar gas 32~408C
- Highest temperature in insulator penthouse ′1508C

Its working life had only to be 20~40days. All were damaged at hot ends (Fig.3).

We have tested this bushing. Good insulation at 268C. No breakdown and temperature rising under DC voltage 108kV. Arc discharging under 140kV at cold end. At 1508C, “zz…zz…” sound was heard and corona discharge occurred near its flange when voltage gradually increased to 15kV. Under 34.6kV, breakdown happened. At 2008C, breakdown happened under 11kV. At 2508C, breakdown happened only under 2.7kV.

So, we can conclude that thermal breakdown is the factor causing insulation failure for this wall Bushing.

Fig. 3 Damaged insulators

.

.

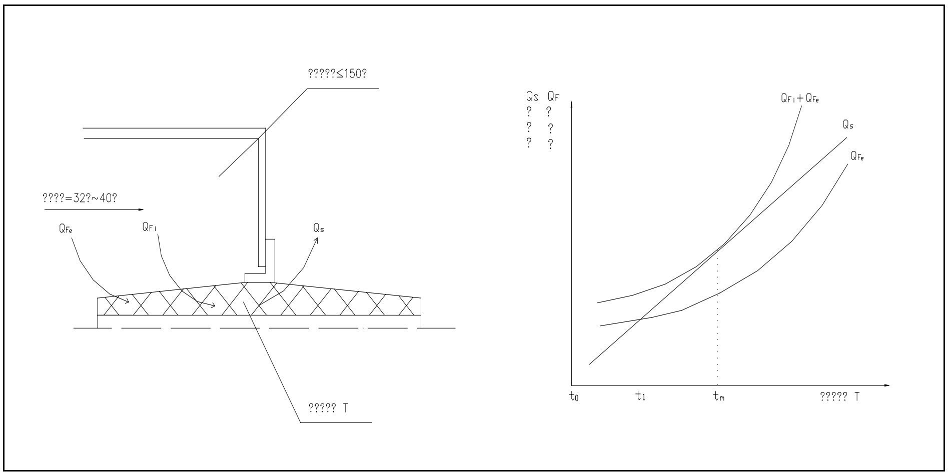

Fig. 4 Wall Bushing under Heating

When ESP starts working, insulator temperature is not high, good insulation maintained. Long time working lead to tar accumulating on insulator surface, leakage current appears and will increased to a extent that thermal breakdown burst out. High silicon ceramic material gives a lower Te, critical condition may reach at ESP starting period and thermal breakdown is very likely appeared.

## Method to avoid thermal breakdown and delay insulation aging

### Select material with excellent electrical characteristic under high temperature.

Mainly ion movement realizes electrical conduction of ceramics material. Ion mobility is an exponential function of temperature. Fig 5 shows the relations between resistivity and temperature of some ceramic crystals.[4]

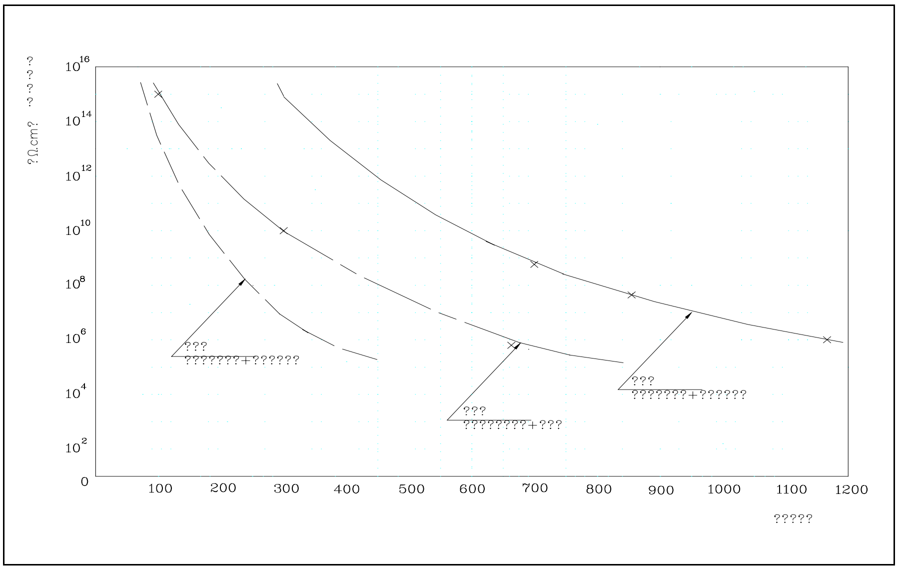

Fig. 5 R-T Curve of Ceramic Insulation Material

From the figure, we can see resistivity-temperature changing rate related with crystal structure. For $SiO_2$, R-T factor varies greatly. While α-$Al_2O_3$ is a stable crystal, its R-T factor varies little. Porcelainite is a melted congruent from $SiO_2$ and $Al_2O_3$, so its R-T factor locate between $SiO_2$ and $Al_2O_3$ (Table 1). Te values of different electrical ceramic materials listed in Table 1.

Insulator materials are not 100% pure, normally are composted from several kinds of crystals, as Table 2.

Table 2. Crystal composition of insulation ceramics

| | Mass ratio | | | |
|---|---|---|---|---|
| □ | Silicon | Cristobalite | Mullite | Corundum |
| Standard ceramics | 1 | | 1.5 | |
| Silicon ceramics | 1 | 4 | 3 | |
| High aluminum ceramics | 1 | | 10 | 10 |
| Alumina ceramics | □ | □ | 1 | 10 |

Recently, insulator's content of $SiO_2$ declines and $Al_2O_3$ rises [5] (Table 3).

Table 3 Formulation trends in different period

| Year decade | 1870 | 1950 | 1960 | 1975 |
|---|---|---|---|---|
| Chemical compositions □□By weight□ | □ | □ | □ | □ |
| $SIO_2$ | 70~73 | 60~62 | 50~52 | 35~40 |
| $Al_2O_3$ | 22~24 | 33~35 | 44~47 | 57~63 |
| $K_2O+Na_2O$ | 3~405 | 3~4.5 | 3~5 | 3~4.5 |
| ICE672/DIN VDE0335 Standard type | C110 | □ | C120 | C130 |

As the cost consideration, much clay is added into the insulator formulation, the alkaline oxides in clay ($K_2O+Na_2O$) are very bad to high temperature insulation. High silicon cristobalite has a high mechanical strength in normal temperature, but its mechanical, electrical and thermal performances are unstable under high temperature [6]. In Table 4 component and characteristics of common electrical ceramics in China are listed. Their Te values are low, not suitable for making high temperature insulator.

Table 4 Composition and properties of electrical porcelain

| □ | Feldspar | High silicon | High aluminum |
|---|---|---|---|
| Mineral components | | | |
| Clay | 45~60 | 45~55 | 45~55 |
| Silicon | 20~30 | 30~40 | |
| Feldspar | 25~35 | 18~22 | 25~30 |
| Bauxite or Alumina | □ | □ | 20~40 |
| Chemical composition | | | |
| $SiO_2$ | 68~72 | 72~75 | 40~45 |
| $Al_2O_3$ | 20~24 | 20~23 | 40~55 |
| $K_2O+Na_2O$ | 3.5~5.0 | 2.5~3.0 | 3.5~4.5 |
| $Fe_2O_3$ | □1.0 | □1.0 | □1.0 |
| CaO+MgO | □1.2 | □1.2 | □1.5 |
| $TiO_2$ | □0.4~0.8 | □0.4~0.8 | □0.4~0.8 |
| Properties | | | |
| Volume density /g.cm$^{-3}$ | 2.30~2.44 | 2.33~2.42 | 2.5~2.8 |
| Water absorption rate /□ | 0 | 0 | 0 |
| Porosity □60MPa.h□ | Non red color absorbed | Non red color absorbed | Non red color absorbed |
| $\sigma_b$ /Mpa Non-glazed | 70~90 | 90~115 | 120~170 |
| /Mpa Glazed | 80~110 | 105~125 | 145~200 |
| $\sigma_t$ /Mpa Non-glazed | 25~35 | 30~40 | 45~65 |
| /Mpa Glazed | 30~40 | 35~45 | 60~80 |
| $\sigma_c$ /Mpa Non-glazed | 400~500 | 500~600 | 700~800 |
| Linear expansion coefficient X10$^{-6}$/□$^{-1}$ | 4.5~6.5 | 6~7 | 5~6 |
| Thermal shock resistance /□ | 150~200 | 130~180 | 180~230 |
| Breakdown strength□50Hz□20□□/Kv.mm$^{-1}$ | 25~35 | 25~30 | 25~35 |
| Dielectric coefficient □50Hz□20□□ | 6~7 | 6~7 | 6.5~7.5 |
| Dielectric loss □50Hz□20□□tgδ | 0.02~0.04 | 0.02~0.03 | 0.02~0.03 |
| Module of elasticity /GPa | 50~80 | 50~80 | 100~110 |

In developed countries, normal high voltage electrical ceramics is no longer used in ESP for a long time. Instead of it, 50% aluminum is for low temperature (less than 50□), 85% aluminum is used for 150-240□. For temperature higher than 250□, 95%aluminum will be used. Now in China, only Nanjing Tailong Co. and Zhuzhou Spark Plug Factory introduced 95% aluminum to make insulators. Now products of Nanjing Tailong has been exported to USA and Korea.

Table 5  Formulations of domestic ESP insulators

| Manufacturer | Ceramic | Main crystal | Chemical composition ω/□ | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | $Al_2O_3$ | $SiO_2$ | $K_2O+Na_2O$ | CaO+MgO | $Fe_2O_3$ | $TiO_2$ |
| Tongchuan | Feldspar | Feldspar | 20~24 | 65~72 | 3.5~5.0 | □1.2 | □1.0 □ | 0.4~0.6 |
| Jiujiang | | | | | | | | |
| Xuanhua□8□ | High silicon | Cristobalite | 26.5 | 63.5 | 2.85 | 0.6 | 0.8 | 0.4 |
| Nanjing Tailong | High alumina□50□ | Mullite | 51.2 | 41.5 | 3.9 | 0.8 | 0.8 | 1.9 |
| | Corundum□95□ | Corundum | 95.0 | 3.5 | □ | 1.5 | □0.1 □ | □ |

As in high aluminum ceramics the main component is α-$Al_2O_3$ (85% and above), no or very few clay induced, so it electrical characteristics under high temperature is very good [9](Table. 6).

Table 6  Properties of alumina ceramics

| Percentage of alumina□% | 85 | 90 | 95 | 99 |
|---|---|---|---|---|
| Heat conductivity /W.□$^{-1}$.cm$^{-2}$ | □ | □ | □ | □ |
| 20□ | 0.14 | 0.16 | 0.24 | 0.33 |
| 100□ | 0.12 | 0.13 | 0.19 | 0.27 |
| 400□ | 0.06 | 0.08 | 0.10 | 0.13 |
| 800□ | 0.04 | 0.05 | 0.05 | 0.06 |
| Dielectric coefficient at room temp.□25□□ | | | | |
| 1kHz | 8.2 | 8.8 | 9.0 | 9.9 |
| 1MHz | 8.2 | 8.8 | 9.0 | 9.8 |
| 100MHz | 8.2 | 8.7 | 9.0 | |
| 1GHz | 8.2 | | 8.9 | |
| 10GHz | 8.2 | 8.7 | 8.9 | 9.8 |
| 50GHz | □ | □ | 8.7 | □ |
| Dielectric strength at room temperature□50Hz, 25□□ | | | | |
| Thickness 0.63cm /kV.cm$^{-1}$ | 94.5 | 92.4 | 82.6 | 94.5 |
| 0.31cm /kV.cm$^{-1}$ | 133.8 | 125.9 | 108.2 | 127.9 |
| 0.13cm /kV.cm$^{-1}$ | 173.2 | 177.1 | 145.6 | 181.1 |
| 0.06cm /kV.cm$^{-1}$ | 216.5 | 228.3 | 177.1 | 232.3 |
| 0.02cm /kV.cm$^{-1}$ | 283.4 | 299.2 | 228.3 | 314.9 |
| Volume resistivity at 25□ /Ω.cm$^2$.cm$^{-1}$ | □$10^{14}$ | □$10^{14}$ | □$10^{14}$ | □$10^{15}$ |
| 300□ /Ω.cm$^2$.cm$^{-1}$ | $4.6X10^{10}$ | $1.4X10^{11}$ | $1.1X10^{13}$ | $1.0X10^{15}$ |
| 500□ | $4.0X10^{8}$ | $2.8X10^{8}$ | $4.0X10^{9}$ | $3.3X10^{12}$ |
| 700□ | $7.0X10^{6}$ | $9.0X10^{6}$ | $1.0X10^{8}$ | $9.0X10^{9}$ |
| 1000□ | | | $1.0X10^{6}$ | $1.1X10^{7}$ |
| Te□/□ | 850 | 960 | 1000 | 1170 |

## Prevent local discharging

To avoid local discharging, first of all, internal bubbles, pores and cracks must be eliminated as much as possible. Secondly, reasonable structure design helps uniform electric field distribution.

Moreover, based on particulates characteristic (such as stickiness, resistivity, etc.) enough surface leaking distance should be maintained. Finally, increase the material high voltage durability; material with high Te should be used for making insulators.

Nowadays, there are two methods to make insulator mould: vacuum wet and uniform static pressure. The first one gives the mould high water content, and also lead to laminate, cracking or porous structure, some of them will be broken under high temperature, all these will cause internal bubbles and cracks [10]. No clay is used in uniform static pressure process, gives the mould very low water content. Under 100 MPa pressure compressing, mould internal structure is uniform and highly compact, rarely has bubble and crack inside.

Making a uniform field distribution near the insulator surface can reduce the possibility of local corona discharge. For uniform field, non-uniform field and extra-non-uniform field (see Fig. 6), the corona onset field strength is approximately 10, 5 and 2.5 kV/cm respectively.

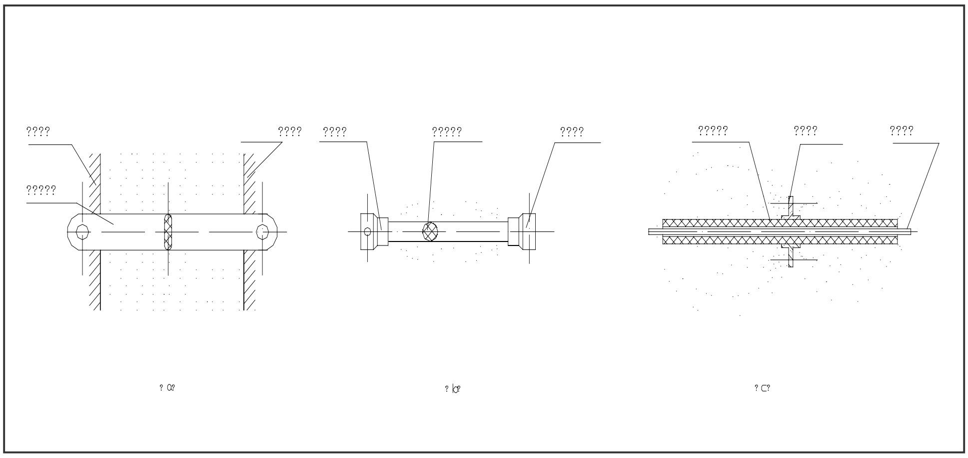

Fig. 6 Several types of electric fields close to Insulator

Basically speaking ESP insulators is a non-uniform field insulation structure, such as rotating shaft, rapping bar, supporting bar and pull rod, etc. Wall bushing belongs to extra-non-uniform field insulation structure. Support bushing located at the middle of both above.

The following provisions can reduce the non-uniform degree of insulators.

- For wall bushing, keep the ratio of outside and inside diameter D/d about 2.7. As we know in a cylinder capacitor, the strongest field strength is at the $r_1$, of the inside surface. Where $Er_1 = \frac{U}{r_1 \ln \frac{r_2}{r_1}}$. When $\ln \frac{r_2}{r_1} = 1$, *i.e.* $\frac{r_2}{r_1} = e$, value of $Er_1$ is minimum,
- Shape the hot end (insert into ESP) of wall bushing to be an umbrella, as Fig.7,
- Conductive layer are applied on the surfaces of inside hole and outside roots at the ends close to the flange. Insert a spring leaf between high voltage rod and inner hole so as to make the air gap to be a short circuit. This not only makes electric force line passes through just one medium, but also reduce field concentration,
- All corners of the metal parts are round to eliminate local high voltage concentration,
- A hyperbolic protection tube (Fig 8) added at the bottom end of support bushing will endure the biggest field. It not only prevented the bushing from flashover but also even the field strength and keep dust free [12].
- Increase the insulator's leakage length (76~100mm/10kV average and 350mm/10kV Max.) and reduce the insulator's diameter. Generally do not use umbrella, if have to use, use downward shape umbrella for vertical insulator and symmetrical wave shape umbrella for horizontal insulator. For 95% alumina ceramic wall bushing, $\phi$50mm is enough for general high voltage use. Small diameter is beneficial to heat dissipation.

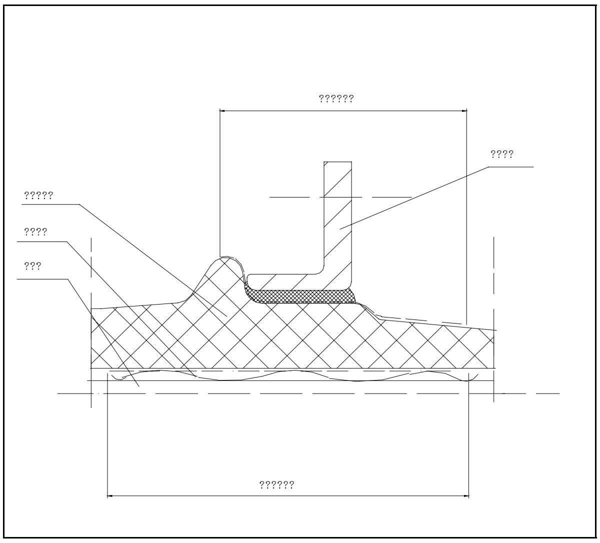

Fig. 7 Wall Bushing Detail

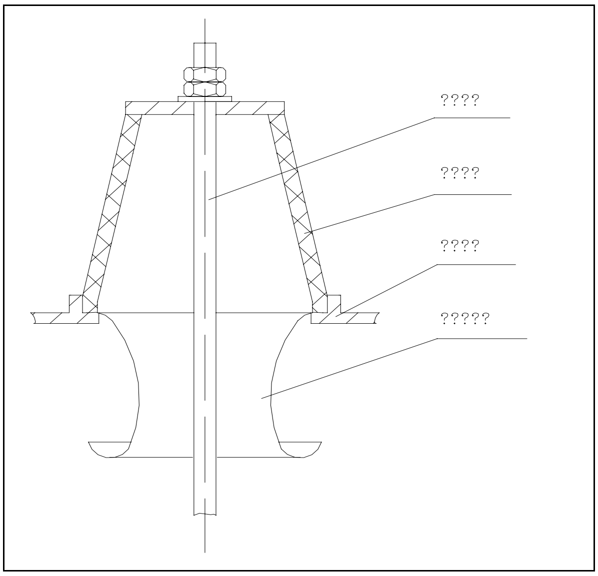

Fig. 8 Support bushing with hyperbolic protector

- Cleaning insulator periodically is necessary to prevent insulator aging. Clean once a month normally, but for heavy polluted insulator, every 15days and heat air purging system is recommended.
- Using uniform static pressure shaping high alumina insulator is a good choice. Occasionally flashover will not lead to heat breakdown, on the contrary, due to the electro-dynamic effect, contamination attached to the insulator surface can be cleaned away, *i.e.* so-called self-cleaning.

Although high aluminum insulator is relatively expensive, yet customers having tried it would not like to use ordinary electrical ceramics insulator again. We have plenty of experience to conclude that the aluminum ceramic insulator is the right selection to keep ESP operation reliability.

## Conclusion

It is important to select insulator material with higher Te. High Corundum□$\alpha$-$Al_2O_3$) ceramics with a Te of 850□, has stable structure under high temperature and higher heat conductivity, is the ideal material for insulator. Long time tests shown that 50% $Al_2O_3$ ceramics is suit for ESP under 150□, 85% $Al_2O_3$ ceramic is suit for 150~200□ and 95% $Al_20_3$ is suit for temperature above 250□.

Good design will give insulator an even electric field with a reasonable leakage gap at the hot end. Meanwhile advanced process (uniform static pressure) will eliminate minor defects in insulator to raise its local discharging voltage. Of course, regular maintenance is also necessary.

## References

[1] Steinknhler. Bill: ***ESP Insulator Design and Selection***, ESP & Flue Gas Purifying, 1997□2□P29~31

[2] Sladek R. ***Quality Warrantee to High Pressure Insulator from Modern Kiln*** Technology International Ceramic Chinese Version 1994, 43(“C”), P21

[3] Ding Zishang Chief Editor: ***Physics & Chemistry of Silicate***. Beijing, China Construction Industrial Press,1980

[4] Xia Aisheng: ***High Voltage Engineering and Insulator Design***, Changsha, Hunan University Press 1983

[5] ***Ceramic (Silicate) Guide ’96, China Silicate Society Handbook***, Vol. 2, Beijing, China Construction Material Press, 1996, P44

[6] Hans Liebermann: ***Reliability of High Voltage Insulator Material***, Porcelain Lighting Arrester, 1980(5): P13-16

[7] Yixing Ceramic Industrial School: ***Science of Ceramic Process***, Beijing Light Industrial Press, 1985: P503-504

[8] Li Baichen,et.al: ***Development and Utilizing of Xuanhua Ceramic Stone***, Hebei Ceramic Vol. 26, No1. 1998, P32-36.

[9] Lynch, C. T. ***Handbook of Materials Science***□Vol. 2, CRC Press□1974, P360~362

[10] Liu Shikang, Chief Editor: ***Science of Ceramic Process***, Beijing China Construction Press,1981

[11] Zhang Guansheng, Chief Editor: ***Science of Electric Appliance***, Beijing Machinery Press,1980

[12] Ling Hong***: Electrostatic Precipitator*** Beijing, China Construction Press, 1987

[13] Long Tao, et.al: ***Design and Selection of ESP Insulator***, Electrostatic Precipitation and Gas Cleaning, 2003(2), P29-33