

CHAPTER 2

THEORIES

This chapter reviews the atmospheric correction factors, definition of breakdown in gas, an application and modification of atmospheric correction factor, to convert the flashover voltage under laboratory conditions to standard conditions. The reviewed standards are: the IEC publication no. 60060-1: 1989, the IEEE4 Amendment 1 Std. 4a: 2001 and the ANSI C29.1: 1973.

2.1 Atmospheric Conditions

Temperature (T)

Air temperature is a measure of the heat content of the air. One can think of it as a measure of the average speed or kinetic energy level of molecules. The temperature of our atmosphere is controlled by a complex set of interactions between the biosphere, lithosphere and atmosphere. Energy is constantly being exchanged between the surface and the air above a place. The temperature is measured on an instrument called a Thermometer as can be seen in Fig 2.1a and measured in units called degree.

Absolute Humidity (h)

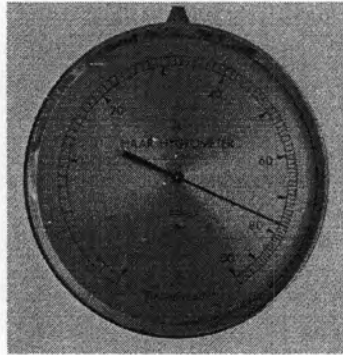
Absolute Humidity expresses the water vapor content of the air using the mass of water vapor contained in a given volume of air. It may be measured in grams of vapor/cubic meter of air see figure 2.2. A problem with using absolute humidity is that an air parcel changes volume as the ambient temperature and pressure change. This means that the absolute humidity changes when the volume changes, even though the mass of water vapor has not changed.

Specific Humidity measures the water vapor content of the air using the mass of the water vapor for a given mass of air. It may be measured in grams of water vapor per kilogram of air. The kilogram of air measured includes the water vapor present

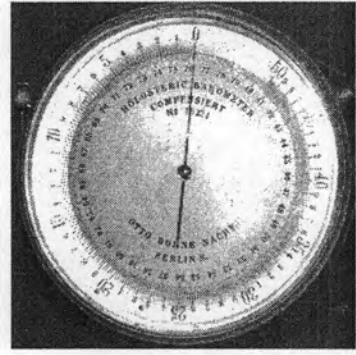
(compare this to mixing ratio, below). Unlike absolute humidity, specific humidity doesn't change as the air parcel expands or is compressed.



a. Thermometer



b. Hygrometer



c. Barometer

Figure 2.1 Air Atmospheric Instruments

Air Pressure

Air pressure is the weight of the atmosphere pressing down on the earth. It is measured by a Barometer in units called millibars. Most barometers use mercury in a glass column, like a thermometer, to measure the change in air pressure as can be seen in Fig 2.1c.

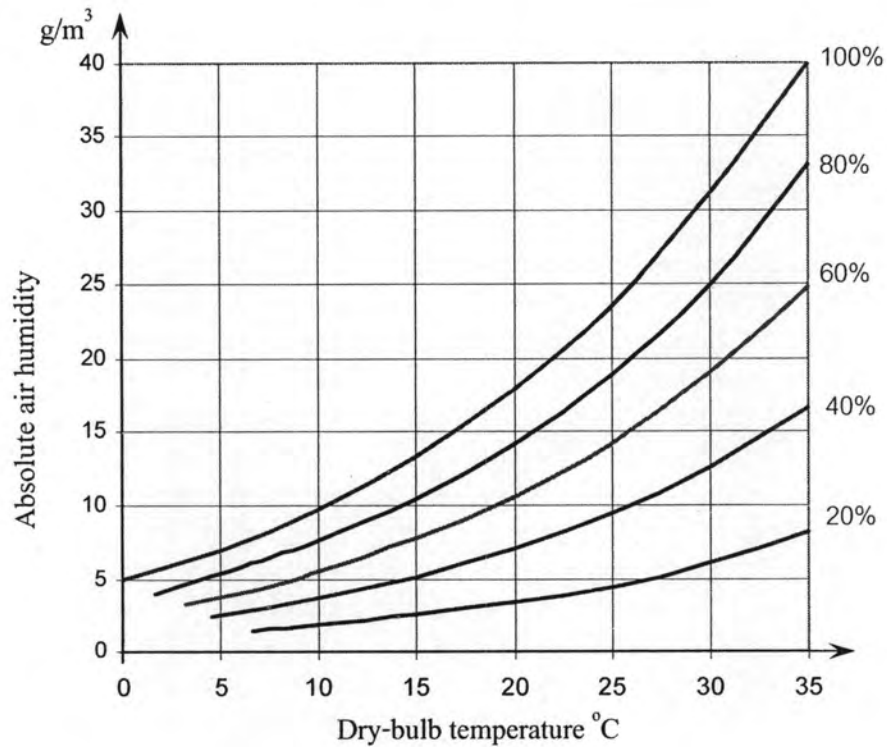


Figure 2.2 Relationship between relative humidity, absolute humidity and temperature

Saturated Vapor Pressure

The process of evaporation in a closed container, Fig 2.3, will proceed until there are as many molecules returning to the liquid as there are escaping. At this point the vapor is said to be saturated, and the pressure of that vapor (usually expressed in mmHg) is called the saturated vapor pressure.

Since the molecular kinetic energy is greater at higher temperature, more molecules can escape the surface and the saturated vapor pressure is correspondingly higher. If the liquid is open to the air, then the vapor pressure is seen as a partial pressure along with the other constituents of the air. The temperature at which the vapor pressure is equal to the atmospheric pressure is called the boiling point.

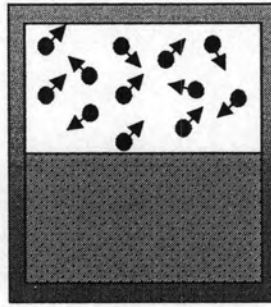


Figure 2.3 Saturated Vapor Pressure

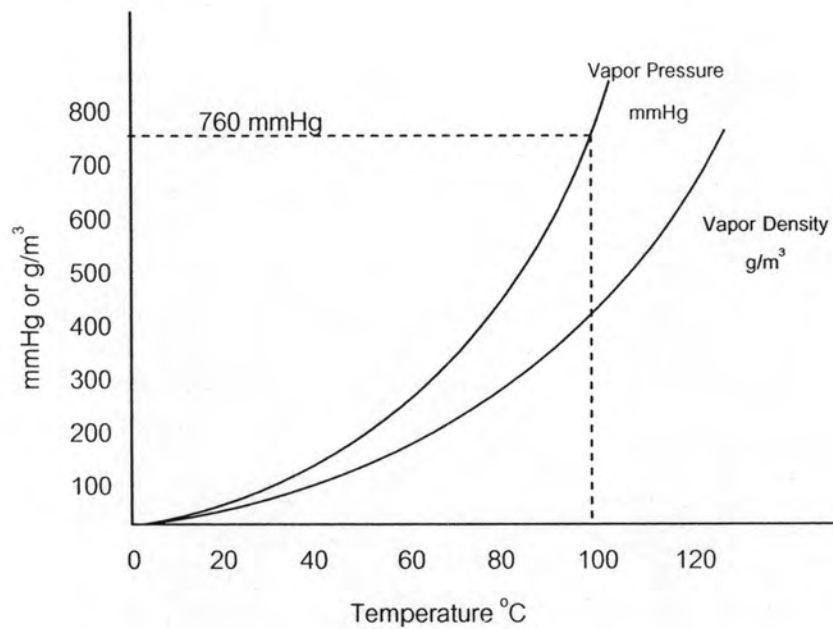


Figure 2.4 Saturated Vapor Pressure for Water and Saturated Vapor Density for Water

Evaporation

Ordinary evaporation is a surface phenomenon - some molecules have enough kinetic energy to escape. If the container is closed, figure 2.5, equilibrium is reached where an equal number of molecules return to the surface. The pressure of this equilibrium is called the saturation vapor pressure.

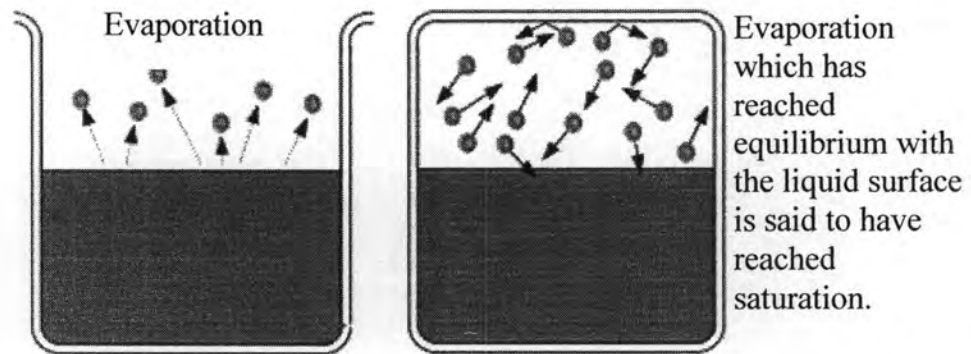


Figure 2.5 Evaporation

In order to evaporate, a mass of water must collect the large heat of vaporization, so evaporation is a potent cooling mechanism. Evaporation heat loss is a major climatic factor and is crucial in the cooling of the human body.

Dew point

If the air is gradually cooled while maintaining the moisture content constant, the relative humidity will rise until it reaches 100%. This temperature, at which the moisture content in the air will saturate the air, is called the dew point, figure 2.6. If the air is cooled further, some of the moisture will condense.

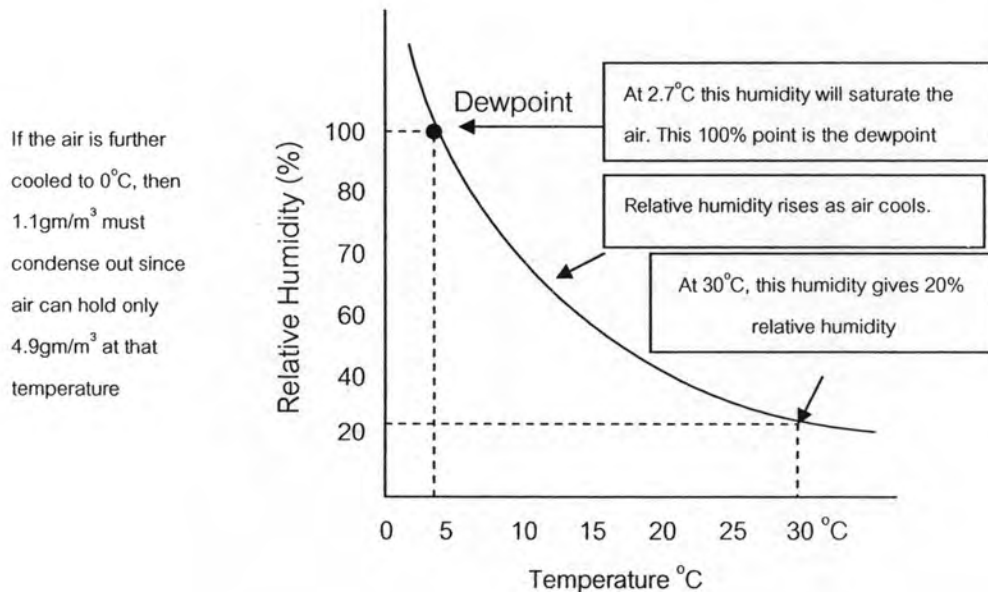


Figure 2.6 Relationship between relative humidity, temperature and dew-point

2.2 Characteristic of Gases

In the gas, the atoms or molecules constituting the matter basically move independently, with no forces keeping them together or pushing them apart. Their only interactions are rare and random collisions. The particles move in random direction, at high speed. The range in speed is depend on the temperature and defined by the Maxwell-Boltzman distribution. Therefore, the gas phase is a completely disordered state Fig. 2.7. Following the second law of thermodynamics, gas particles will immediately diffuse to homogenously fill any shape or volume of space that is made available to them.

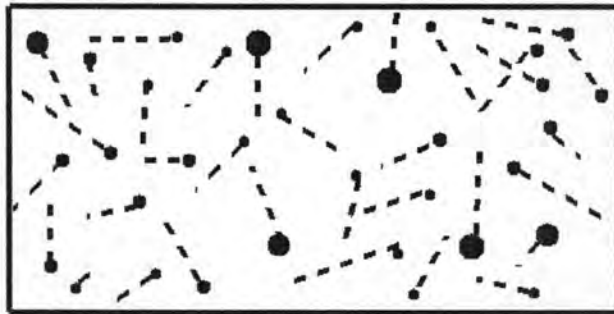


Fig 2.7 Molecule Model: Small molecules relative to distant apart, Molecules in constant random motion, Frequent collisions between molecules, Ordered motion superimposed on random motion

The thermodynamic state of a gas is characterized by its volume, its temperature, which is determined by the average velocity or kinetic energy of the molecules, and its pressure, which measures the average force exerted by the molecules colliding against a surface. These variables are related by the fundamental gas laws, which state that the pressure in an ideal gas is proportional to its temperature and number of molecules, but inversely proportional to its volume.

The absolute temperature T corresponds to the average kinetic energy of the particles.

$$\frac{1}{2}mv^2 = \frac{3}{2}K_B T \quad (2.1)$$

Here m is the mass of the particle and v is the velocity. As we can see the higher temperature causes a higher velocity.

On the other hand the pressure is caused by the momentum transfer from the gas components to the wall. This means if more or higher velocity particles impinge on the wall the pressure increases. Therefore the relation that an increase in the gas temperature causes an increased pressure is clear. The higher temperature leads to higher average velocities and hereby more particles (with higher velocities) can reach the wall in a given time so that the momentum transfer is increased and the pressure rises.

2.3 Breakdown in Gases

The electrical discharges in gases are two types, i.e. (i) non-sustaining discharges, and (ii) self-sustaining types. The breakdown in a gas, called spark breakdown is the transition of a non-sustaining discharge into a self-sustaining discharge. The built-up of high current in a breakdown is due to the process known as ionization in which electrons and ions are created from neutral atoms or molecules, and their migration to the anode and cathode respectively leads to high currents. At present two types of theories, viz. (i) Townsend theory, and (ii) Streamer theory are known which explain the mechanism for breakdown under different conditions. The various physical conditions of gases, namely, pressure, temperature, electrode field configuration, nature of electrode surfaces, and the availability of initial conducting particles are known to govern the ionization processes.

2.3.1 Ionization Processes

A gas in its normal state is almost a perfect insulator. However, when a high voltage is applied between the two electrodes immersed in a gaseous medium, the gas becomes a conductor and an electrical breakdown occurs.

The processes that are primarily responsible for the breakdown of a gas are ionization by collision, photo-ionization, and the secondary ionization processes. In insulating gases (also called electron-attaching gases) the process of attachment also plays an important role.

2.3.2 Pre-discharge

In an air gap with inhomogeneous field (e.g. rod-plate) the electrical breakdown is initiated by pre-discharges. Depending on the value of inhomogeneity of the field, the distance and the kind of voltage stress, different kind of pre-discharge will occur. In figure 2.8 the different region of existence of these kind pre-discharge are to be seen. The curves are valid for an air gap rod-plate with normal conditions for a.c and positive d.c depending on the distance. With positive d.c and on principal with a.c., the first discharge with rising voltage consists of impulse-like streamers. In region I the breakdown voltage is equal to inception voltage of the gap. Here breakdown occurs after exceeding the inception voltage, that means the first streamer at one bridge the whole gap and leads to breakdown. In region II with greater distance this first streamer does not bridges the whole gap; it only introduces a steady glow discharge with no impulses in the current oscillogram. The electrode is surrounded by a thin, glowing skin, and from this glow discharge breakdown occurs. The electrical strength of the gap increases with increasing distance with the well known value of about 5KV/cm. With negative d.c after exceeding the inception voltage only brush discharge is to be seen; with sufficient height of the voltage it leads directly to breakdown.

Theses region where the different kind of pre-discharge exist are influenced by a change of the humidity of the air, shown by the content of water vapour. This is also the main reason for the humidity influence on the breakdown voltage of the gap.

Two factors are relevant:

The loss of free electrons in the region between the electrodes by increasing attachment of these electrons on the water molecules of the air.

The absorption of photons by the water vapour of the air leads to the development of large discharge channels with smaller current compared with dry air.

With a.c. the proceedings are more complicated than with d.c. : during each half cycle the pre-discharge have to start again and the remaining charges from the preceding half-cycle influence the following discharge.

It is known that one must be vary cautious if the time interval between two successive tests or the air content of the test chamber chosen are too small: the products of the

preceding breakdown or of long term pre-discharges in the air (O_3 , NO , NO_2 among others) are produced in different amounts

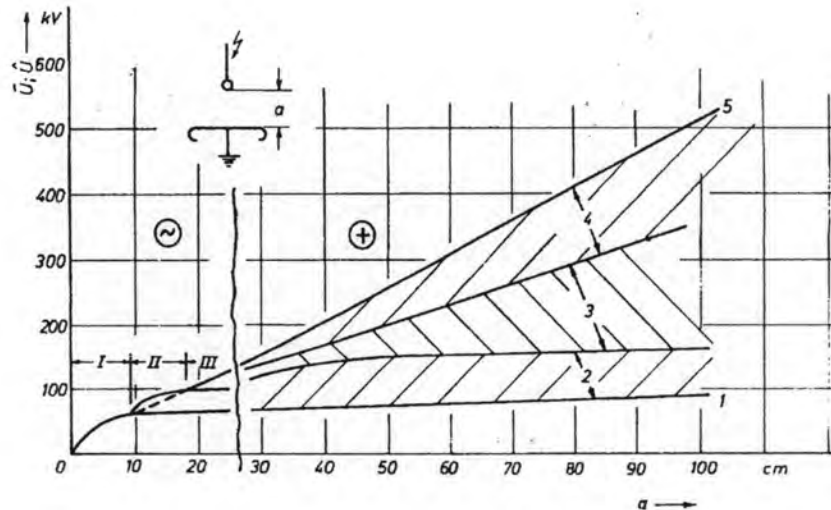


Figure 2.8 Rod-plate arrangements

and react in a different way depending on the amount of water vapour. In region I of figure 2.8 where breakdown voltage has the same value as inception voltage, there is no remarkable influence of these products to be seen. In region II where breakdown is preceded by glow discharge there exists a great influence on breakdown voltage. If, in this region, repeated breakdowns occur within short intervals (shorter than 1 min) then with increasing number of tests, the measured breakdown voltage falls to a lower limit, which could be reached in dry air soon after some tests. In the air with high humidity however, it is not reached before a great number of tests. In region III of figure 2.8, where breakdown is preceded by brush discharge, a short interval between breakdowns leads to an enlargement of breakdown voltage which can be more than 10%. The dissociation products of the air can bring out a similar result on breakdown voltage as does increasing the humidity. The attachment of free electrons to the water molecules and to the discharge products will be the main effect in both cases. Therefore, during all these tests time intervals of one minute and more were used, and it was proved that this chosen interval was sufficient.

2.3.3 Density Effect

Temperature and pressure together determine the density of the air. The ionisation processes involved in corona and breakdown depend primarily upon the air density and not, to any significant degree, specifically upon temperature except insofar as it changes of density. Moreover, many experiments have shown that over limited range of density, breakdown voltages vary linearly with density. Thus, it has proved a relatively straightforward matter to define a set of conditions that can be regarded as characteristic of a standard atmospheric, and to relate other conditions of pressure and density to the standard atmospheric, assuming the simple gas laws to be correct. A standard atmospheric is defined for these purposes as at 1013mbar (760mmHg) and 293K (20°C). Then at any temperature T and pressure P, the density has changed from that at the standard atmosphere by Eq. 2.2

$$\delta = \frac{P}{760} \times \frac{293}{T} \quad (2.2)$$

and clearly the value of δ is the ratio of the density at (P, T) to that at the standard condition. δ is called the relative air density; $\delta = 1$ at the standard condition.

If now, the value of breakdown voltage at relative air density $\delta = 1$ is denoted by U_0 , then the value U at (P,T) is given by Eq. 2.3

$$U = U_0 \cdot \delta \quad (2.3)$$

It should be observed here that this discussion has ignored any effects due to change of humidity. These effects will be discussed below, but it should be noted that the standard atmospheric condition assumes an absolute humidity of 11 g moisture content per cubic metre of air.

2.3.4 Humidity Effect

Atmospheric humidity can change from a moisture content of less than 1 gm^{-3} in very cold countries to the order of 30 gm^{-3} in the tropics. The effects of humidity on sparkover are quite complex, but the following general points can be made:

- a. Humidity has its strongest influence on the positive pre-breakdown discharge. In particular, the streamer gradient E_1^+ increases at the rate of roughly 1% per gm^{-3} increase in moisture content.
- b. Humidity has no significant effect on the leader gradient E_1^+ and E_1^- though it does have the effect of increasing the leader velocity.
- c. Humidity has no significant effect on the negative spark-over under lightning impulse and under direct voltage.

A rough general rule therefore follows from (a), (b) and (c) where a sparkover is preceded only by positive corona, there is a significant humidity influence, but where is preceded only by negative corona, there is no significant effect. Thus, for instance, under lightning impulse, humidity shows a maximum effect on sparkover in the positive rod-plane gap but no effect in the negative rod-plane gap.

2.4 Atmospheric correction factor

2.4.1 IEC 60060-1: 1989 and IEEE4-1995

The IEC60060-1:1989^[1] and IEEE4-1995^[2] stated that the flashover voltage in air at any atmospheric conditions U is equal to the flashover voltage in air at standard atmospheric conditions U_0 multiplied by K

$$\begin{aligned} U &= K \times U_0 \\ &= (K_1 \times K_2) \times U_0 \end{aligned} \quad (2.4)$$

Where: K_1 is the air density correction factor

K_2 is the humidity correction factor

On the other hand, the flashover voltage in air at standard atmospheric conditions U_0 is equal to the flashover voltage in air any atmospheric conditions U divided by K

$$U_0 = \frac{U}{K} \quad (2.5)$$

Here, the standard atmospheric conditions of both standards are:

$$p_0 = 1013\text{mbar}, t_0 = 20^\circ\text{C} \text{ and } h_0 = 11\text{g/m}^3.$$

The air density correction factor K_1 can be found from the equation

$$K_1 = \delta^m \quad (2.6)$$

Where the relative air density δ is equal to

$$\delta = \left(\frac{p}{p_0} \times \frac{273 + t_0}{273 + t} \right)^m \quad (2.7)$$

In equation (2.7), p and t is the pressure and temperature during the test respectively. Note that the dimension of p and p_0 should be the same and the dimension of t and t_0 must be in $^\circ\text{C}$.

For the humidity correction factor K_2 , it can be computed by equation

$$K_2 = k^w \quad (2.8)$$

Where k can be found from figure 2.9 and please note that k depends on test voltage waveform. From figure 2.9, we can clearly see that the value of k is valid only in a range of $1 < h/\delta \leq 15\text{g/m}^3$.

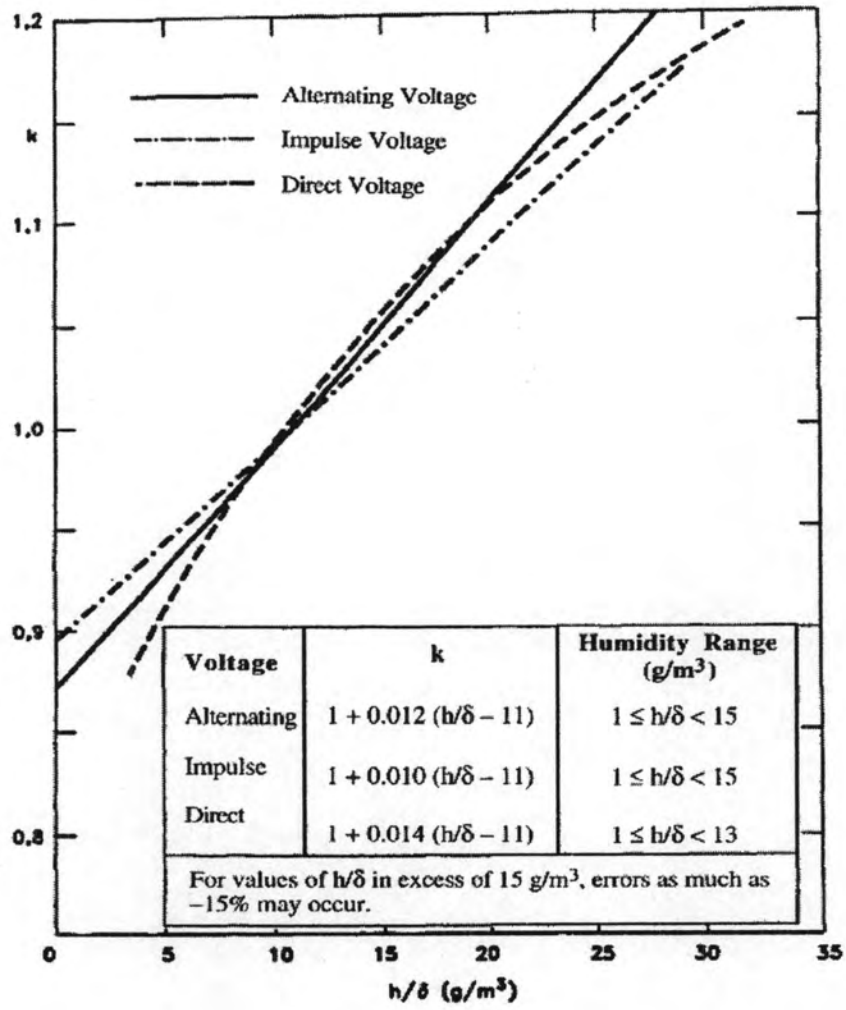


Figure 2.9 k in a function of h/δ for different test voltage waveform

Now, the parameter δ and k are known for a given atmospheric condition. It left only the value of exponent m and w to be determined. Both exponents can be determined from figure 2.10.

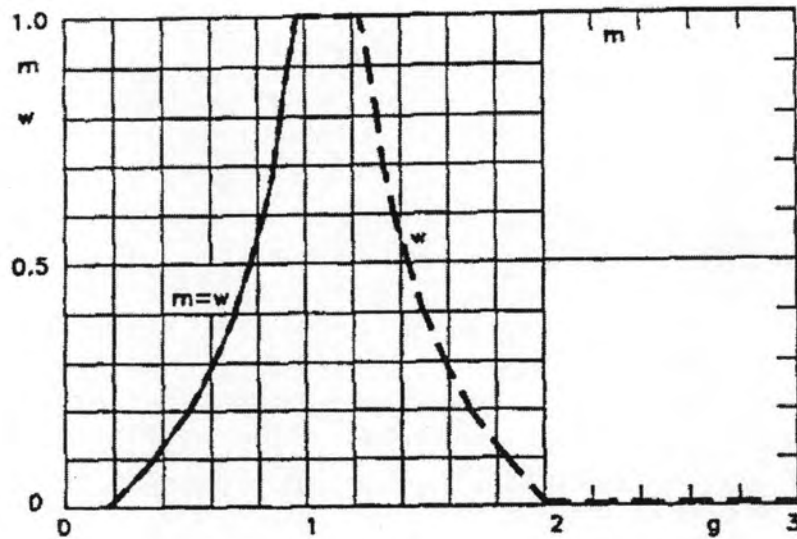


Figure 2.10 Exponent m and w in a function of g

The parameter g can be computed from the equation

$$g = \frac{U}{500 \cdot \ell \cdot k \cdot \delta} \quad (2.9)$$

Where ℓ is the discharge path in m and U is the breakdown voltage in kV

2.4.2 Amendment to IEEE4-1995^[3]

In 2001, IEEE issued an amendment to IEEE4-1995. This amendment proposed an alternative atmospheric correction factor to IEEE4-1995 in a case where discharge path is less than 1m. This standard stated that the flashover voltage in air at any atmospheric condition U is equal to the flashover voltage in air at standard atmospheric conditions U_0 multiplied by K_d and divided by K_h .

$$U = U_0 \times \frac{K_d}{K_h} \quad (2.10)$$

Where K_d is the air density correction factor and K_h is the humidity correction factor. On the other hand, the flashover voltage in air at standard atmospheric conditions U_0 is equal to the flashover voltage in air any atmospheric conditions U multiplied by K_h and divided by K_d .

$$U_0 = U \times \frac{K_h}{K_d} \quad (2.11)$$

The standard atmospheric conditions are the same as in section 2.4.1.

The air density correction factor K_d can be found by equation

$$K_d = \left(\frac{p}{p_0} \right)^m \times \left(\frac{273 + t_0}{273 + t} \right)^n \quad (2.12)$$

In equation (2.12), p and t is the air pressure and temperature during the test respectively. Note that the dimension of p and p_0 should be the same and the dimension of t and t_0 must be in °C.

For humidity correction factor K_h , it can be computed by the equation

$$K_h = k^w \quad (2.13)$$

Where k can be found from figure 2.10 and note that k depends on test voltage waveform.

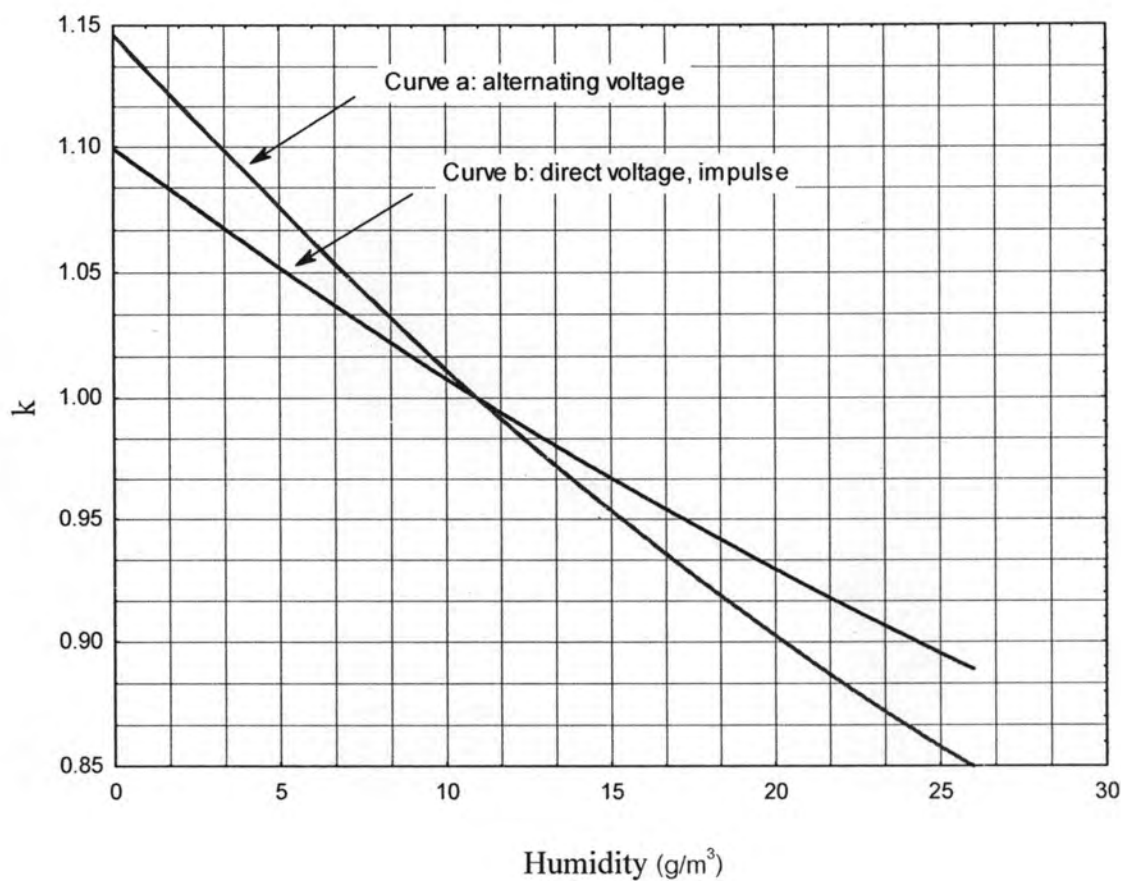


Figure 2.11 k in a function of h/δ for different test voltage waveform.

The value of exponent m , n and w in a function of discharge path ℓ can be determined from figure 2.12 and Table 2.1.

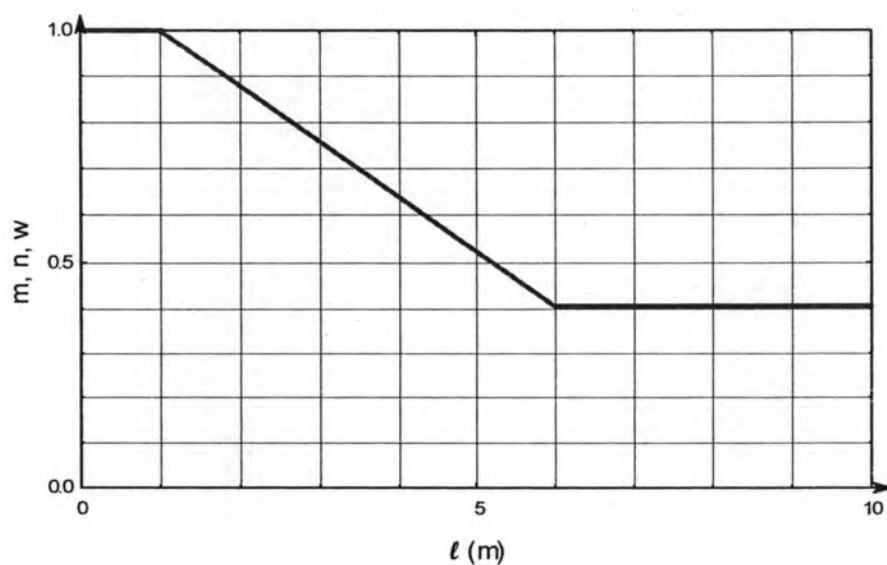


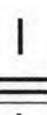


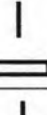




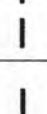
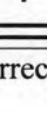


Figure 2.12 Exponents m , n and w in a function of discharge path ℓ

Table 2.1 Application of atmospheric correction factors

Type of test voltage	Electrode form	Polarity	Air density correction	Humidity correction	
			Exponents m and n	Factor K	Exponent w
Direct voltage	  	+	1.0	See Figure 2.11 Curve <i>b</i>	0
		-			0
		+			1.0
		-			1.0
		-			0
Alternating Voltage	  	~	1.0	See Figure 2.11 Curve <i>a</i>	0
		~	See Figure 2.12		See Figure 2.12
		~			
Lightning impulse Voltage	  	+	1.0	See Figure 2.11 Curve <i>b</i>	0
		-			0
		+			1.0
		-			0.8
		+			1.0
		-			0
Switching impulse voltage	  	+	1.0	See Figure 2.11 Curve <i>b</i>	0
		-	1.0		0
		+	See Figure 2.15		See Figure 2.12
-	0 ^a	0 ^a			
		+			
		-			

0^a No guidance or correction given

2.4.3 ANSI C29.1-1988^[4]

ANSI C29.1 is a generic standard for insulator. It recommend that the conversion of flashover voltage obtained under atmospheric conditions to flashover voltage at standard atmospheric conditions ($p_0 = 760\text{mmHg}$, $t_0 = 25^\circ\text{C}$ and $h_0 = 15\text{g/m}^3$) can be done by using equation (2.14). But the air density and humidity correction factor are different from [3]. The air density correction factor is computed by using equation (2.12) with $m = n = 1$. The humidity correction factor is determined from graph in figure 2.13 and 2.14 for lightning impulse and AC test voltage respectively.

$$U = U_0 \times \frac{K_d}{K_h} \quad (2.14)$$

Here, U is the flashover voltage during test [KV]

U_0 is the flashover voltage at standard atmospheric condition [KV]

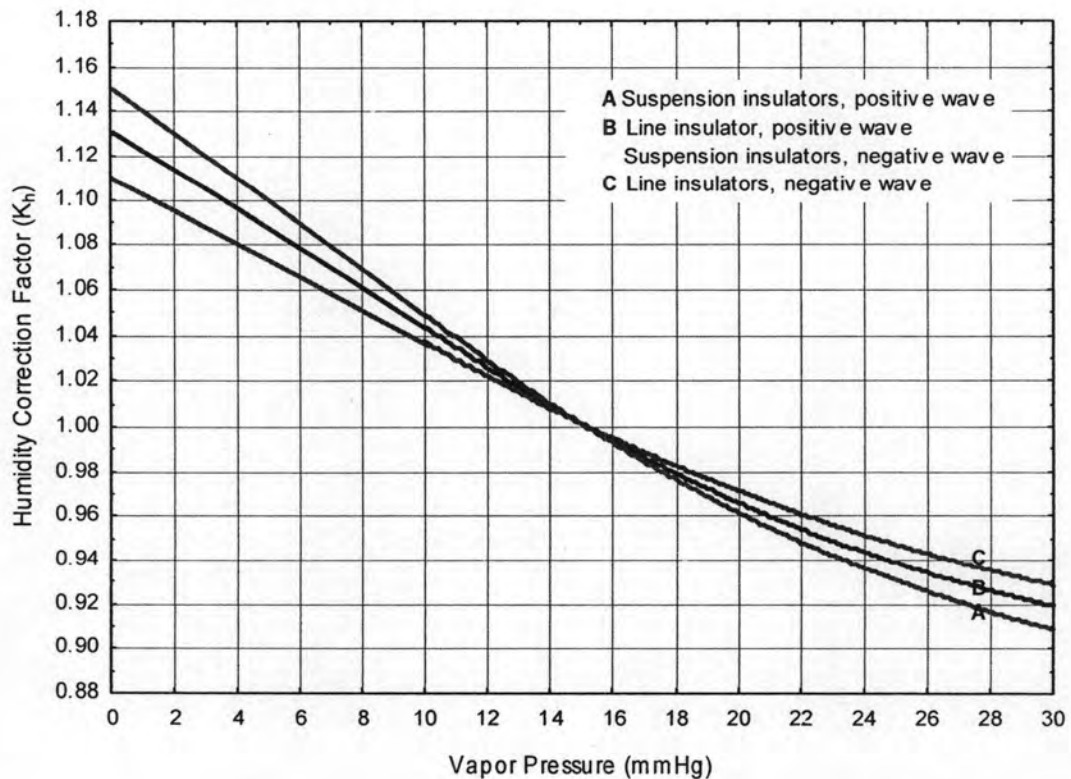


Figure 2.13 Lightning Impulse Humidity Correction Factor

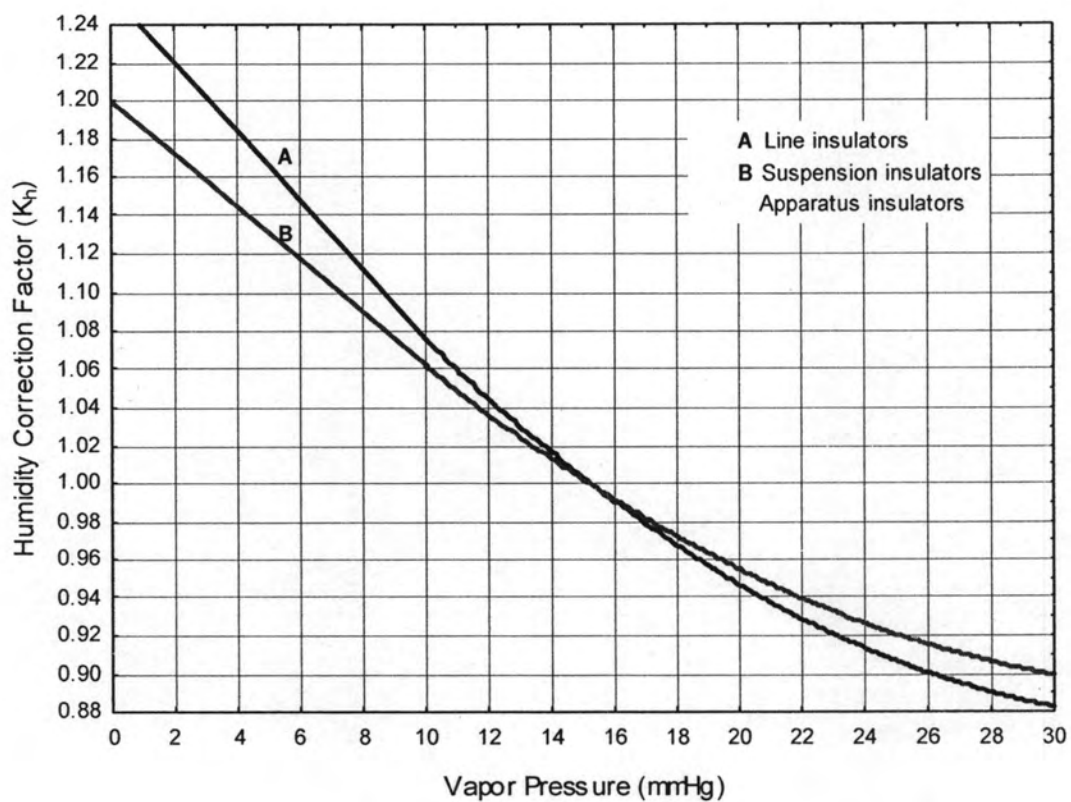


Figure 2.14 Low-Frequency Humidity Correction Factor