CHAPTER 4

EXPERIMENTAL RESULTS

This chapter presents the experiment results carried out by lightning impulse and AC voltage tests under natural atmospherics conditions of high voltage laboratory, Chulalongkorn University. The correction of test voltage at laboratory atmospheric conditions to standard conditions by using correction factors recommended by IEC 60060-1: 1989 and IEEE4: 1995, ANSI C29.1: 1988 and IEEE4 Amendment 1 Std-4a: 2001 and a new propose humidity correction factor for IEC is described.

4.1 Experiment results

All flashover voltage U_i are plotted against absolute humidity to air density h/δ, the standard division of which are in the range of ±3%. The analysis of test results divided into two humidity range, namely: 1. $1g/m^3 < h/\delta \leq 15g/m^3$. 2. $h/\delta > 15g/m^3$. Each point in all figures represents 20 measured U_i values by using up-down method to find 50% breakdown voltage under tests with both polarities lightning impulse, called $U_{50\%}$. For the testing AC voltage, it is the average of flashover voltage 6 measured U_i values.

Figure 4.1 to 4.12 show test results that are corrected by using only air density correction factor recommended by IEC 60060-1: 1989 and ANSI C29.1: 1988 (Appendix B). We can see that the corrected values have some difference. This is because the standard temperature of IEC is 20°C while it is 25°C for ANSI. We can also see clearly that the breakdown voltage increase with the h/δ.

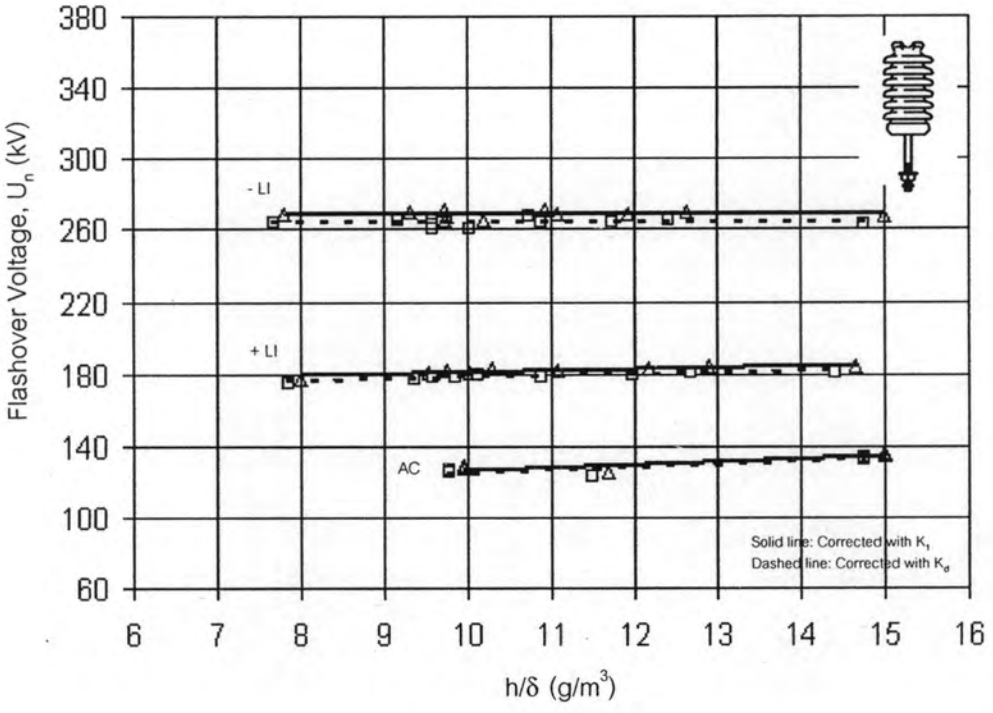

Figure 4.1 Flashover voltage of line-post insulator class 57-2

$1g/m^3 < h/\delta < 15g/m^3$, corrected only with K_1 for IEC and K_d for ANSI

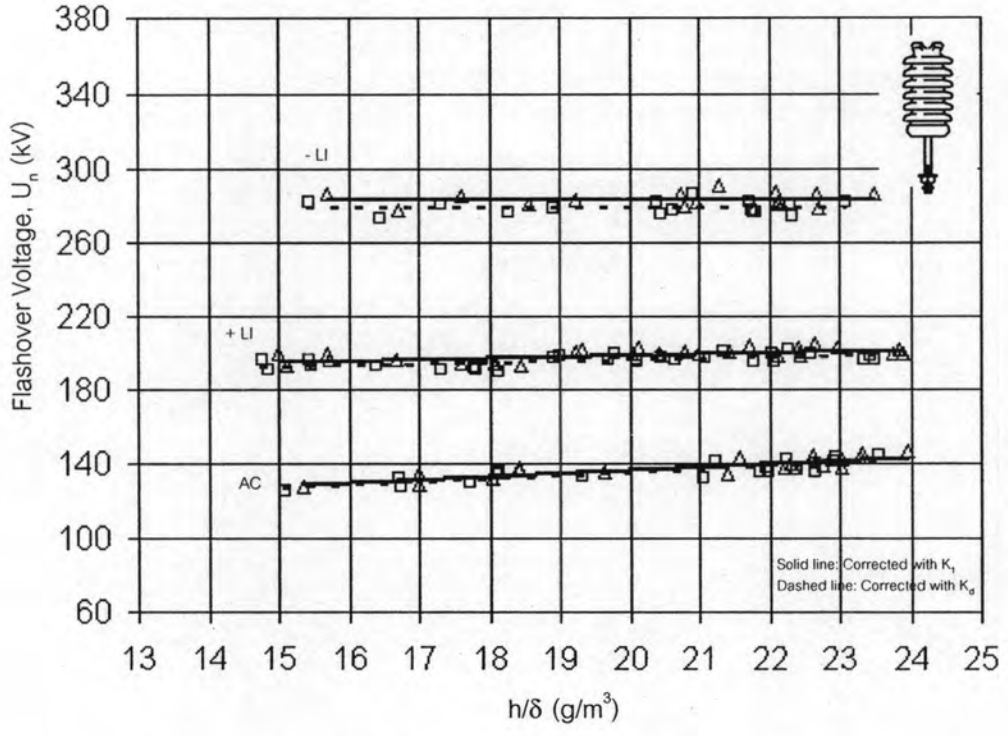

Figure 4.2 Flashover voltage of line-post insulator class 57-2

$h/\delta > 15g/m^3$, corrected only with K_1 for IEC and K_d for ANSI

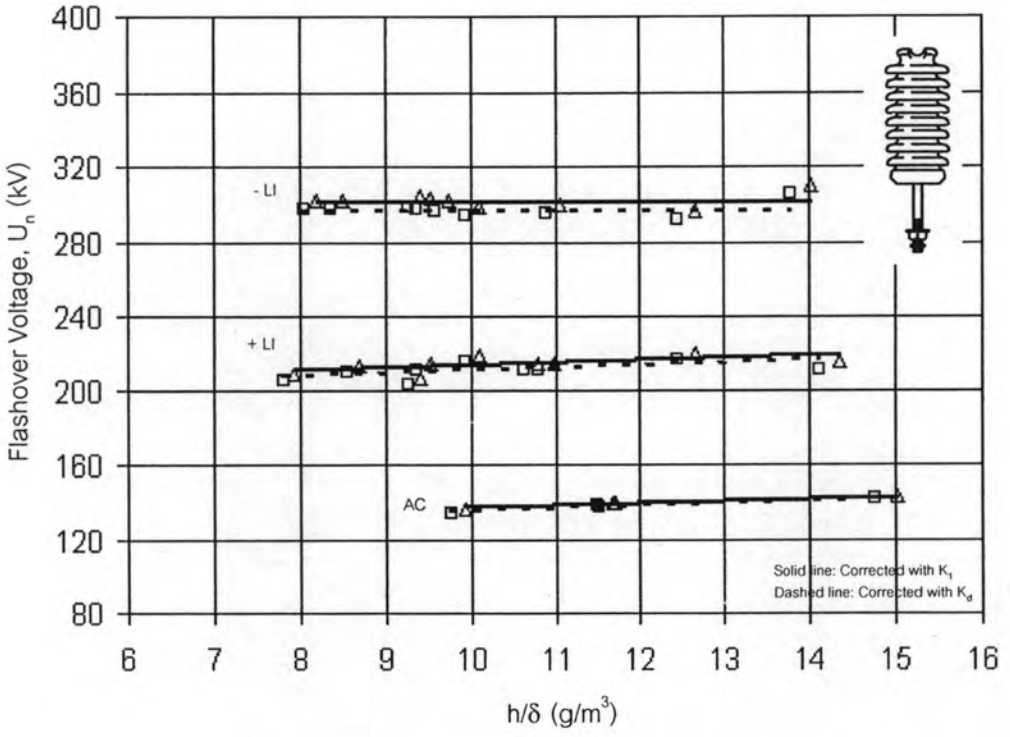

Figure 4.3 Flashover voltage of line-post insulator class 57-3

$1g/m^3 < h/\delta < 15g/m^3$, Correct only with K_1 for IEC and K_d for ANSI

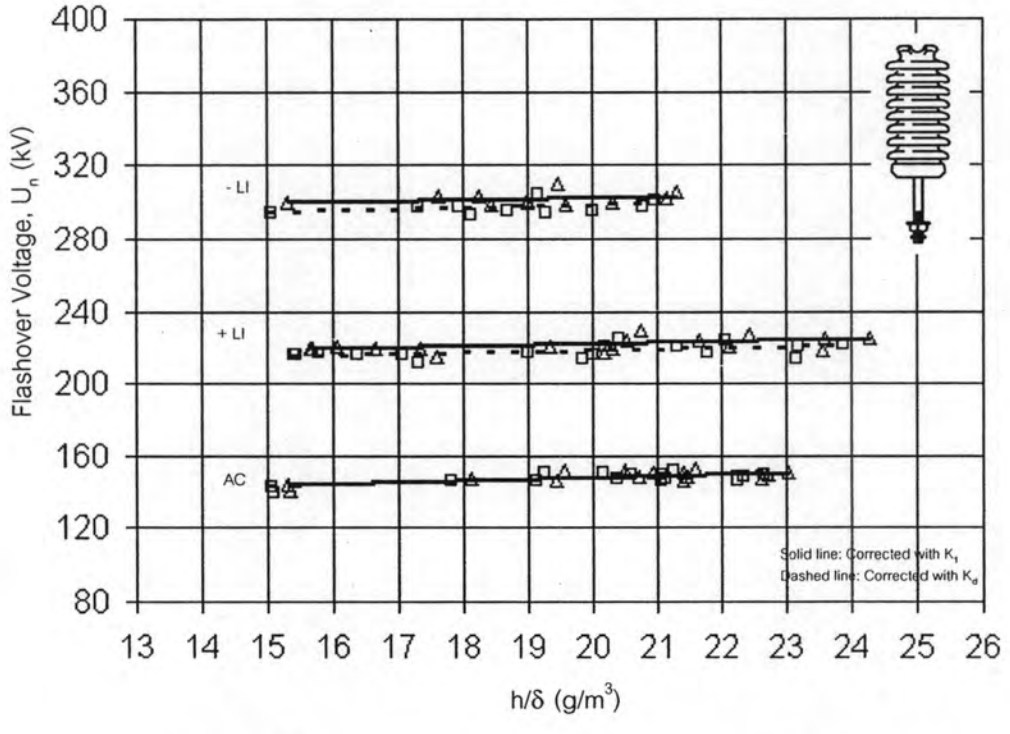

Figure 4.4 Flashover voltage of line-post insulator class 57-3

$h/\delta > 15g/m^3$, Correct only with K_1 for IEC and K_d for ANSI

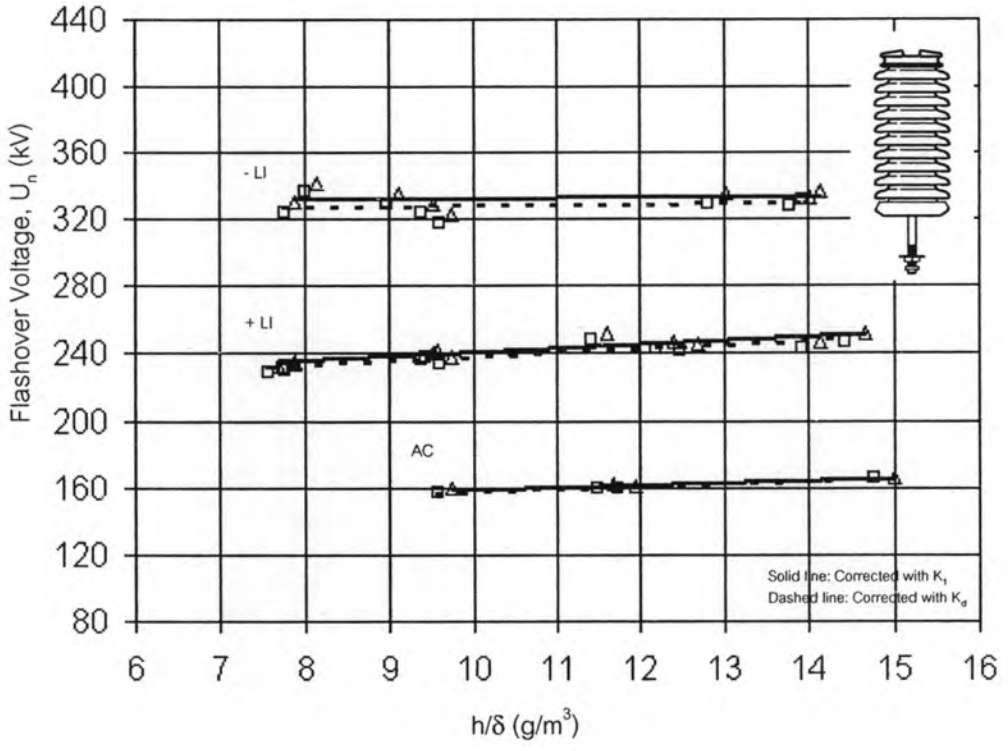

Figure 4.5 Flashover voltage of line-post insulator class 57-4

$1g/m^3 < h/\delta < 15g/m^3$, Correct only with K_1 for IEC and K_d for ANSI

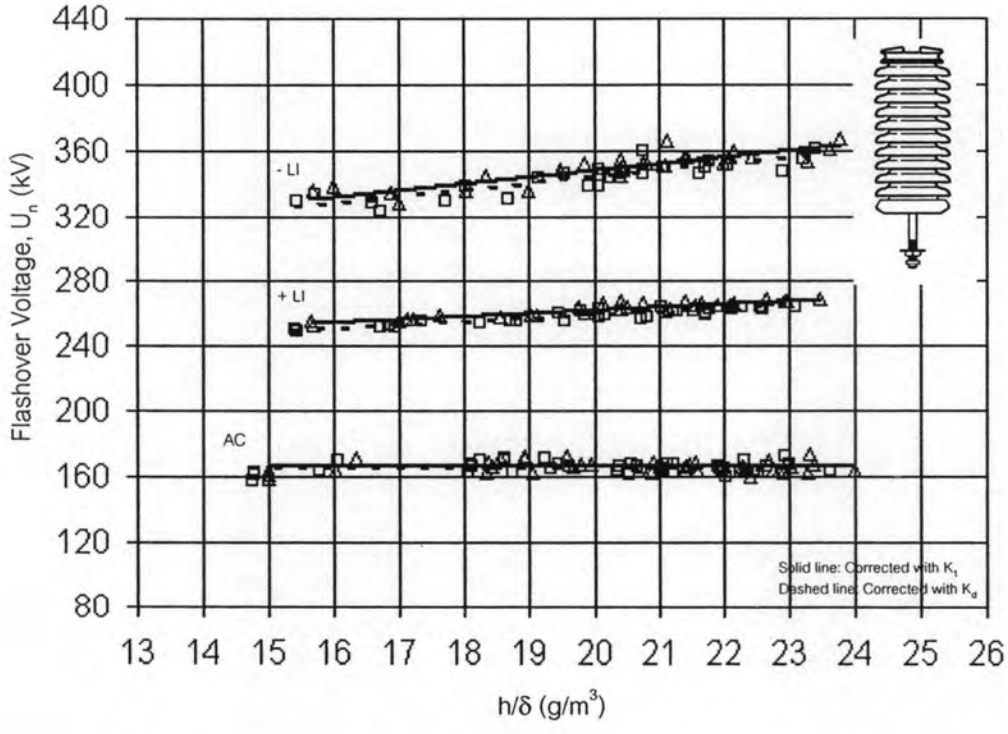

Figure 4.6 Flashover voltage of line-post insulator class 57-4

$h/\delta > 15g/m^3$, Correct only with K_1 for IEC and K_d for ANSI

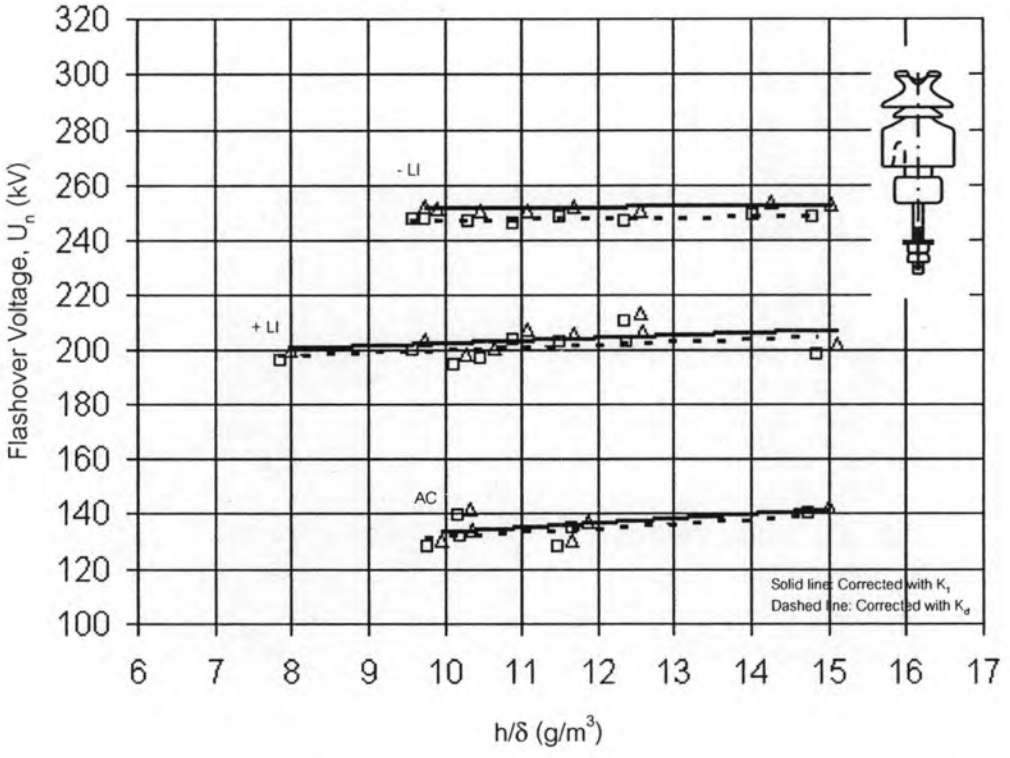

Figure 4.7 Flashover voltage of pin-post insulator class 56/57-2

$1g/m^3 < h/\delta < 15g/m^3$, Correct only with K_1 for IEC and K_d for ANSI

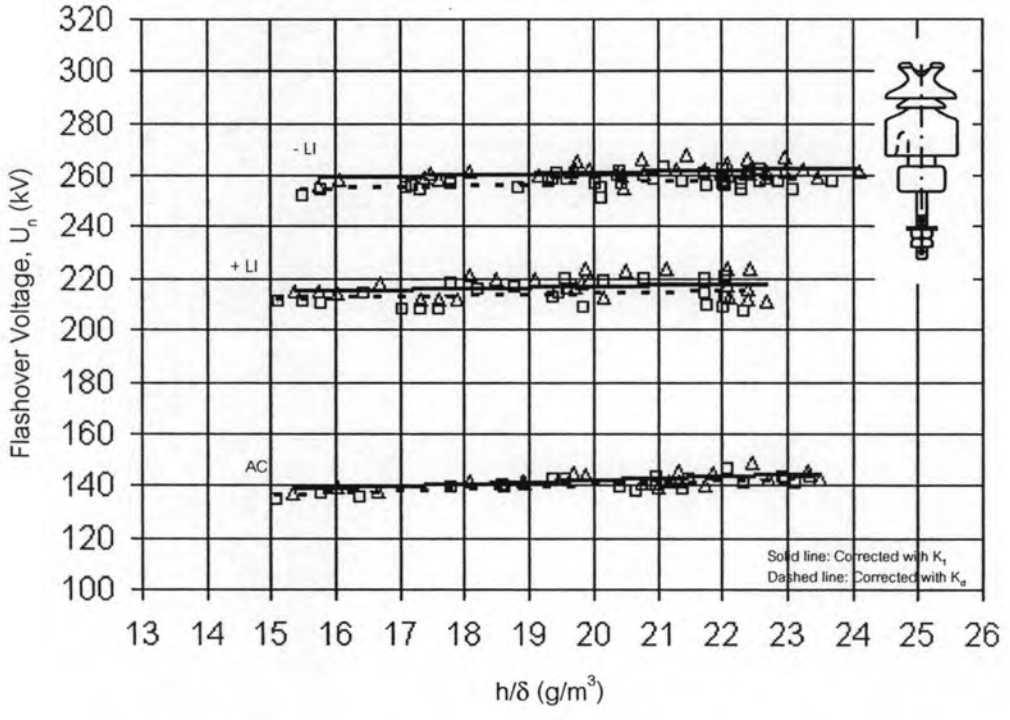

Figure 4.8 Flashover voltage of pin-post insulator class 56/57-2

$h/\delta > 15g/m^3$, Correct only with K_1 for IEC and K_d for ANSI

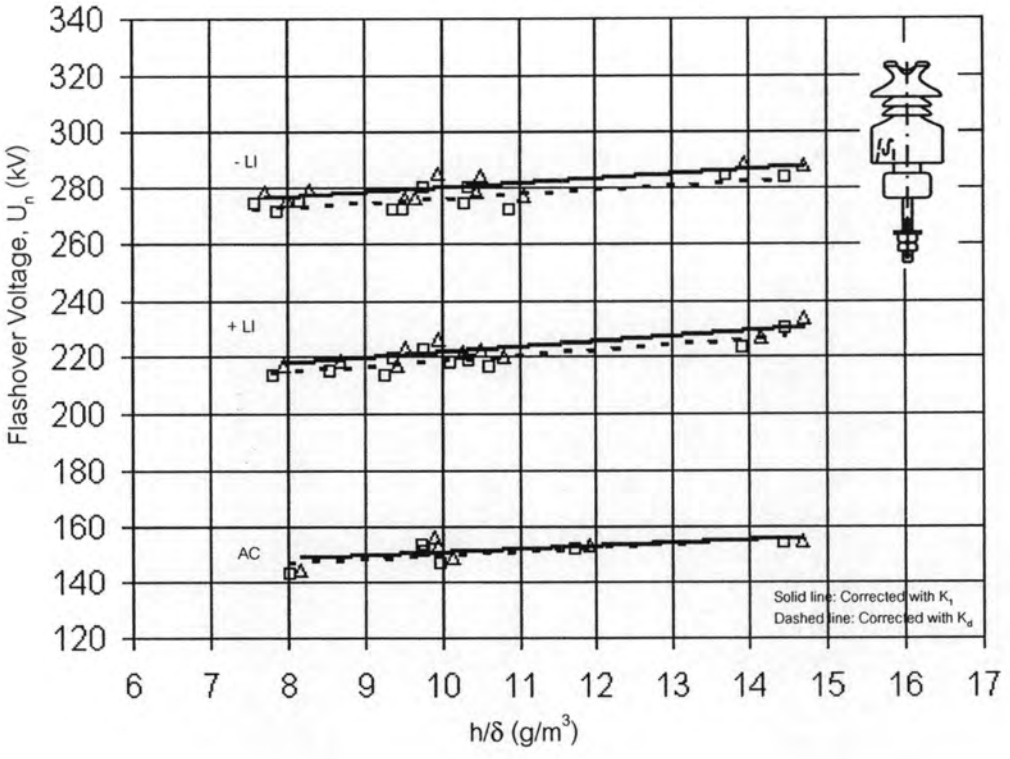

Figure 4.9 Flashover voltage of pin-post insulator class 56/57-3
$1g/m^3 < h/\delta < 15g/m^3$, Correct only with K_1 for IEC and K_d for ANSI

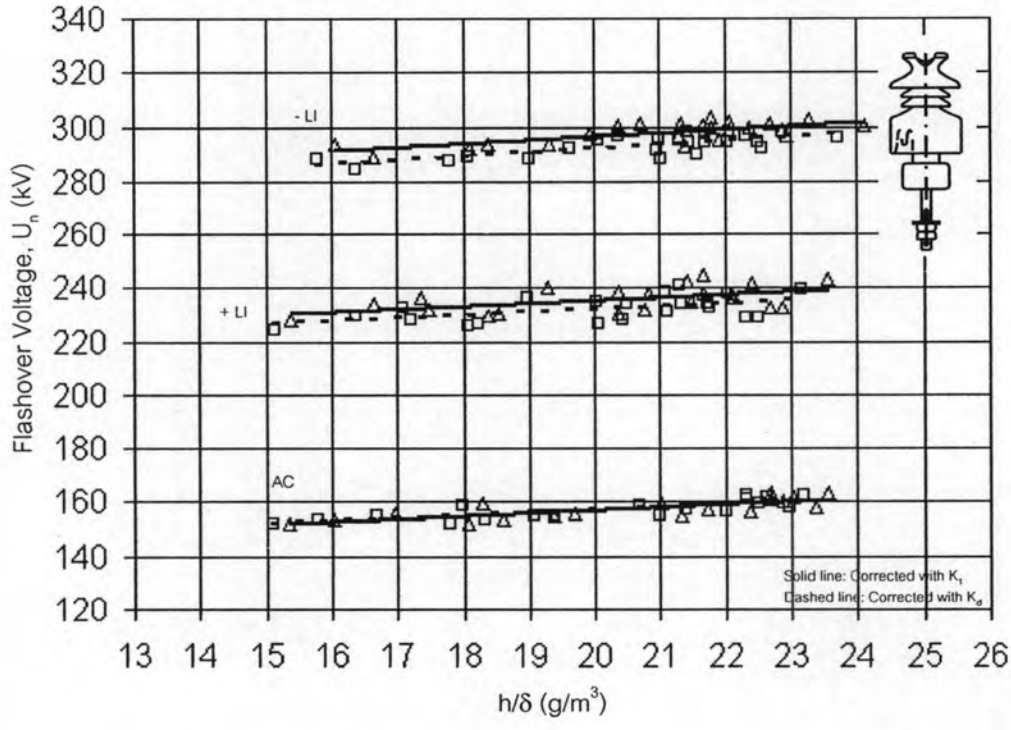

Figure 4.10 Flashover voltage of pin-post insulator class 56/57-3 $h/\delta > 15g/m^3$
Correct only with K_1 for IEC and K_d for ANSI

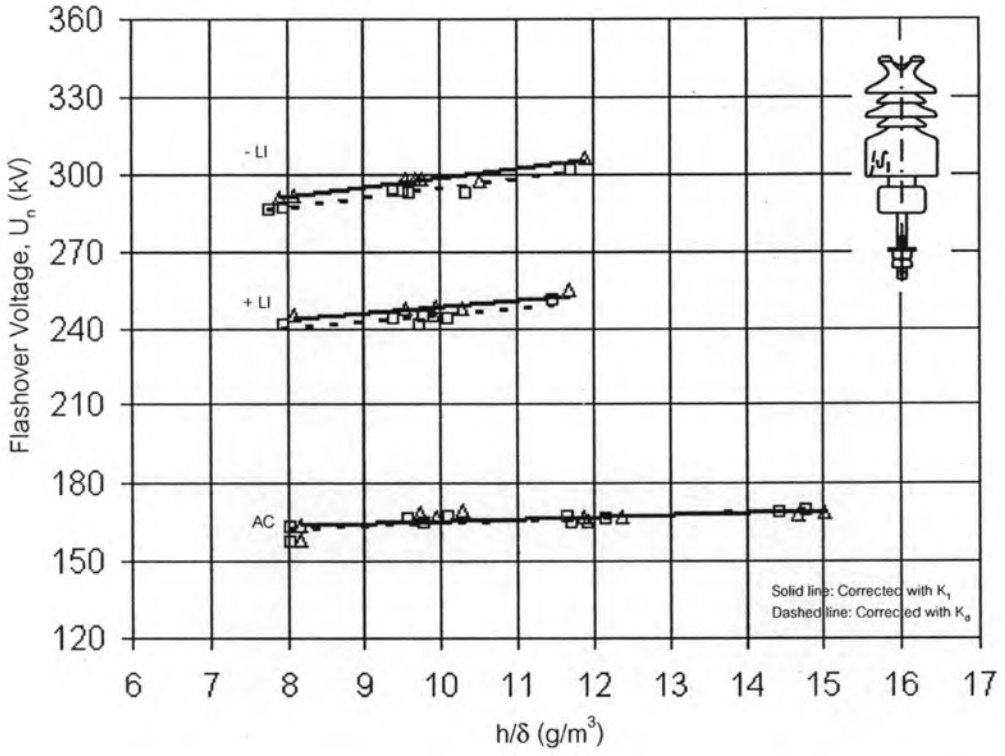

Figure 4.11 Flashover voltage of pin-post insulator class 56/57-4
$1g/m^3 < h/\delta < 15g/m^3$, Correct only with K_1 for IEC and K_d for ANSI

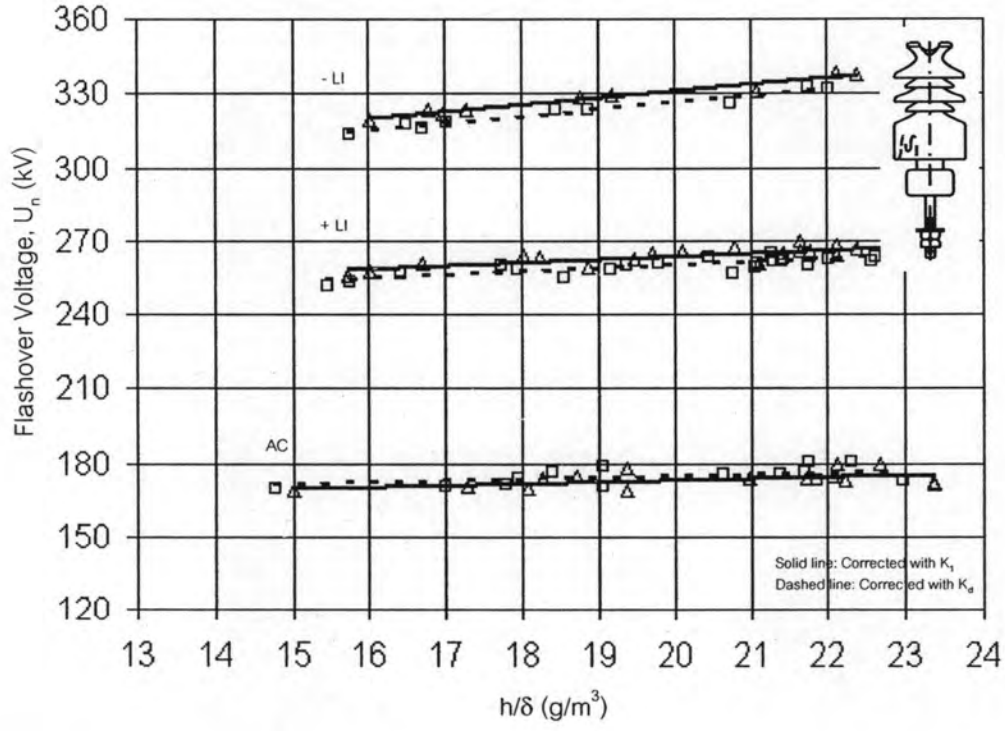

Figure 4.12 Flashover voltage of pin-post insulator class 56/57-4
$h/\delta > 15g/m^3$, Correct only with K_1 for IEC and K_d for ANSI

4.2 Effect of humidity Correction Factors

The breakdown voltage of insulators and other apparatus are normally referred to the reference atmospheric condition. Therefore, this section will be discussed the applicability of humidity correction factor for lightning impulse and AC voltage tests suggested by IEC 60060-1: 1989/IEEE4-1995, Amendment 1 IEEE Std4a: 2001 and ANSI C29.1-1988.

4.2.1 IEC 60060-1: 1989 and IEEE4: 1995

In IEC recommend procedure [2], the standard atmosphere conditions are temperature 20°C, pressure 760mmHg and absolute humidity 11g/m^3. A flashover voltage, U_i, measured at a different atmospheric conditions is converted to the standard condition, U_n by dividing the U_i with a correction factor, $K = K_1.K_2$ (section 2.3 and appendix B). Figure 4.13 - 4.24, shows the breakdown voltage at standard condition when we applied the atmospheric correction factor suggested by IEC 60060-1:1989 and IEEE4: 1995.

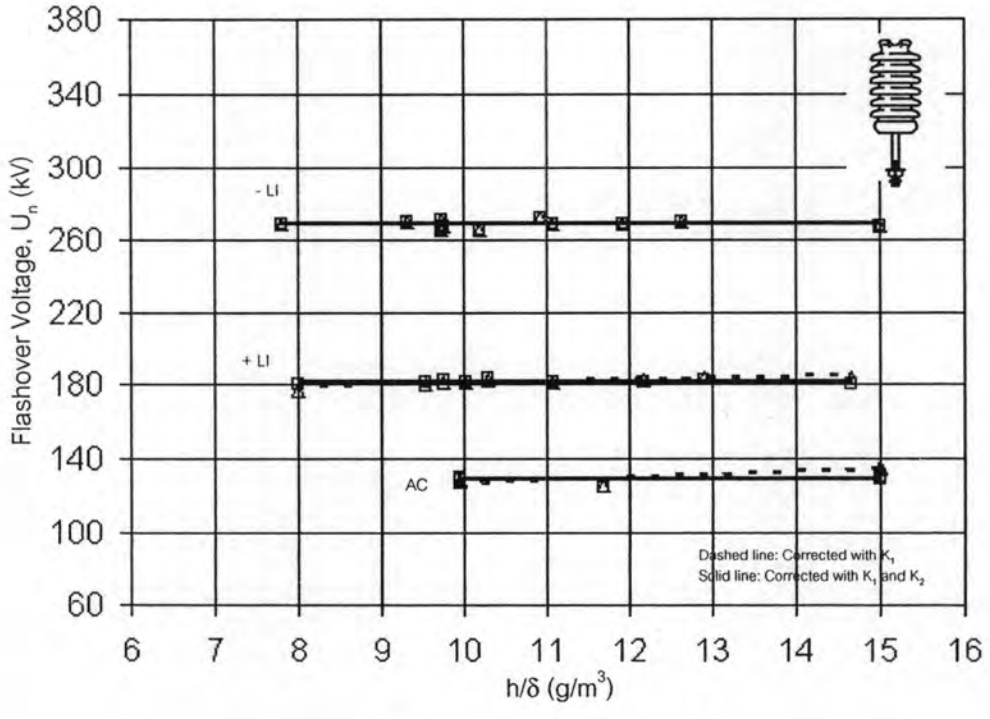

Figure 4.13 Flashover voltage of line-post insulator Class 57-2
1g/m^3 < h/δ < 15g/m^3, Correct by using IEC 60060-1: 1989 recommendation

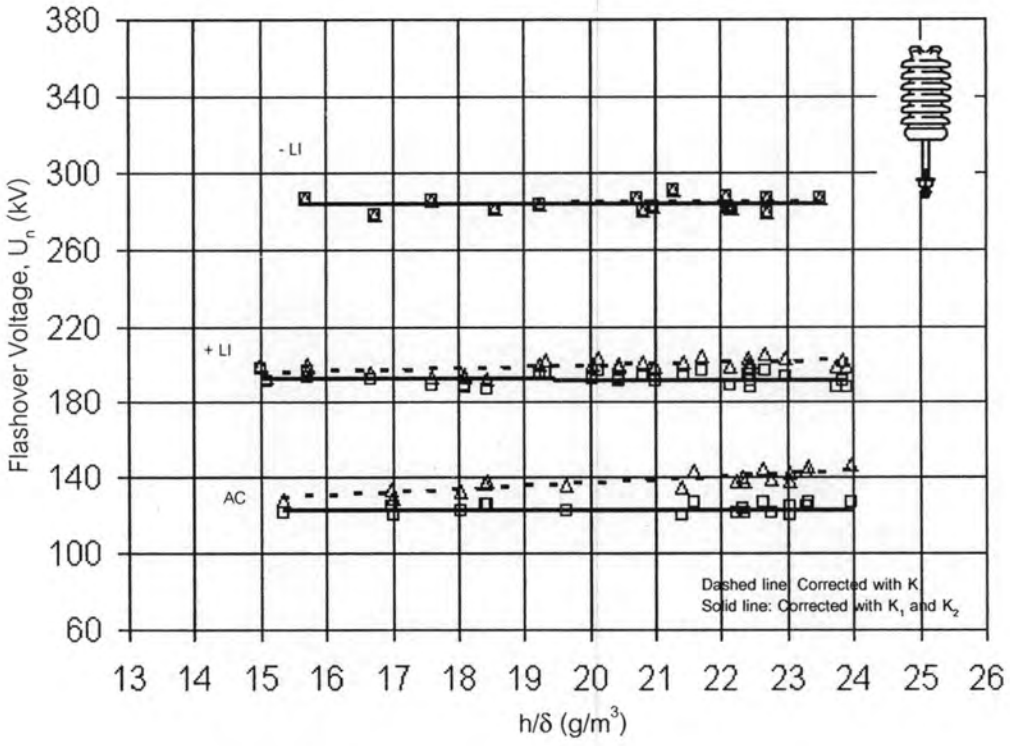

Figure 4.14 Flashover voltage of line-post insulator Class 57-2
$h/\delta > 15 g/m^3$, Correct by using IEC 60060-1: 1989 recommendation

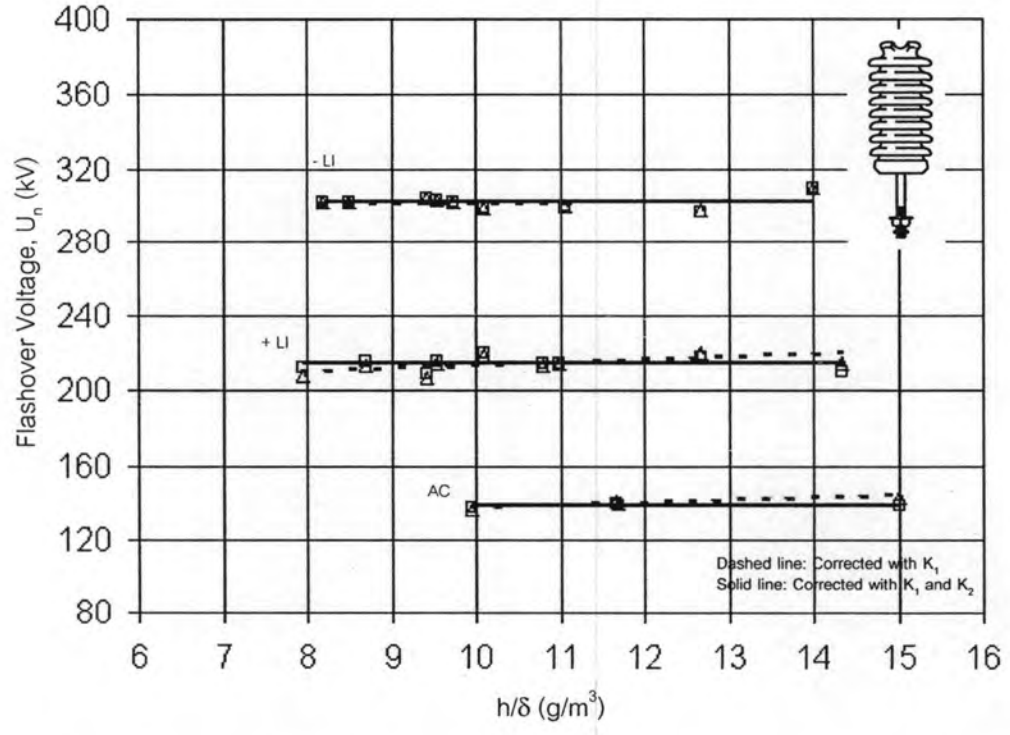

Figure 4.15 Flashover voltage of line-post insulator Class 57-3
$1 g/m^3 < h/\delta < 15 g/m^3$, Correct by using IEC 60060-1: 1989 recommendation

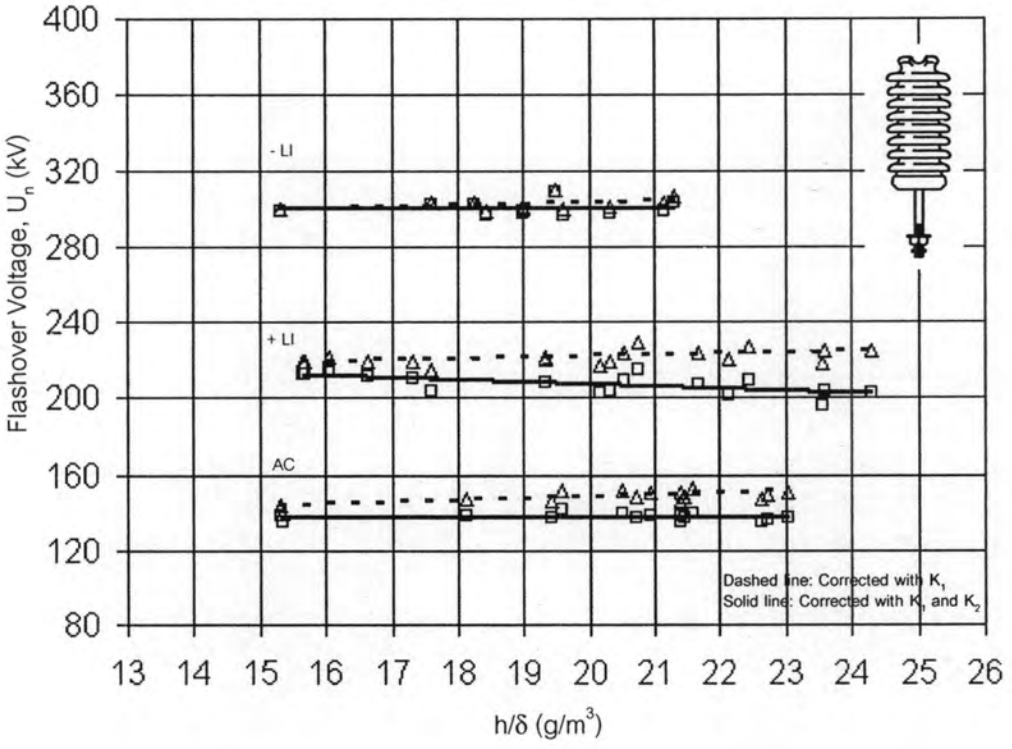

Figure 4.16 Flashover voltage of line-post insulator Class 57-3
h/δ > 15g/m^3, using IEC 60060-1: 1989 recommendation

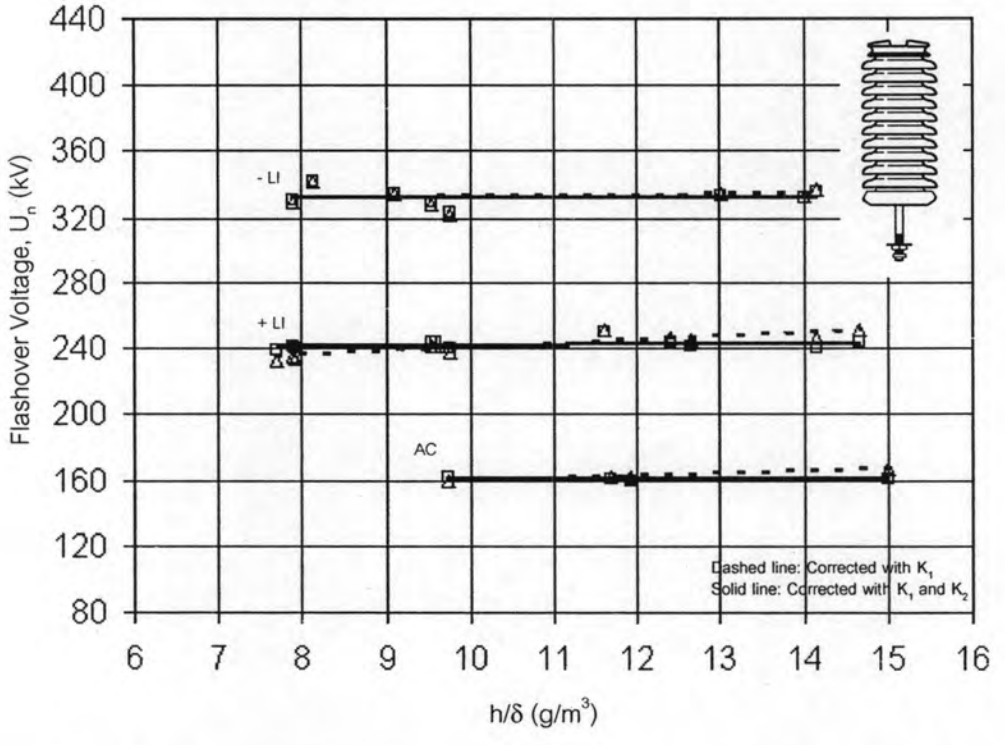

Figure 4.17 Flashover voltage of line-post insulator Class 57-4
1g/m^3 < h/δ < 15g/m^3, Correct by using IEC 60060-1: 1989 recommendation

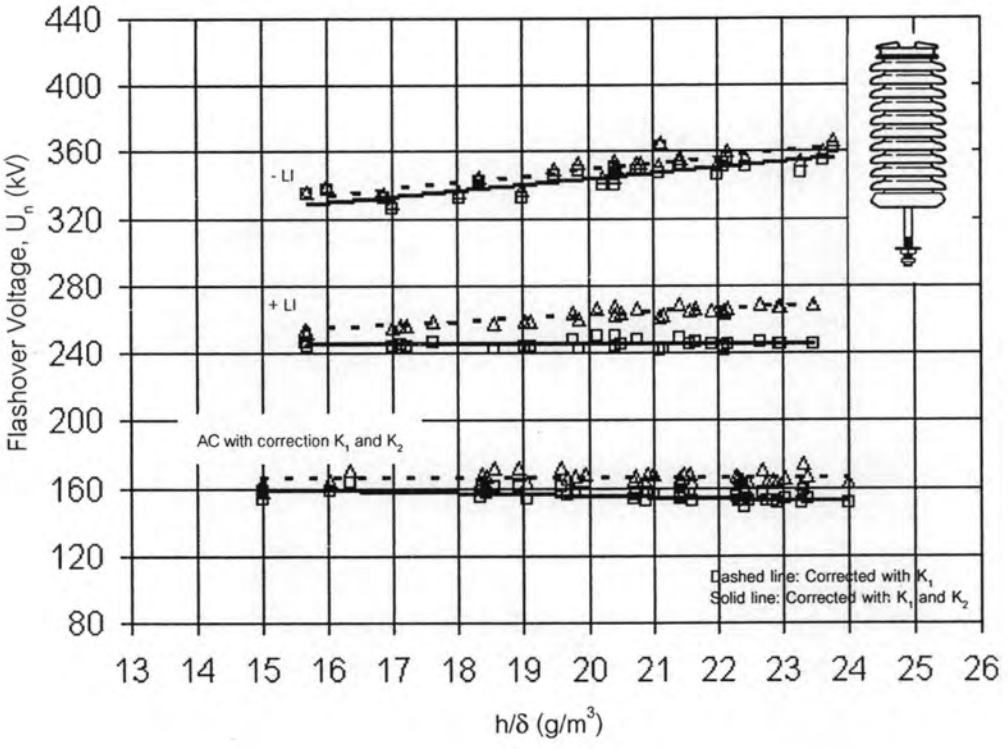

Figure 4.18 Flashover voltage of line-post insulator Class 57-4

$h/\delta > 15 g/m^3$, Correct by using IEC 60060-1: 1989 recommendation

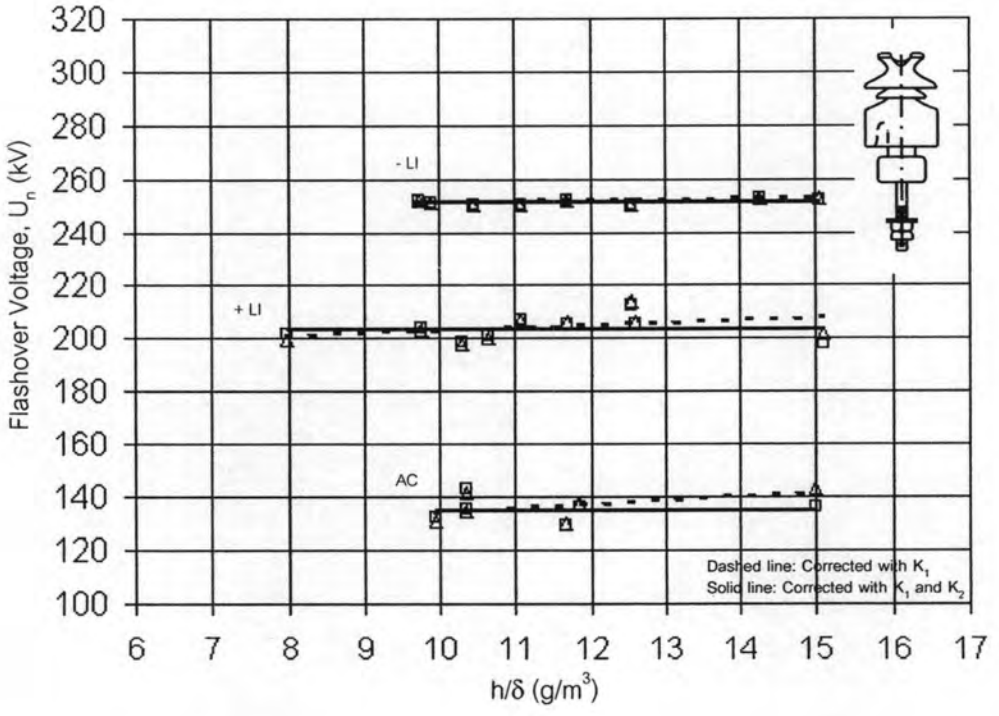

Figure 4.19 Flashover voltage of line-post insulator Class 56/57-2

$1 g/m^3 < h/\delta < 15 g/m^3$, Correct by using IEC 60060-1: 1989 recommendation

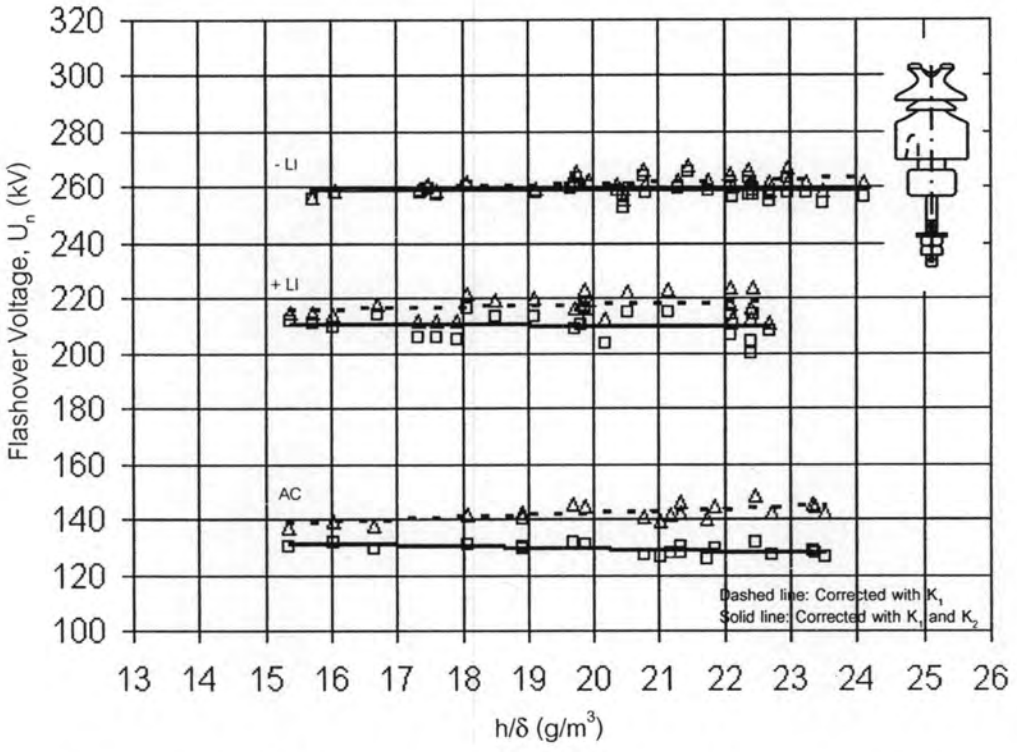

Figure 4.20 Flashover voltage of line-post insulator Class 56/57-2
h/δ > 15g/m^3, Correct by using IEC 60060-1: 1989 recommendation

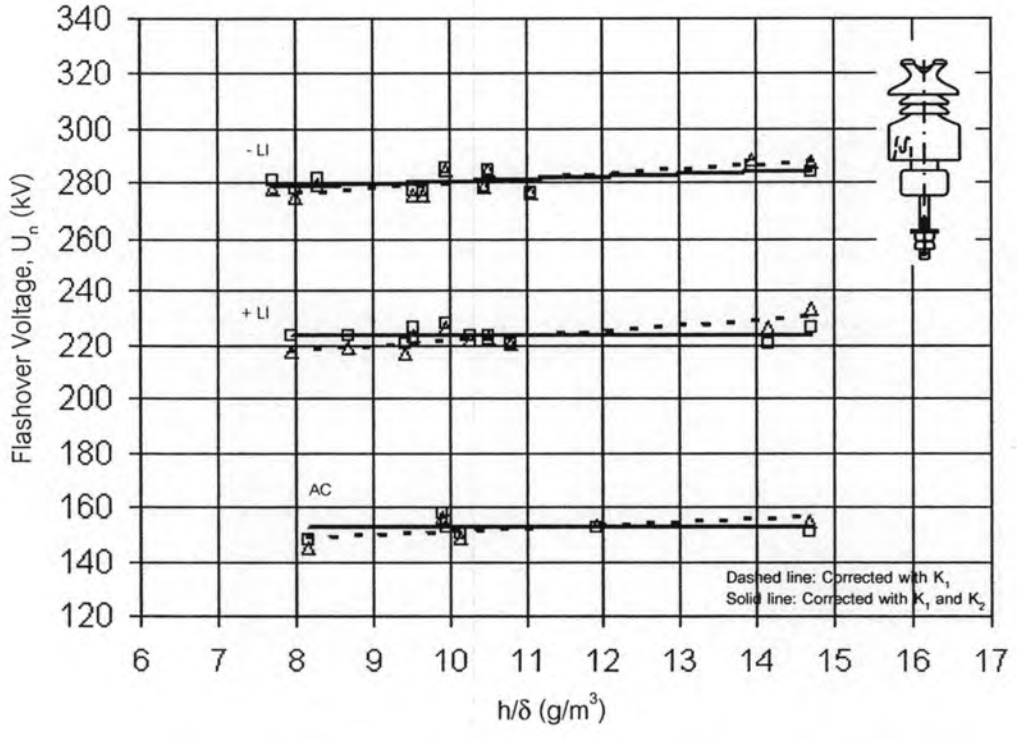

Figure 4.21 Flashover voltage of line-post insulator Class 56/57-3
1g/m^3 < h/δ < 15g/m^3, Correct by using IEC 60060-1: 1989 recommendation

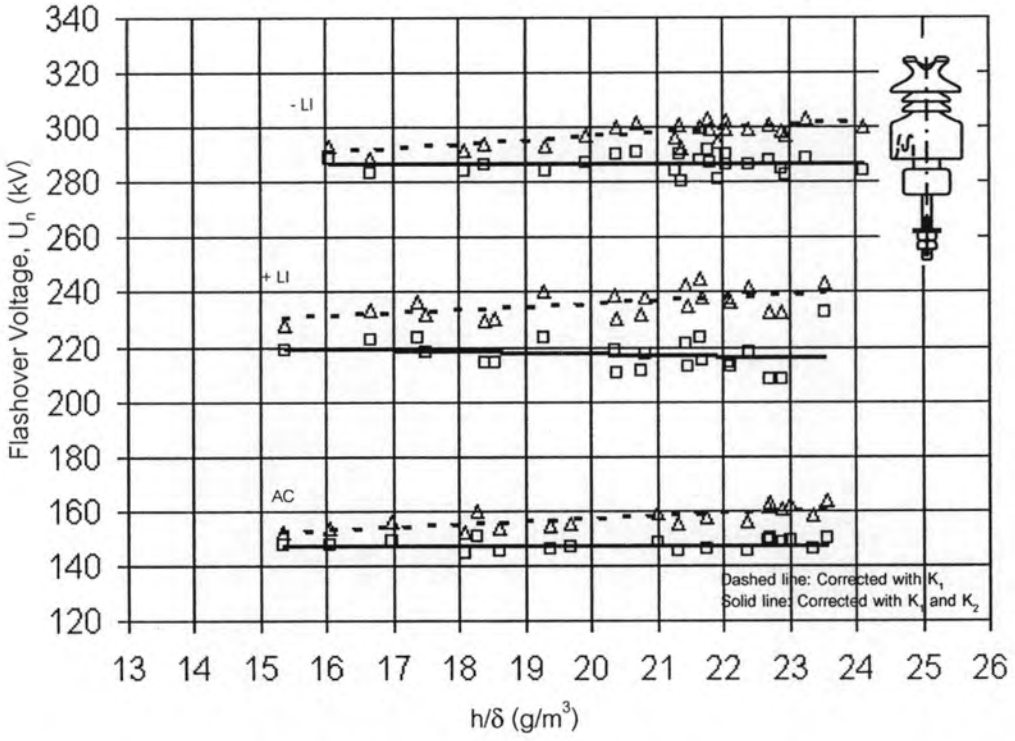

Figure 4.22 Flashover voltage of line-post insulator Class 56/57-3

$h/\delta > 15 g/m^3$, Correct by using IEC 60060-1: 1989 recommendation

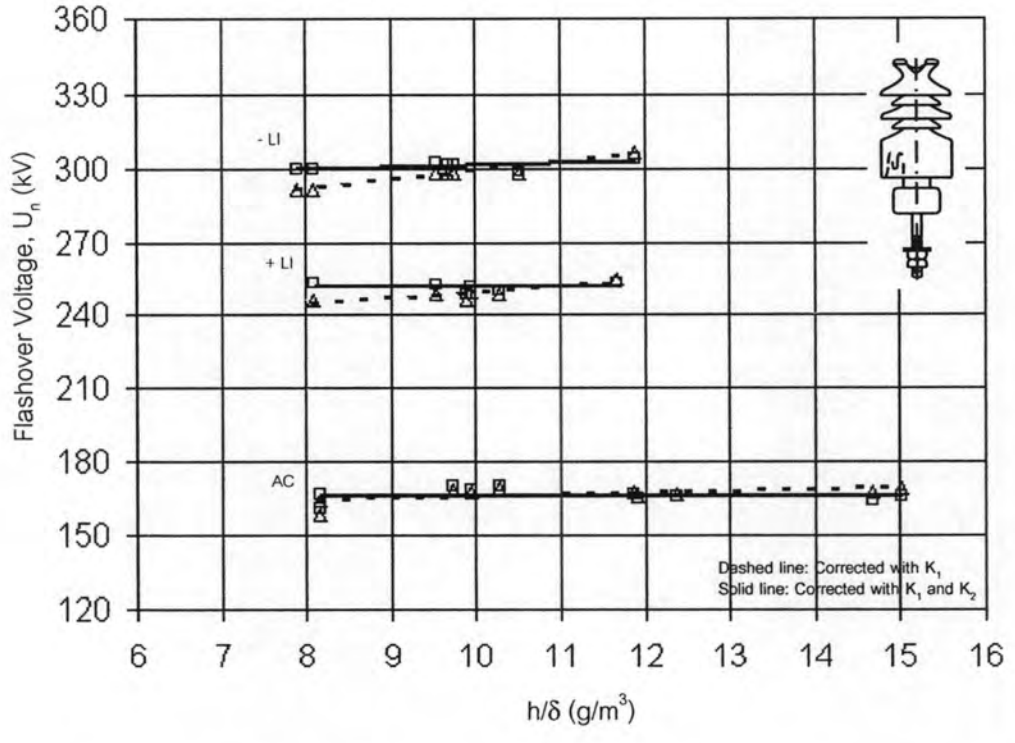

Figure 4.23 Flashover voltage of line-post insulator Class 56/57-4

$1 g/m^3 < h/\delta < 15 g/m^3$, Correct by using IEC 60060-1: 1989 recommendation

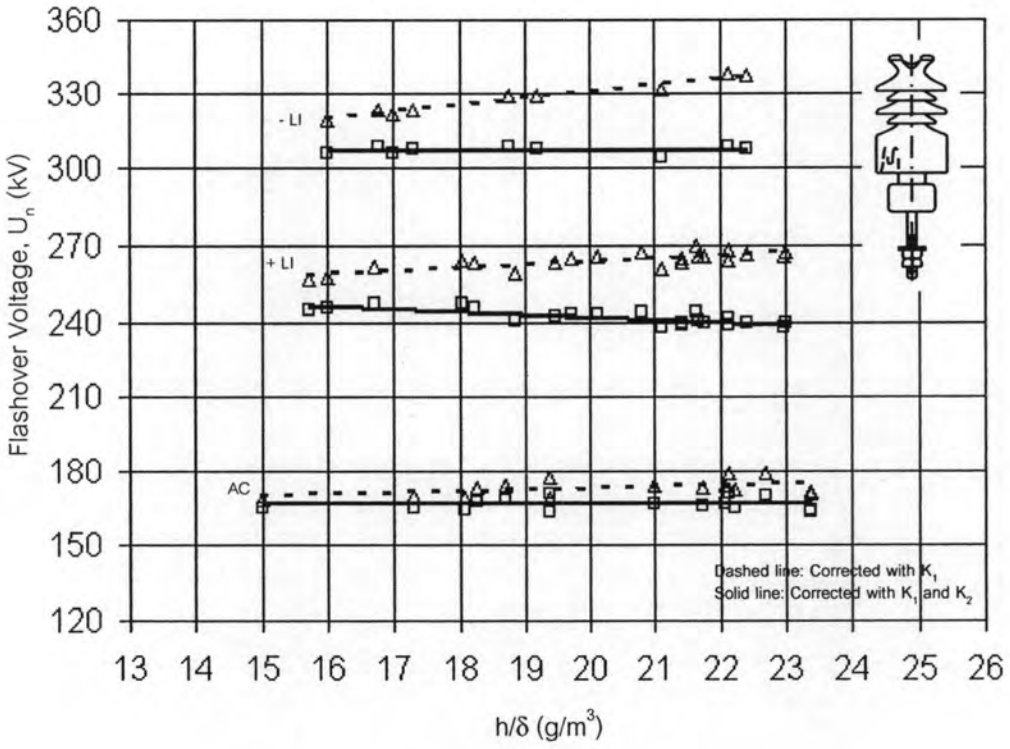

Figure 4.24 Flashover voltage of line-post insulator Class 56/57-4 $h/\delta > 15 g/m^3$, Correct by using IEC 60060-1: 1989 recommendation

From figure 4.13 – 4.24 we can see that:

a. For negative impulse voltage, the flashover voltages at standard conditions are almost the same. This confirms that the application of the IEC correction factor is appropriate.
b. For positive impulse voltage, flashover voltage at standard conditions are also the same when $h/\delta < 15$ g/m^3. But for $h/\delta > 15$ g/m^3 we can observed that flashover voltage at standard conditions are decrease when h/δ increases. Which imply that the factor K_2 of IEC is inappropriate.
c. For AC voltage, the tendency of flashover voltage at standard conditions are similarly to positive impulse voltage.

Therefore, the correction factor recommend by IEC 60060-1: 1989 are not suitable for positive impulse and AC voltage tests under atmospheric condition in Thailand.

4.2.2 Amendment1 IEEE4 Std4a: 2001

The flashover voltage U_n at standard atmospheric conditions is multiplied U_i with K_h and divided U_i with K_d (see 2.4.2). The standard atmospheric conditions are the same as IEC 60060-1: 1989 and IEEE4: 1995. From experiment data in appendix B, figure 4.25 – 4.36 show the flashover voltage at standard condition when applied the atmospheric correction factor recommended by IEEE4 Amendment1 Std-4a: 2001 to the test results.

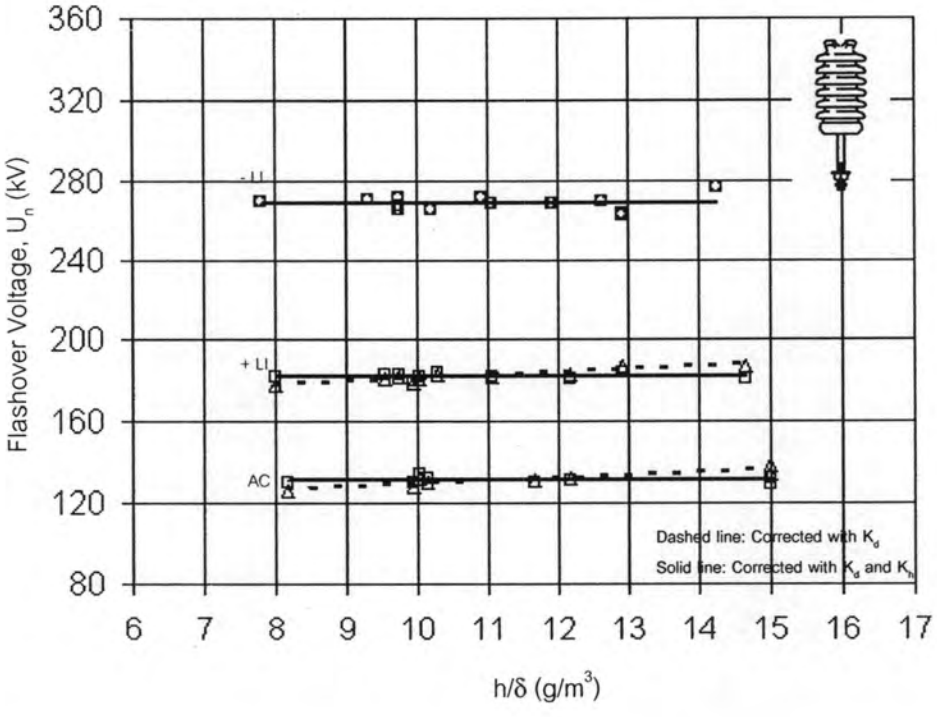

Figure 4.25 Flashover voltage of line-post insulator Class 57-2 $1g/m^3 < h/\delta < 15g/m^3$, Correct by using IEEE4 Amendment 1 Std4a: 2001 recommendation

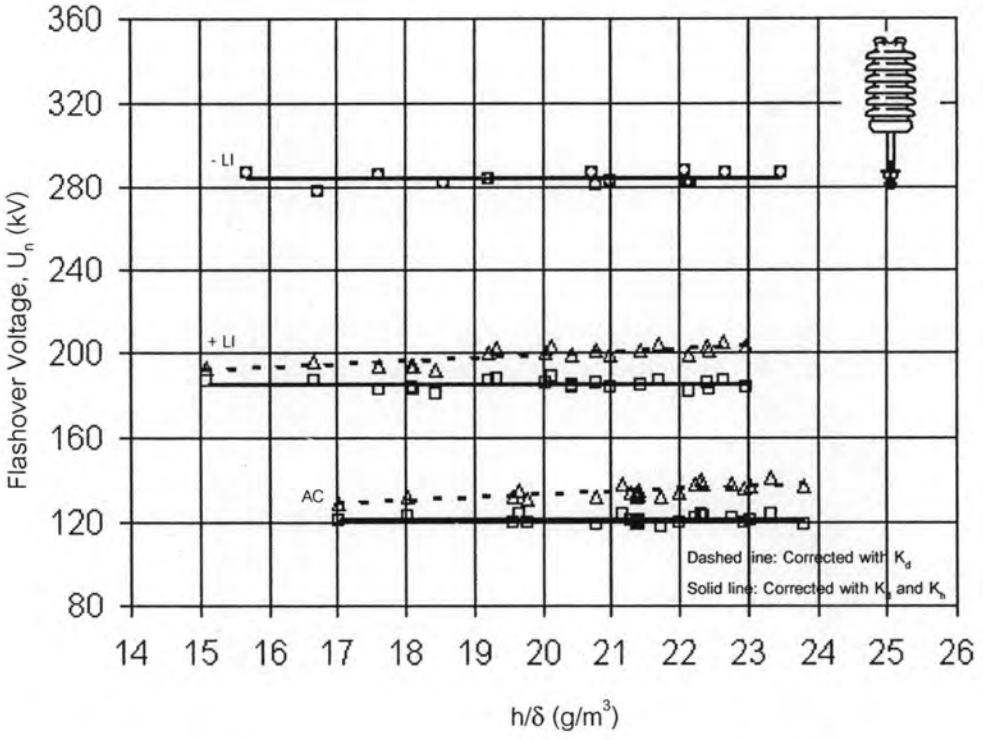

Figure 4.26 Flashover voltage of line-post insulator Class 57-2 $h/\delta > 15g/m^3$, Correct by using IEEE4 Amendment 1 Std4a: 2001 recommendation

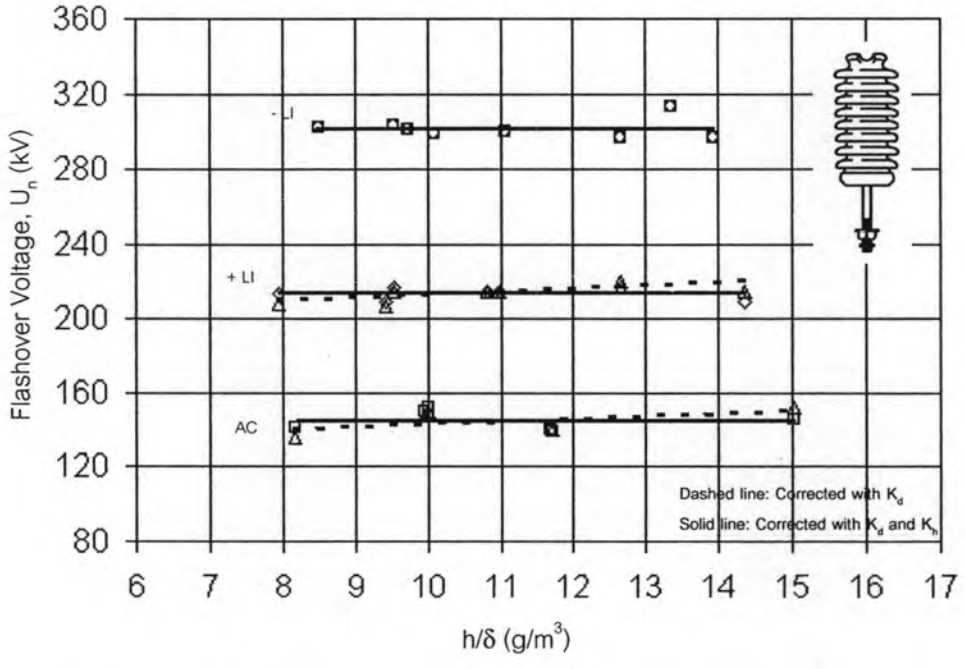

Figure 4.27 Flashover voltage of line-post insulator Class 57-3 $1g/m^3 < h/\delta < 15g/m^3$, Correct by using IEEE4 Amendment 1 Std4a: 2001 recommendation

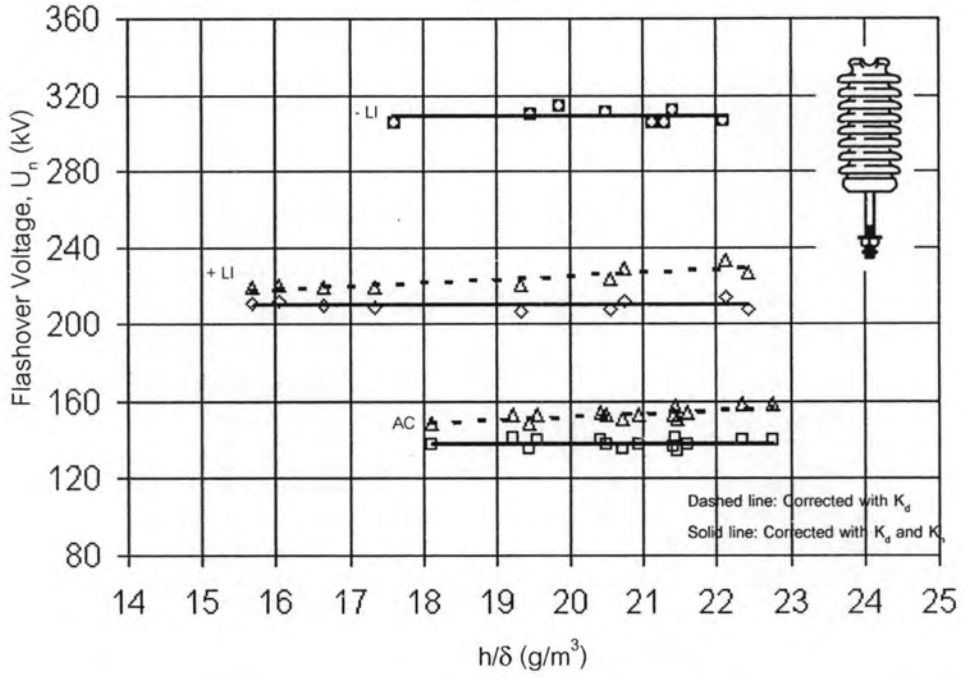

Figure 4.28 Flashover voltage of line-post insulator Class 57-3 $h/\delta > 15g/m^3$, Correct by using IEEE4 Amendment 1 Std4a: 2001 recommendation

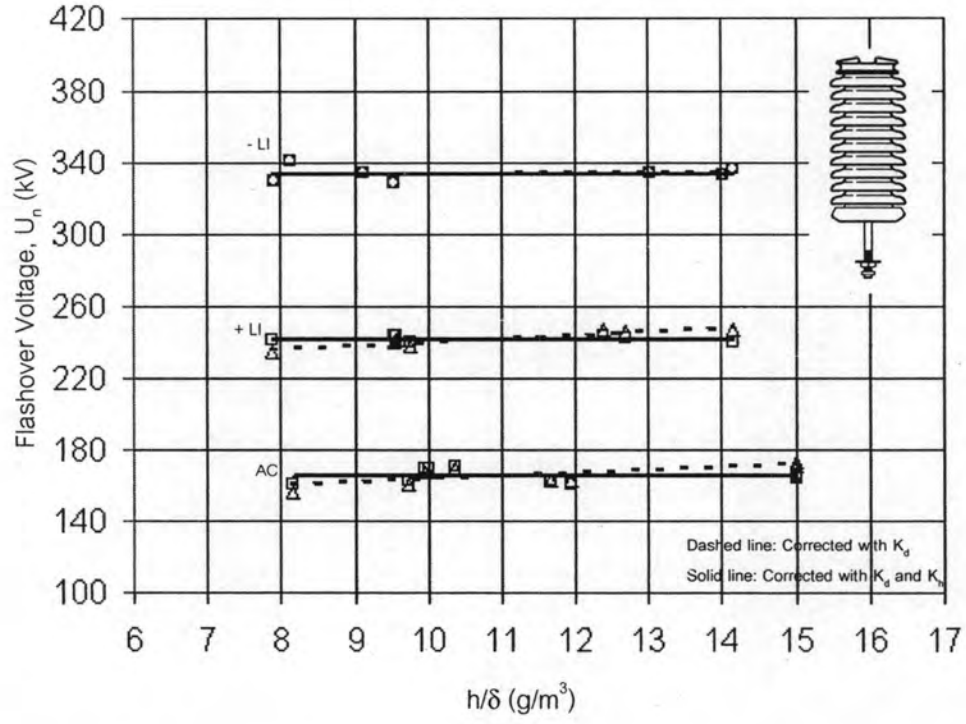

Figure 4.29 Flashover voltage of line-post insulator Class 57-4 $1g/m^3 < h/\delta < 15g/m^3$, Correct by IEEE4 Amendment 1 Std4a: 2001 recommendation

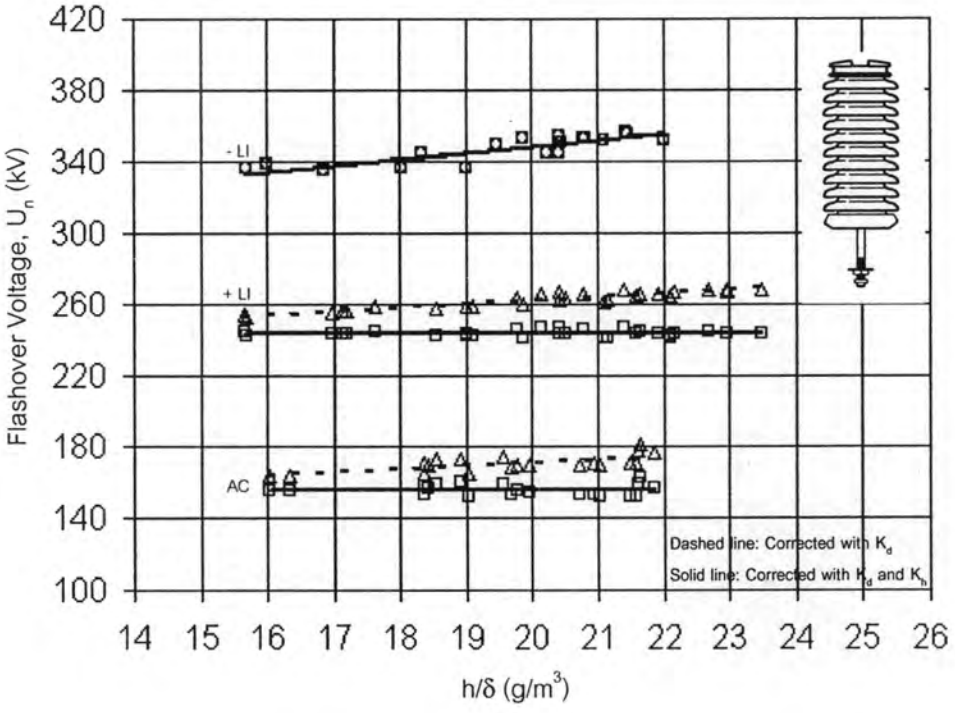

Figure 4.30 Flashover voltage of line-post insulator Class 57-4 $h/\delta > 15g/m^3$, Correct by using IEEE4 Amendment 1 Std4a: 2001 recommendation

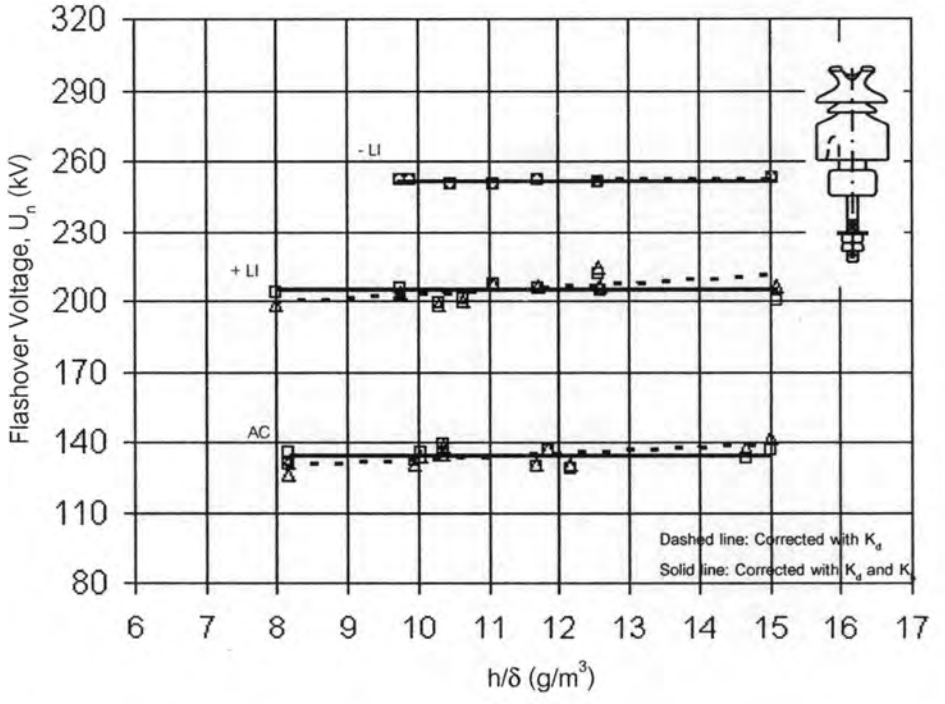

Figure 4.31 Flashover voltage of line-post insulator Class 56/57-2 $1g/m^3 < h/\delta < 15g/m^3$, Correct by using Amendment 1 Std4a: 2001 recommendation

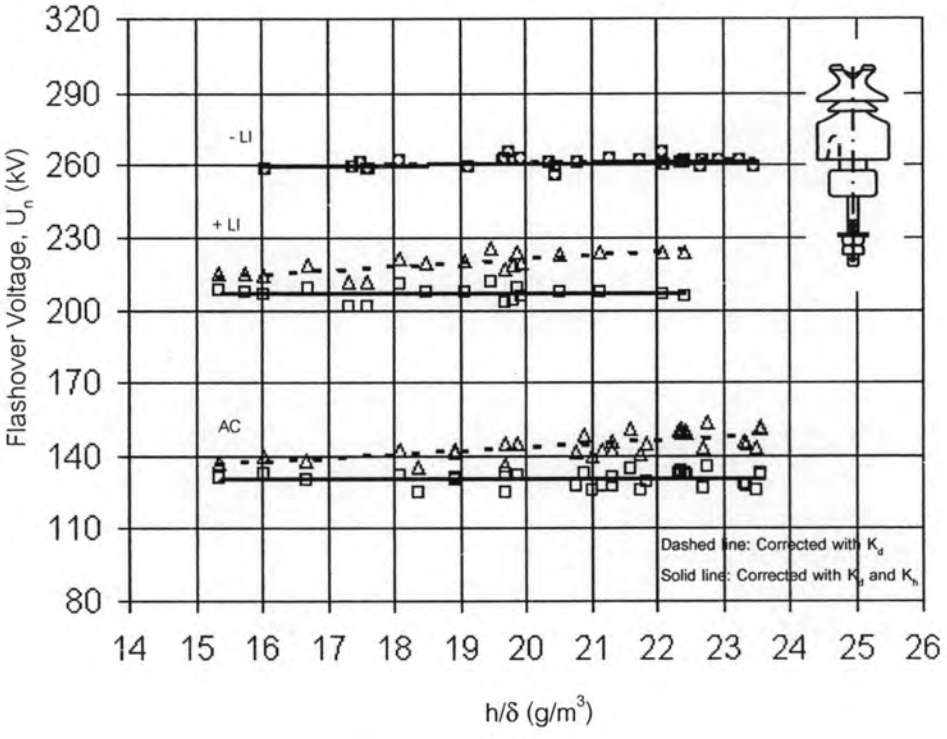

Figure 4.32 Flashover voltage of line-post insulator Class 56/57-2 $h/\delta > 15g/m^3$, Correct by using IEEE4 Amendment 1 Std4a: 2001 recommendation

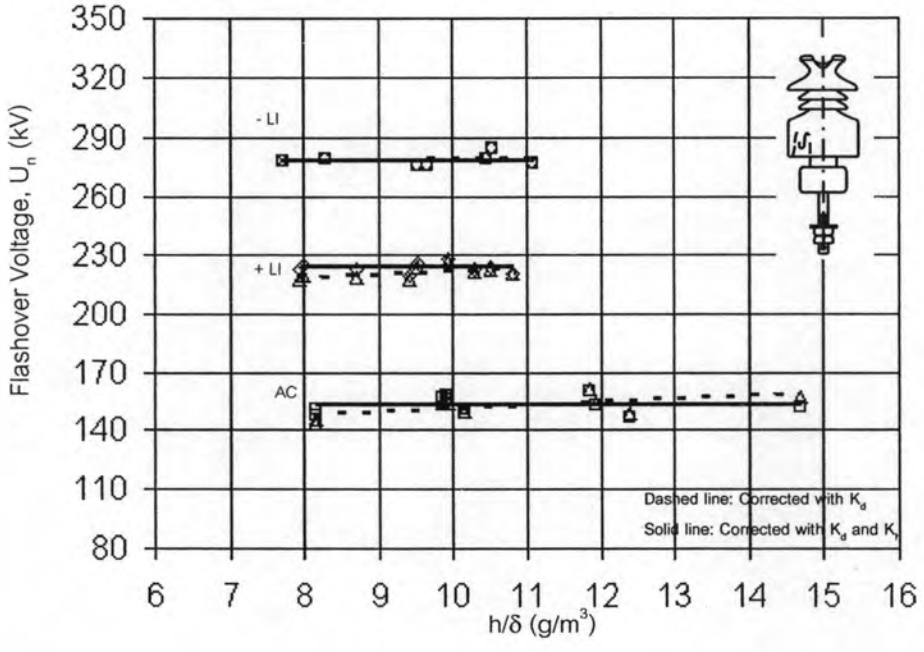

Figure 4.33 Flashover voltage of line-post insulator Class 56/57-3 $1g/m^3 < h/\delta < 15g/m^3$, Correct by using IEEE4 Amendment 1 Std4a: 2001 recommendation

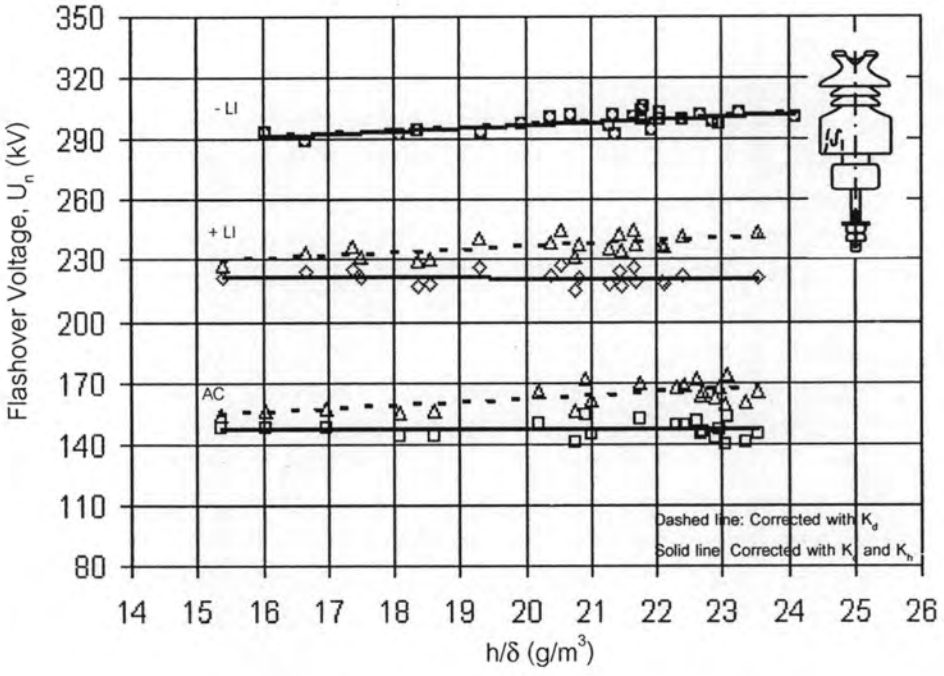

Figure 4.34 Flashover voltage of line-post insulator Class 56/57-3 $h/\delta > 15g/m^3$, Correct by using IEEE4 Amendment 1 Std4a: 2001 recommendation

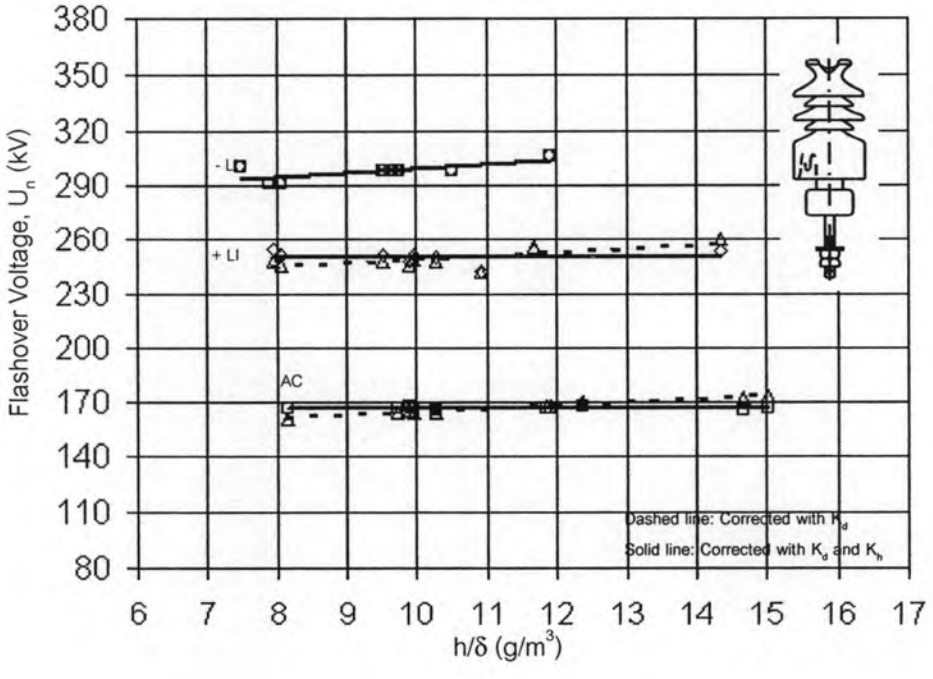

Figure 4.35 Flashover voltage of line-post insulator Class 56/57-4 $1g/m^3 < h/\delta < 15g/m^3$, Correct by using IEEE4 Amendment 1 Std4a: 2001 recommendation

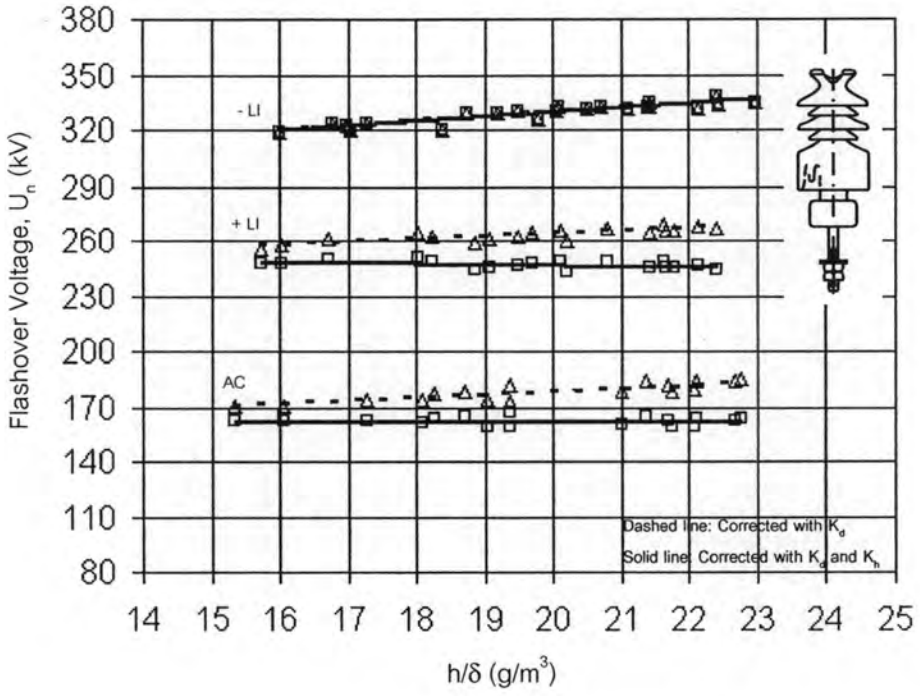

Figure 4.36 Flashover voltage of line-post insulator Class 56/57-4 $h/\delta > 15 g/m^3$, Correct by using IEEE4 Amendment 1 Std4a:2001 recommendation

From figure 4.25 – 4.36, the flashover voltage U_n is independent from h/δ when the h/δ is less than 15 g/m^3. It is also true for $h/\delta > 15$ g/m^3 except in the case of negative impulse voltage.

In this case, the flashover voltage increases with humidity. The reason of this tendency can be explain as follow:

a. The humidity correction factor K_2 is equal to k^w
b. The exponent w of Amendment1 IEEE4 Std4a: 2001 is equal to zero for negative impulse voltage
c. Thus, $K_2 = k^0 = 1$ which mean that humidity has no effect on negative impulse flashover voltage.

But figure 4.25 - 4.36 shows that the humidity do have effect on negative impulse flashover voltage.

Thus, one can conclude that the correction factor for negative impulse voltage as suggested by Amendment1 IEEE4 Std4a: 2001 is not appropriate.

4.2.3 ANSI C29.1: 1988

Flashover voltages in atmospheric air are conventionally adjusted to the values that would be obtained under standard atmospheric conditions. In American practice, the standard atmospheric has a pressure of 760 mmHg, a temperature of 25°C and a humidity of $15g/m^3$.

The flashover voltage at standard conditions when we applied the atmospheric correction factor as suggested by ANSI C29.1: 1988 are shown in Fig. 4.34 – 4.48 and appendix B.

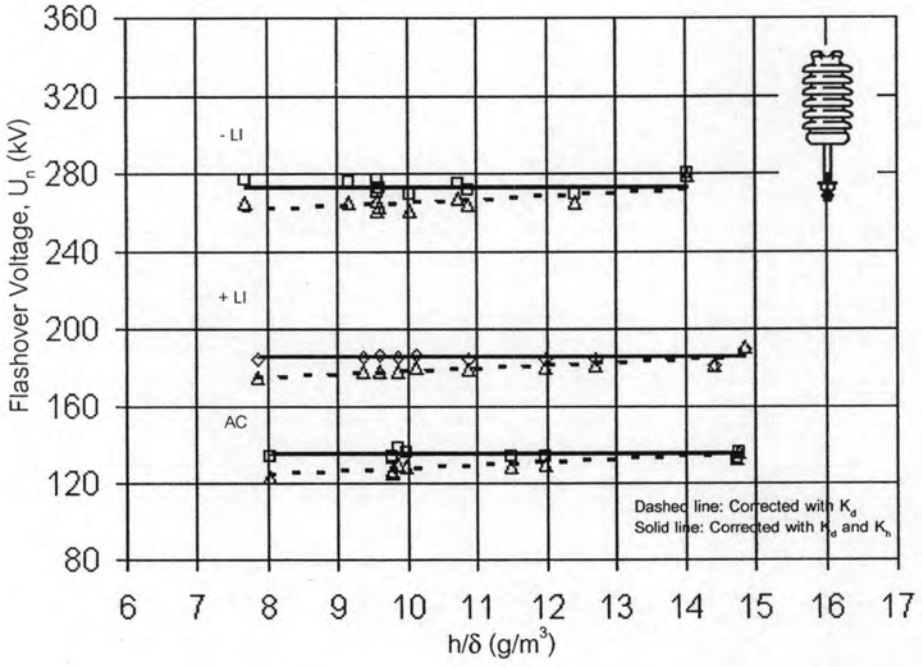

Figure 4.37 Flashover voltage of line-post insulator Class 57-2
$1g/m^3 < h/\delta < 15g/m^3$, Correct by using ANSI C29.1: 1988 recommendation

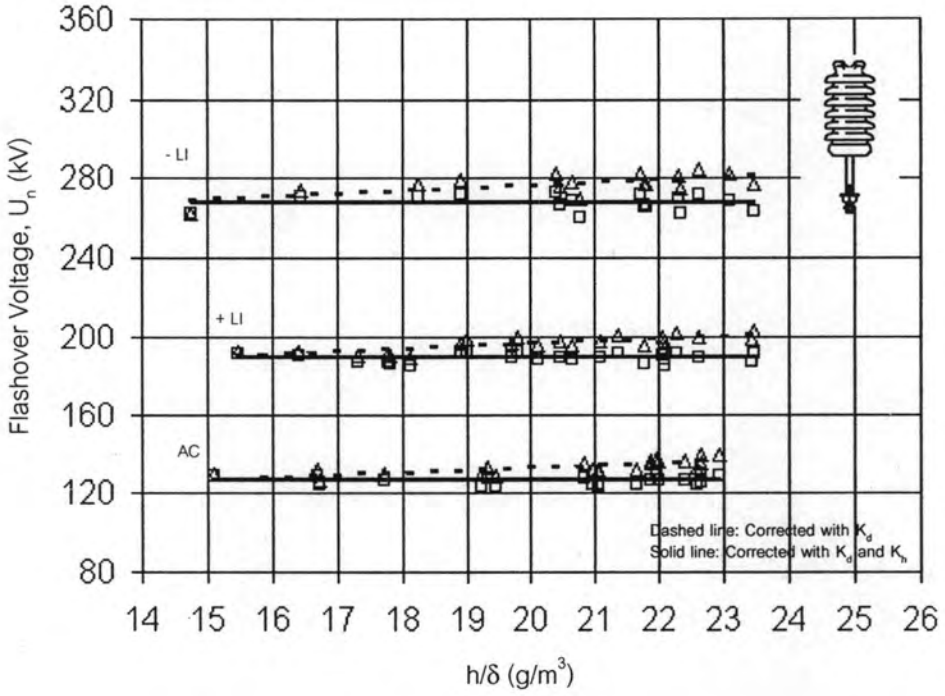

Figure 4.38 Flashover voltage of line-post insulator Class 57-2

$h/\delta > 15 g/m^3$, Correct by using ANSI C29.1: 1988 recommendation

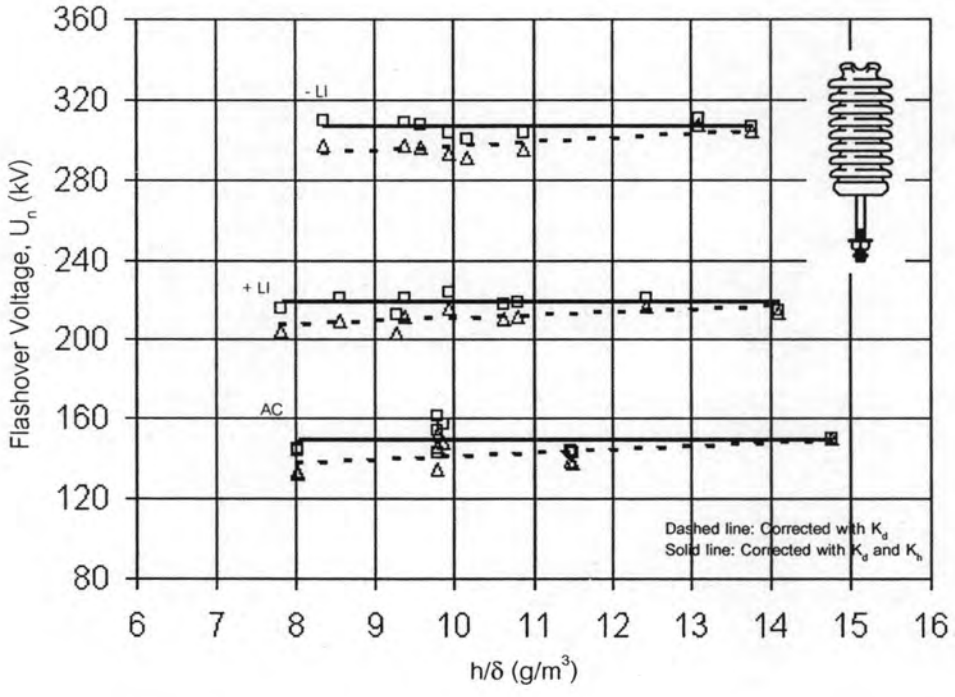

Figure 4.39 Flashover voltage of line-post insulator Class 57-3

$1 g/m^3 < h/\delta < 15 g/m^3$, Correct by using ANSI C29.1: 1988 recommendation

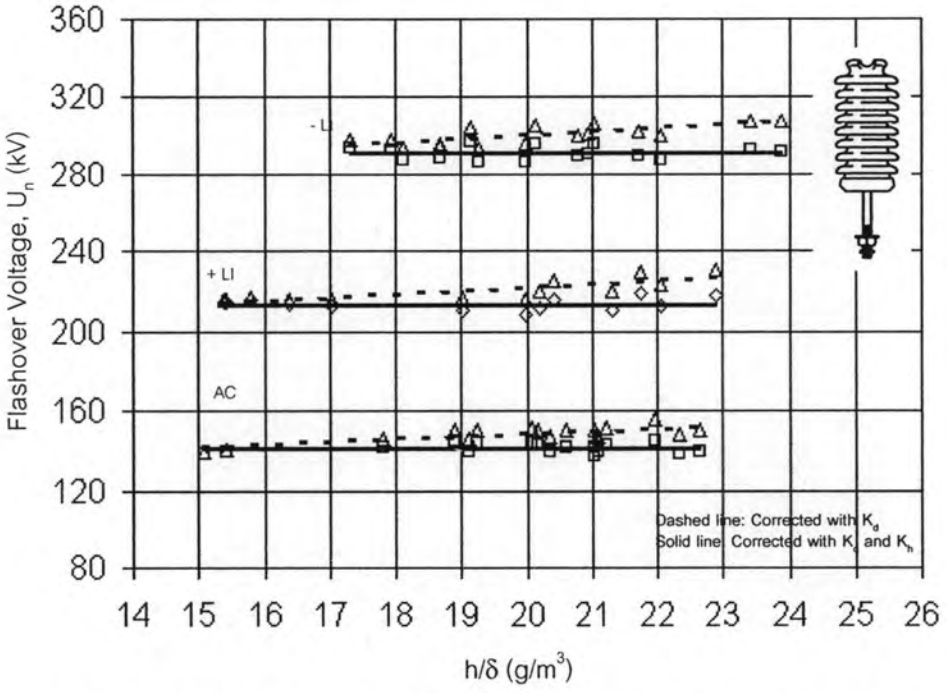

Figure 4.40 Flashover voltage of line-post insulator Class 57-3

$h/\delta > 15 g/m^3$, Correct by using ANSI C29.1: 1988 recommendation

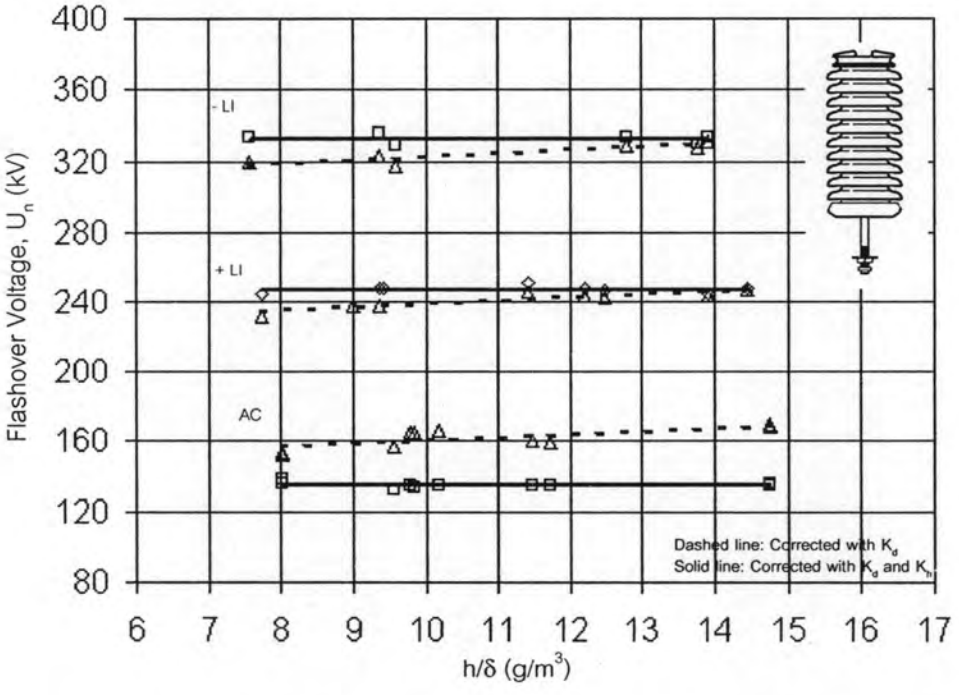

Figure 4.41 Flashover voltage of line-post insulator Class 57-4

$1 g/m^3 < h/\delta < 15 g/m^3$, Correct by using ANSI C29.1: 1988 recommendation

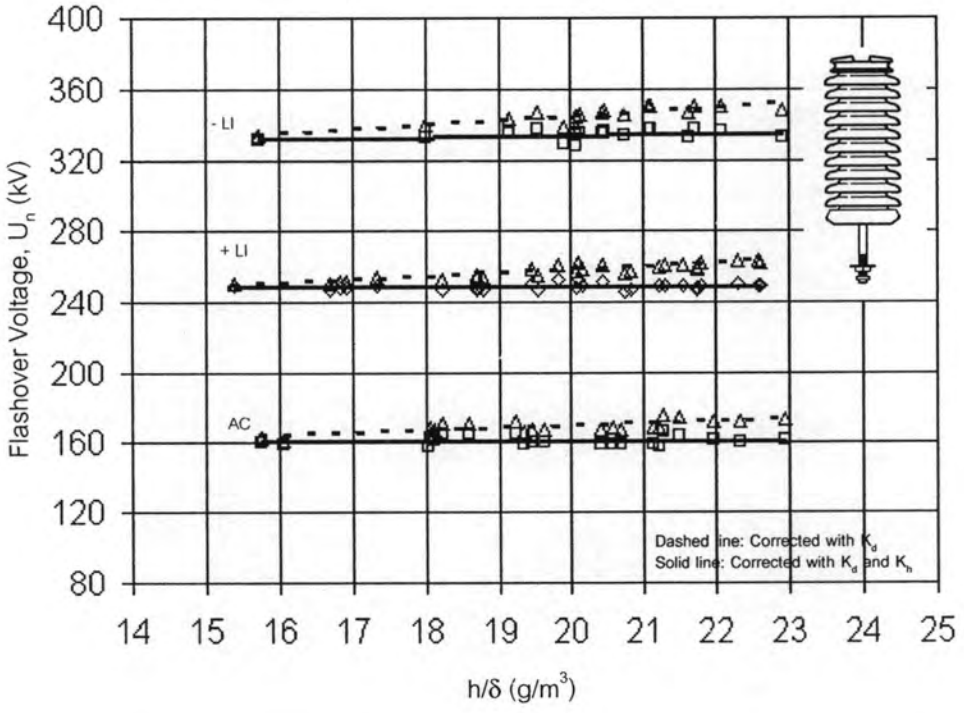

Figure 4.42 Flashover voltage of line-post insulator Class 57-4
$h/\delta > 15 g/m^3$, Correct by using ANSI C29.1: 1988 recommendation

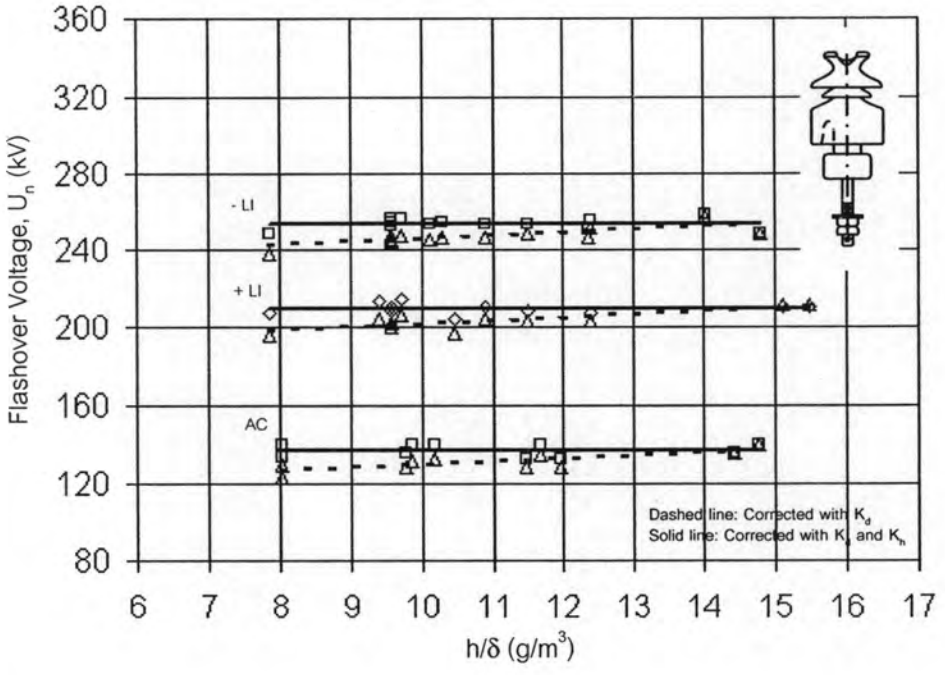

Figure 4.43 Flashover voltage of pin-post insulator Class 56/57-2
$1 g/m^3 < h/\delta < 15 g/m^3$, Correct by using ANSI C29.1: 1988 recommendation

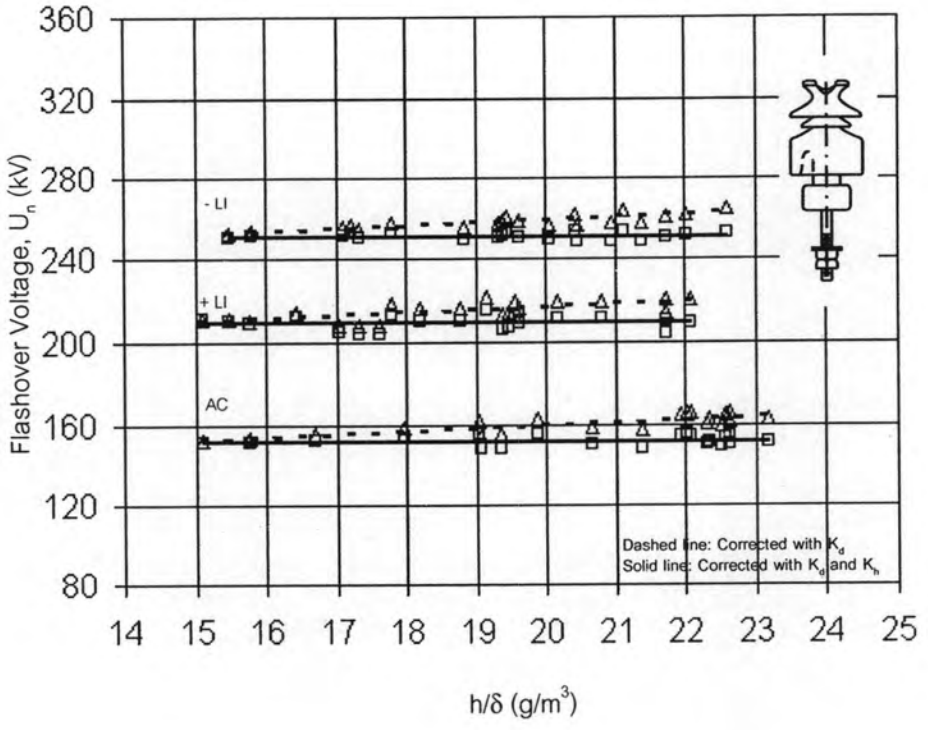

Figure 4.44 Flashover voltage of pin-post insulator Class 56/57-2
h/δ > 15g/m^3, Correct by using ANSI C29.1: 1988 recommendation

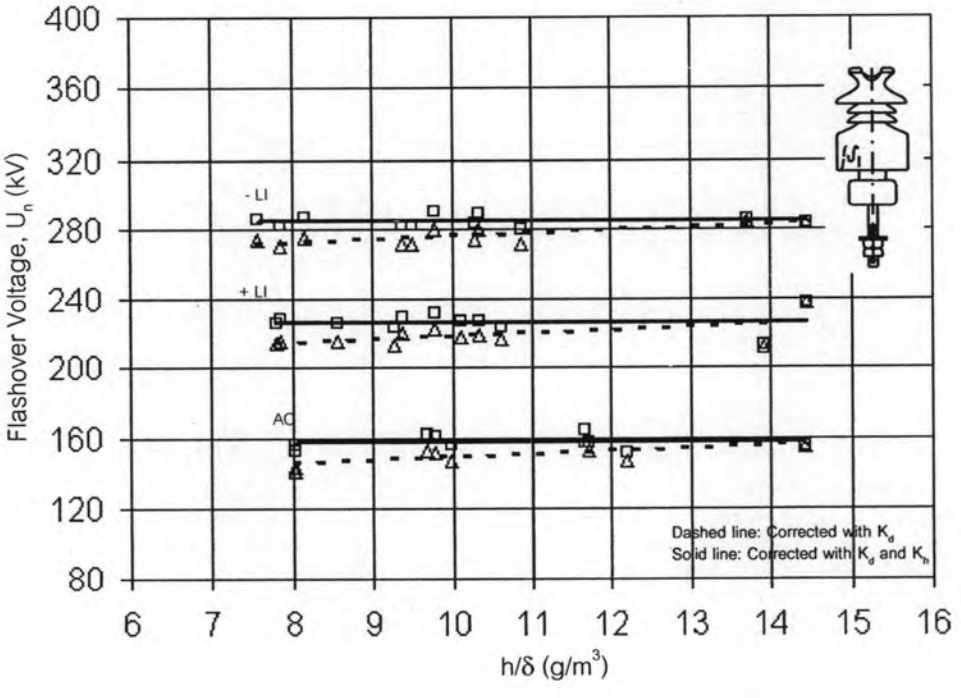

Figure 4.45 Flashover voltage of pin-post insulator Class 56/57-3
1g/m^3 < h/δ < 15g/m^3, Correct by using ANSI C29.1: 1988 recommendation

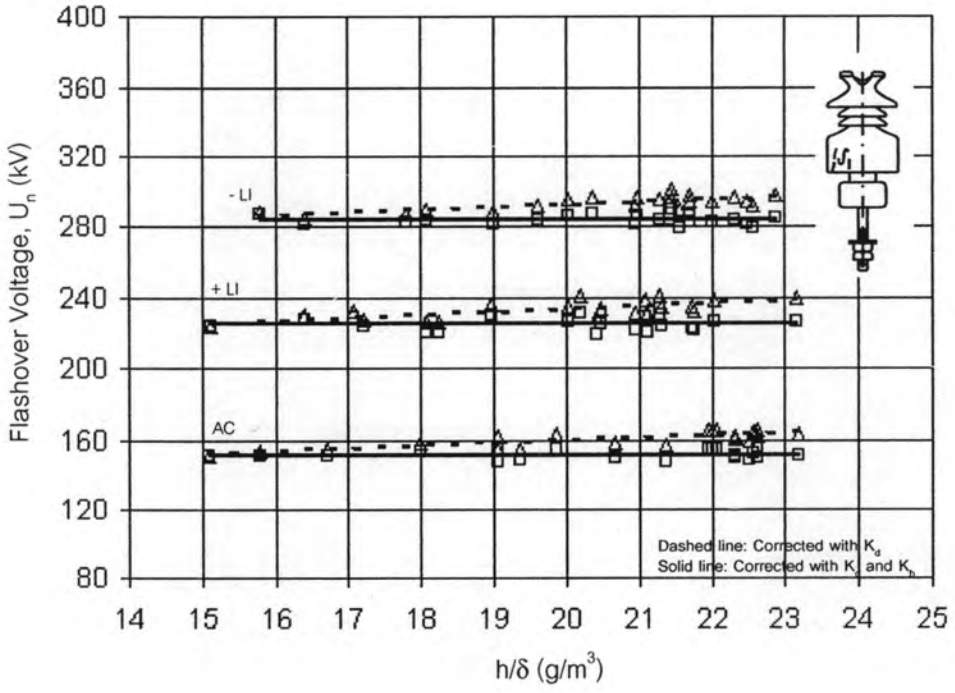

Figure 4.46 Flashover voltage of pin-post insulator Class 56/57-3
$h/\delta > 15 g/m^3$, Correct by using ANSI C29.1: 1988 recommendation

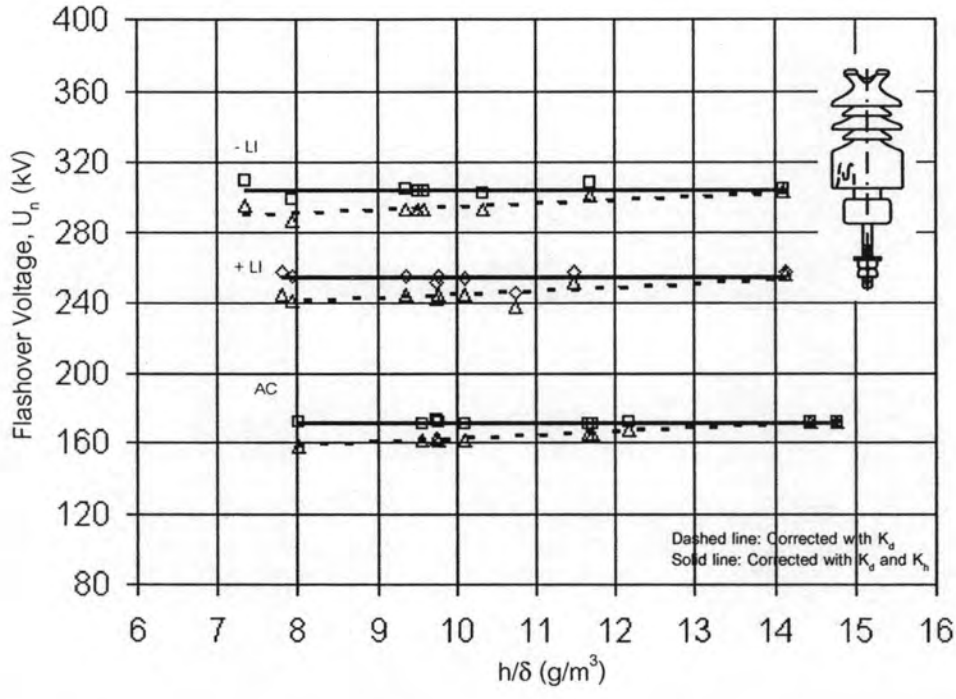

Figure 4.47 Flashover voltage of pin-post insulator Class 56/57-4
$1 g/m^3 < h/\delta < 15 g/m^3$, Correct by using ANSI C29.1: 1988 recommendation

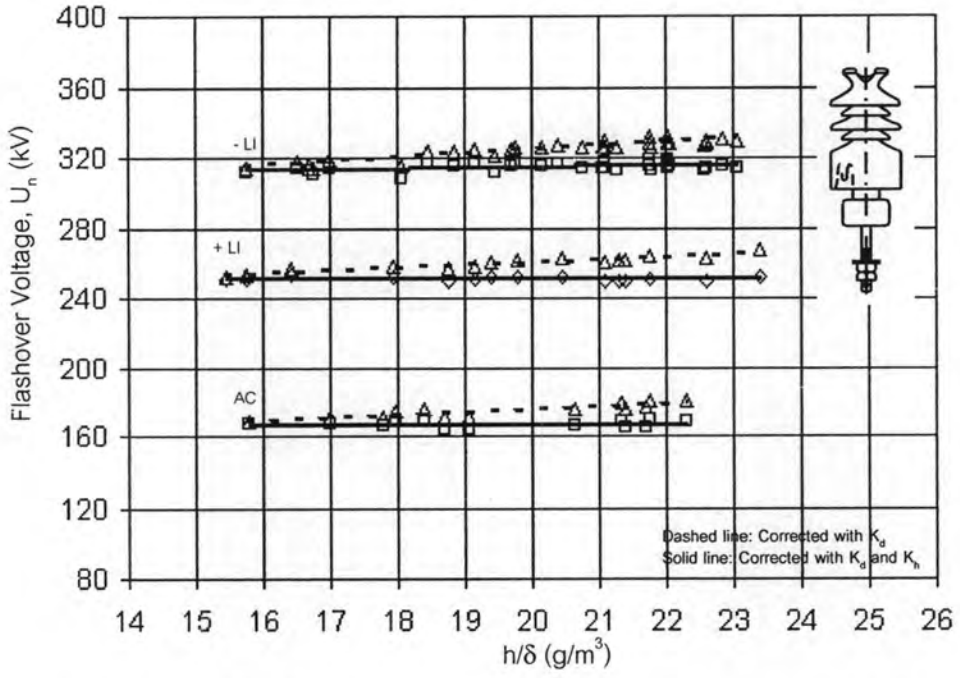

Figure 4.48 Flashover voltage of pin-post insulator Class 56/57-4 $h/\delta > 15 g/m^3$, Correct by using ANSI C29.1: 1988 recommendation

We can see that, for 7 $g/m^3 < h/\delta < 24$ g/m^3 the breakdown voltage shows a very nice straight line. Thus, we can use the atmospheric correction factor recommended by ANSI C29.1, for the determination of flashover voltage of insulator under low and high humidity in Thailand.

4.3 A proposed humidity correction factor for IEC 60060-1: 1989

From previous section, we see that the atmospheric correction factor recommended by ANSI C29.1: 1988 is appropriate for the flashover test under high humidity of Thailand. But if we want to perform flashover voltage test according to IEC 60060-1: 1989 standard, we will have some difficulty with humidity correction factor.

The cross reference of only humidity correction factor to ANSI C29.1:1988, while all test procedure are refereed to IEC 60060-1: 1989 is unusual. Thus, we should have a new humidity correction factor for the flashover test under high humidity conditions.

The following proposed humidity correction factor is only valid for Pin-post and Lin-post insulators for $15 < h/\delta < 24$ g/m^3.

Considering the flashover voltage relationships with absolute humidity to air density h/δ, it can be explained by:

$$U_h = (U_{11}.K_1).(K_2)$$

$$= (U_{11}.K_1).(k)^w$$

$$U_h = (U_{11}.K_1)\left[1+\frac{a}{100}\left(\frac{h}{\delta}-11\right)\right]^w \qquad (4.1)$$

When U_h is a flashover voltage at atmospheric condition in kV

U_{11} is a voltage at reference atmospheric in kV

a is a humidity coefficient in % per g/m^3

But from equation 4.1, we still have not study the effect of exponent w on K_2. We will use only the information from the experiment to adjust the value of k from IEC 60060-1: 1989 to a new k'.

As k and k' at 15 g/m^3 must be the same, k' should have a value of

$$k' = 1.04 + \frac{a_{h/\delta \geq 15}}{100}\left(\frac{h}{\delta} - 15\right) \qquad \text{for Lightning Impulse}$$

$$k' = 1.048 + \frac{a_{h/\delta \geq 15}}{100}\left(\frac{h}{\delta} - 15\right) \qquad \text{for AC voltage}$$

The factor $a_{h/\delta \geq 15}$ can be obtained from the slope of flashover voltage experiment. The new value of k' are shown in Table 4.1.

Table 4.1 Correction Factor k' of Each Insulator

Humidity Correction Factor k'			
Insulator Class	Positive Impulse (+)	Negative Impulse (-)	Power Frequency
57-2	1.04+0.0040(h/δ – 15)	-	1.048+0.0133 (h/δ – 15)
57-3	1.04+0.0036(h/δ – 15)	-	1.048+0.0046 (h/δ – 15)
57-4	1.04+0.0082(h/δ – 15)	-	1.048+0.0022 (h/δ – 15)
56/57-2	1.04+0.0021(h/δ – 15)	-	1.048+0.0058(h/δ – 15)
56/56-3	1.04+0.0054(h/δ – 15)	-	1.048+0.0073(h/δ – 15)
56/57-4	1.04+0.0050(h/δ – 15)	-	1.048+0.0032(h/δ – 15)

By each of $a_{h/\delta > 15}$ we have the results of flashover voltage, U_n at standard condition when apply a new correction k' are shown in figure 4.49 – 4.54 and appendix C.

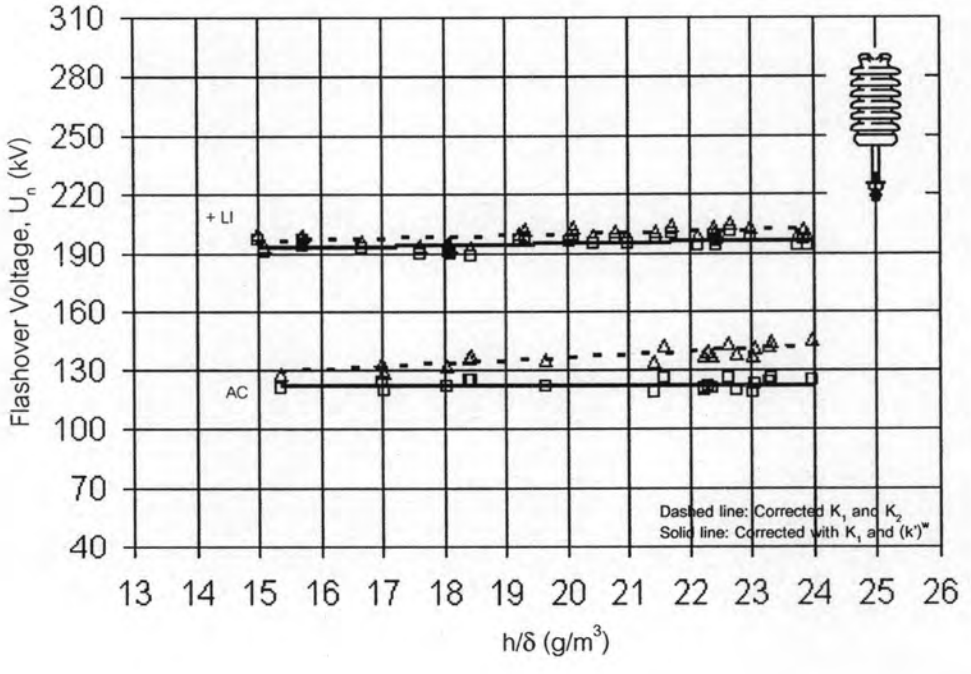

Figure 4.49 New Flashover Voltage Correction, Line-post insulator class 57-2

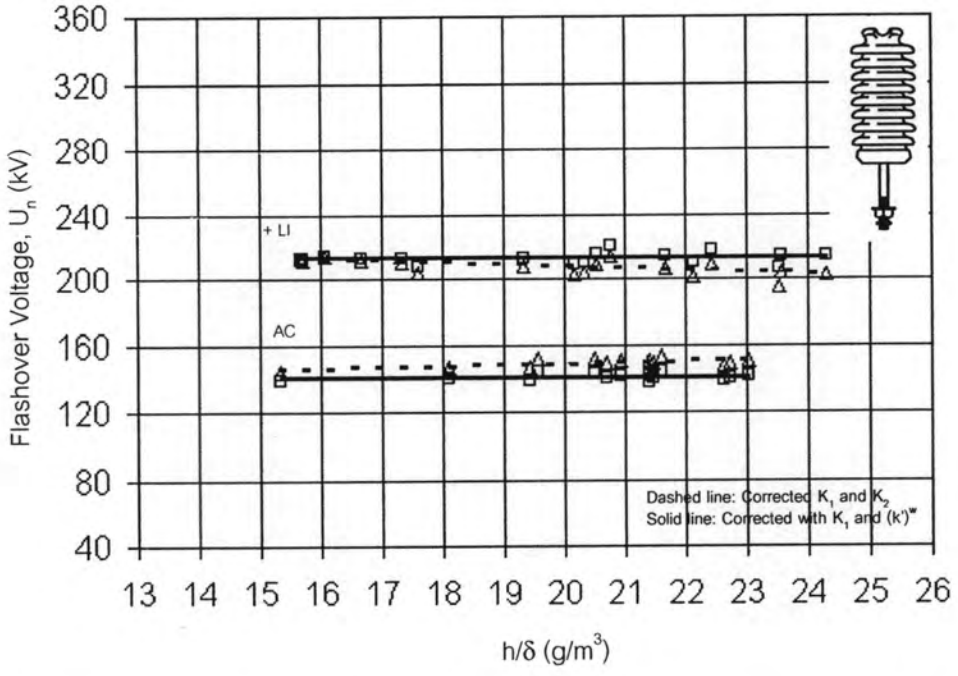

Figure 4.50 New Flashover Voltage Correction, Line-post insulator class 57-3

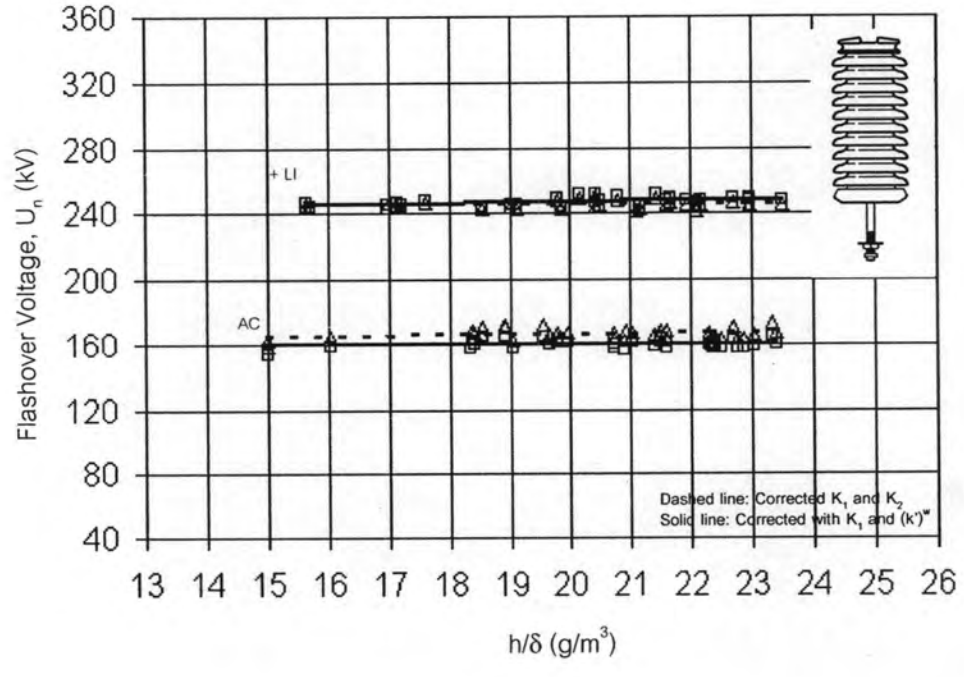

Figure 4.51 New Flashover Voltage Correction, Line-post insulator class 57-4

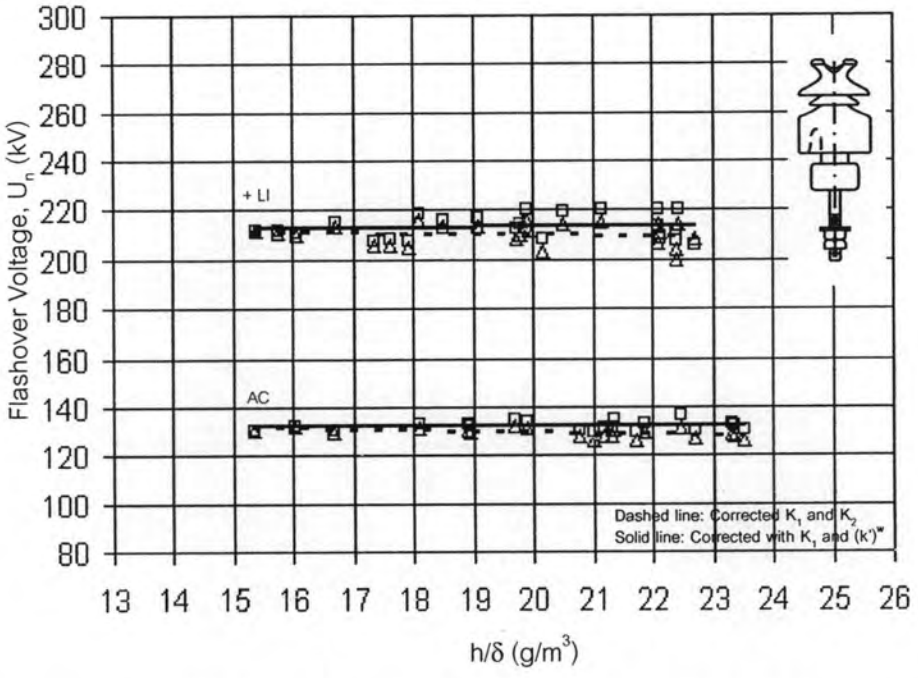

Figure 4.52 New Flashover Voltage Correction, Pin-post insulator class 56/57-2

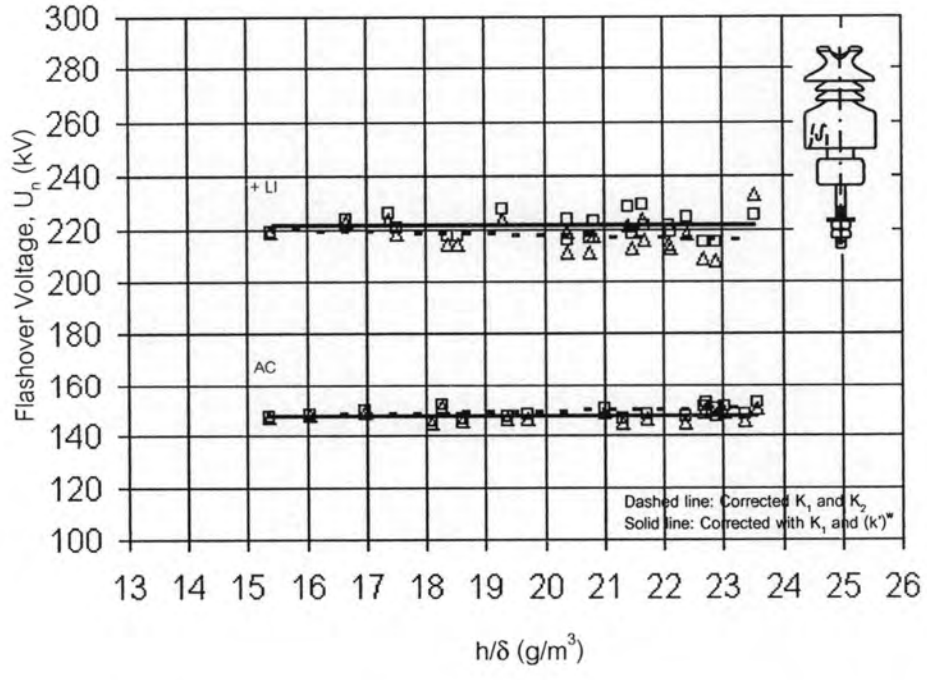

Figure 4.53 New Flashover Voltage Correction, Pin-post insulator class 56/57-3

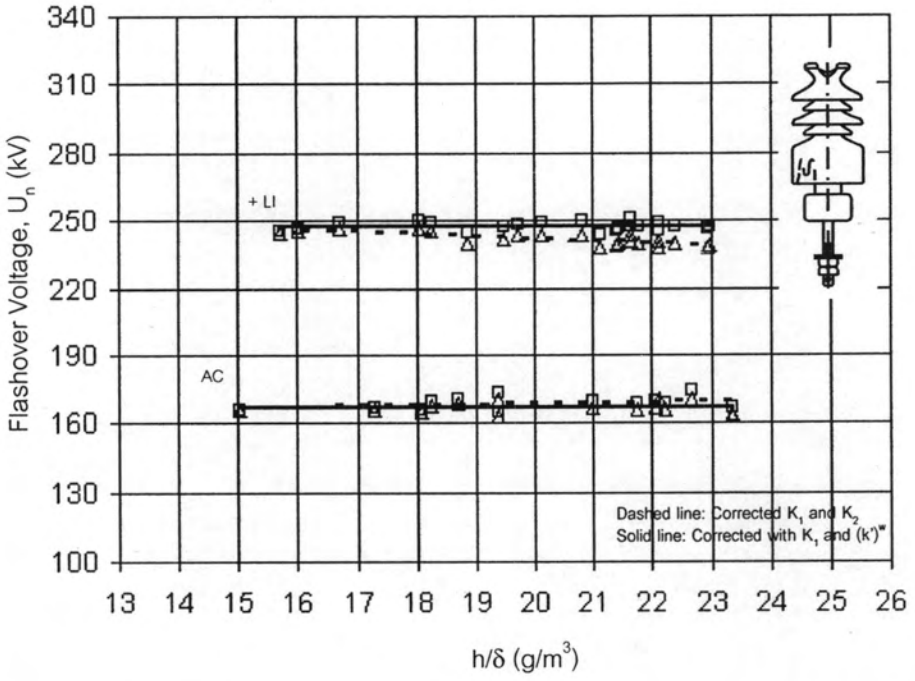

Figure 4.54 New Flashover Voltage Correction, Pin-post insulator class 56/57-4