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Par:
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# MODELING OF AC ARC INSIDE WET SNOW

# MODÉLISATION DE L'ARC ÉLECTRIQUE EN COURANT ALTERNATIF À L'INTÉRIEUR DE LA NEIGE FONDANTE

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## Abstract:

Overhead transmission lines traverse long distances and generally pass over a variety of regions with different kinds of relief (earth topography, altitude, etc), climate (temperature, pressure, wind, etc), and environment (industrial parks, coastal areas, etc). In this regard, high voltage outdoor equipment is subjected to various forms of constraint. Among those, pollution, wet snow and atmospheric icing of outdoor insulators are recognized as being the major factors at the origin of power outages recorded on the transmission lines, and appear to be factors of very high importance in the quality and the reliability of energy distribution. Indeed, outdoor insulators can be covered with dust (slightly conducting but hygroscopic), with atmospheric ice or melting snow. Electric arcs can be initiated under certain conditions, and develop until they cause the total flashover of the insulator. Thus, within the framework of the activities aiming at increasing our basic knowledge of the initiation of electric discharges inside snow and their development into flashover, the Industrial Chair CRSNG/Hydro-Quebec/UQAC on atmospheric icing of power network equipment (CIGELE) undertook a vast research program based on the study and the modeling of the flashover of snow-covered insulators. The main objective of this PhD project consists of establishing a mathematical model able to predict the flashover voltage of snow-covered insulator surfaces. An important project for the adequate design of the insulators intended for cold regions. The comparison of the results obtained by the mathematical model with those obtained in experiments shows a very good agreement.

## Résumé:

Les lignes aériennes de transport d'énergie électrique parcourent de longues distances et traversent en général des régions très différentes de par leur relief (topographie du terrain, altitude, etc.), leur climat (température, pression, vent, etc.), leur environnement (zones industrielles, régions côtières, etc.). De ce fait, les équipements de transport d'énergie électrique sont exposés à diverses contraintes. Parmi celles-ci, la pollution, la neige fondante et le givrage atmosphérique des isolateurs sont reconnues comme étant les facteurs majeurs à l'origine des défauts enregistrés sur les lignes aériennes, et apparaissent ainsi comme des facteurs de très grande importance dans la qualité et la fiabilité du transport d'énergie. Les isolateurs peuvent en effet se recouvrir de poussière (faiblement conductrice mais hygroscopique), de glace atmosphérique ou de neige fondante. Des arcs électriques peuvent prendre naissance dans certaines conditions, et se développer jusqu'à provoquer le contournement total de l'isolateur.

C'est ainsi que dans le cadre de ses activités visant à accroître les connaissances sur les processus à l'origine de l'initiation des décharges à l'intérieur de la neige et leurs développement en étincelle/arc de rupture, la Chaire Industrielle CRSNG/Hydro-Québec/UQAC sur le givrage des équipements des réseaux électriques (CIGELE) a entrepris un vaste programme de recherche basé sur l'étude et la modélisation du contournement des isolateurs recouverts de neige.

L'objectif principal consiste à établir un modèle mathématique capable de prévoir la tension de contournement à la surface des isolateurs recouverts de neige fondante. Il s'agit-là d'un projet important pour la conception appropriée des isolateurs destinés aux régions froides. La comparaison des résultats obtenus par le modèle mathématique avec ceux obtenue expérimentalement montre une très bonne concordance.

## Acknowledgments:

This work was carried out within the framework of the NSERC/Hydro-Quebec/UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) and the Canada Research Chair on Engineering of Power Network Atmospheric Icing (INGIVRE) at the University of Quebec.

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Finally, to my wife Sona: thank you for being so loving, supporting, patient and all understanding during this study.

This work is offered to all my professors, all my friends, and all the members of my family.

**Dedication:**

To those who have filled my life with love:

**My wife, Sona, for her love**

**My Father, for his pain**

**My mother, for her hands**

**My brothers, my sister**

**And, my dear Aylin**

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## List of abbreviations and symbols:

| Symbol | Explanation | Unit |
|---|---|---|
| UQAC | University of Quebec in Chicoutimi, Université du Québec à Chicoutimi | ----- |
| CIGELE | NSERC/Hydro-Quebec/UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment | ----- |
| INGIVRE | Canada Research Chair on Engineering of Power Network Atmospheric Icing | ----- |
| DC | Direct Current | kV |
| AC | Alternative Current | kV |
| HV | High Voltage | kV |
| $\delta$ | Snow density | $g/cm^3$ |
| $\sigma$ | Water melted from snow conductivity | μS/cm |
| $V_{app}$ | Applied Voltage | kV |
| $V_m, V_{peak}$ | Voltage peak value | kV |
| $V_{arc}$ | Arc Voltage | kV |
| $E_{arc}$ | Arc voltage gradient | kV/cm |
| $I_m$, $I_{peak}$ | Current peak value | A |
| $I_{arc}$ | Arc current | A |
| A | Arc gradient constant | ----- |
| $A_a$ | Arc gradient constant in airgap | ----- |
| $A_s$ | Arc gradient constant inside snow sample | ----- |
| n | Arc gradient component | ----- |
| $n_a$ | Arc gradient component in airgap | ----- |
| $n_s$ | Arc gradient component inside snow sample | ----- |
| k | Arc re-ignition constant | ----- |
| $k_{as}$ | Arc re-ignition constant in airgap and inside snow | ----- |
| b | Arc re-ignition component | ----- |
| $b_{as}$ | Arc re-ignition component in airgap and inside snow | ----- |
| $V_e$ | Electrode drop voltage | V |

| | | |
|---|---|---|
| $r_p$ | Pollution resistance per unit | Ω/m |
| $R_p$ | Pollution resistance | Ω |
| $R_s$ | Snow residual resistance | Ω |
| X | Arc length | m |
| $X_1$ , $X_2$ | Arc length in airgap and inside snow respectively | m |
| $X_c$ | Critical arc length | m |
| L | Arcing distance | m |
| $U_c$, $V_c$ | Critical voltage | kV |
| $\eta_e$, LWC | liquid water content | % |
| $\rho$ | density of water dripping from snow sample | $g/cm^3$ |
| $\upsilon$ | water volume contained in the snow | $cm^3$ |
| $W_E$ | weight of water dripped from the snow sample | g |
| $W_T$ | Total weight of the snow sample | g |
| T | Temperature | $^oC$ |
| K | Conductivity parameters used in the relation 3.6 | μS/cm |
| $K_1$ | Conductivity parameters used in the relation 3.6 | $^oC^{-1}$ |
| $K_2$ | Conductivity parameters used in the relation 3.6 | $^oC^{-1}$ |
| V-I | Voltage - Current | ----- |
| $\gamma_e$ | Snow Equivalent conductivity | μS/cm |

## List of Publications related to this research:

### Refereed Journal Papers:

1. M. Farzaneh, H. Javadi, I. Fofana and H. Hemmatjou, "*An Analytic Model to Simulate the Leakage Current of a Snow-Covered* ", (to be submitted).
2. H. Hemmatjou, I. Fofana and M. Farzaneh, "*Modeling of the AC Arc Discharge inside Wet Snow*", IEEE Transactions on Dielectrics and Electrical Insulation (submitted).
3. M. Farzaneh, I. Fofana and H. Hemmatjou, "*Parameters Affecting Electrical Characteristics of Snow Accumulated on an HV Insulator*", IEEE Transactions on Dielectrics and Electrical Insulation (in press).

### Refereed Conference Papers:

1. M. Farzaneh, I. Fofana and H. Hossein, "*The electrical properties of snow*", 2004 IEEE CEIDP, Boulder, Colorado (USA), pp. 611-614, October 17-20$^{th}$, 2004.
2. H. Javadi, M. Farzaneh, H. Hemmatjou, "*V-I characteristic of Snow and its Electrical Behavior under High Alternating Voltage*", Power System Conference, PSC2004, Tehran, Iran, 12-E-HVS-347,5p, November 21-24$^{th}$, 2004.
3. H. Hemmatjou, and M. Farzaneh, "*Electrical Behavior of Snow Accumulated on a Post Insulator under AC High Voltage*", 11th International Workshop on Atmospheric Icing of Structures, Montreal, Canada, pp. 243-247, June 12-16$^{th}$, 2005.
4. H. Hemmatjou, I. Fofana, M. Farzaneh, "*Propagation of AC Arc Discharge Inside Wet Snow*", The 14th International High Voltage Engineering, Beijing, China, Paper D-27 August 25-29$^{th}$, 2005.
5. H. Hemmatjou, M. Farzaneh, I. Fofana, "*AC Arc Characteristics on a Snow-Covered Cylinder*", 2005 IEEE Conference on Electrical Insulation and Dielectric Phenomena, Nashville, Tennessee, USA, pp. 329-332, October 16-19$^{th}$, 2005.
6. H. Javadi, M. Farzaneh, H. Hemmatjou, "*An Analytic Model to Simulate Electrical Behavior of Snow Deposited on a HV Insulator*", 2005 IEEE

Conference on electrical insulation and dielectric phenomena, Nashville, pp. 317-320, Tennessee, USA, October 16-19th , 2005.

7. H. Javadi, M. Farzaneh, H. Hemmatjou, "*Process and Modeling of Arc on a Snow-Covered Insulator*", Transmission and Distribution Conference and Exposition, 2005/2006 IEEE PES, Dallas, Texas, USA, pp. 62-68, May 23-25th , 2006.

**Conferences/Colloquiums with Published Abstracts**

1. H. Hossein, I. Fofana, M. Farzaneh and V. Markon, "*The DC conductivity of atmospheric snow near the melting temperature*", 6th CIGELE/INGIVRE Annual Colloquium, Chicoutimi (Québec, Canada), February 11-12th 2004

# CHAPTER 1:

# GENERAL INTRODUCTION

## 1-1 Description of the problem

When designing insulation coordination of transmission lines and substations, emphasis is placed on the environmental and meteorological conditions of the routes or sites. The insulation design for a contaminated area is based on the contamination withstand-voltage characteristics under the operating voltage. In Nordic regions, yearly snowfall is between 70 and 300 inches [1-3]. In cold climates, the accumulation of glaze ice or wet snow on the outdoor insulators of power networks may considerably affect their electric performance, as well as cause structural damage. Particularly in heavy snowfall areas, wet snow and superimposed contamination can be at the origin of corona discharges and partial arc initiation, leading under certain conditions to insulator flashover and consequent power outages [2, 4-7]. Such problems generally appear on tension insulator assemblies, and rarely on suspension assemblies, since tension assemblies are more prone to large amounts of snow accumulation [2]. Snow covered-insulator flashover resulting in occasional power outages have been reported in many countries such as Canada [8-14] the United States [15, 16] Japan [4, 17], etc. These reports confirm that the presence of atmospheric snow together with superimposed contamination sometimes leads to flashover and occasional outages.

Although the frequency of snow related insulator flashovers is relatively low when compared to ice, the scale of a flashover-caused service interruption is often large and it takes a long time to bring the affected lines back to service [17]. As many transmission lines in cold climate regions experience heavy snowfall, it is essential to investigate the electrical properties of natural snow in order to ensure the adequate functioning of the insulators.

In contrast to ice–covered insulators, few studies have been carried out on the flashover performance of snow-covered insulators [2, 4-7, 17, 18].

A number of worthwhile experimental investigations have furthered our basic knowledge on the effects of snow parameters on the critical flashover voltage of snow-covered insulators [e.g. 19, 20] and proposed several mitigation methods. A review of most of the investigations in this field was done by a CIGRE Working Group [2]. In spite of a good number of valuable investigations, these reviews revealed the necessity of further fundamental and comprehensive research on arc physic and its behaviour inside snow. The study of the flashover process of insulators under snow conditions still requires a comprehension of snow characteristics, and some physical, electric, thermal, mechanical and aerodynamic phenomena associated to the arc insufficiently known to date. Indeed, until now, there has been almost no exploratory research work related to the physical mechanisms leading to the flashover of snow-covered insulators. In this regard, systematic studies on the development of electric arc, including the identification of the fundamental mechanisms leading to inception and propagation of the partial discharge inside wet snow as well as the analysis of these dielectric breakdown conditions will be of great importance for the comprehension of the phenomena of the flashover of snow-covered insulators.

Also, a satisfactory mathematical model, one that is able to predict the flashover voltage of outdoor insulator under wet snow accumulation, is not yet available. Even though extensive studies on the snow phenomena have not been carried out to date by researchers in this domain. Fundamental studies for identifying the parameters affecting the electrical characteristics of snow, understanding discharge initiation, local arc formation and the mechanisms of their development and propagation inside snow are necessary for the prediction of arc on snow-covered insulators. This is also necessary for the appropriate design and dimensioning of insulators destined for use in the cold regions of the world, experiencing ice and snow accretions.

## 1-2 Main Objectives

In order to further our knowledge and understanding the discharge initiation inside snow and its development into arc flashover, a comprehensive research program has been integrated into the framework of the CIGELE throughout this PhD project. The present research project aims at furthering our basic knowledge of wet snow-covered insulator flashover.

Specifically, the final objective consists of establishing mathematical models able to predict the flashover voltage of snow-covered insulators, an important project for the adequate design of the insulators intended for the cold areas. The socio-economic repercussions of this project for Canada are foreseeable and important in order to increase the reliability of transport and distribution of electric power.

The development of a static model able to predict the flashover arc on actual insulators covered by snow is a complex and ambitious task. Firstly, the shape of the insulators, often with a large dry arcing distance and often covered with a pre-contaminant film as well as a thick, non-uniform snow layer with varying characteristics, makes the modeling difficult. Secondly, the physics of the electric arc is extremely complex, involving various phenomena of electrical, mechanical and thermal origins. The best-known existing models for arc behavior on an insulating polluted surface are strictly limited as far as their validity is concerned and may not be applied indiscriminately to engineering systems [21-23].

It is expected to use similar approaches already used by Farzaneh et al. [24-26] for the static modeling of the electric discharge on ice-covered insulator surface. In order to understand the flashover processes of snow-covered insulators and to establish design criteria for outdoor insulators, the electrical characteristics of natural snow should first be investigated. Attention will therefore be focused on the identification and analysis of snow related parameters affecting the flashover performance of snow-covered insulators.

The anticipated results of these investigations will be of great importance in increasing the reliability of insulators, finally closing some major gaps in the present state of knowledge relating to snow-covered insulator flashovers.

## 1-3 Methodology

The proposed research is carried out using the following steps, which have been demonstrated to be both effective and successful in the CIGELE laboratory.

- Since industrial insulator has a complex shape and is difficult to use for fundamental process investigations, simplified physical models were used during the earlier stage of these investigations;
- A series of tests were carried out for analyzing the factors influencing snow conductivity;
- The residual snow resistance, arc voltage-current characteristics, and arc voltage drops were obtained using regressions on the test results.

- Recording arc voltage and current in air gap and inside wet snow, the arc constants and re-ignition parameters in air gap and inside wet snow separately. The arc reignition conditions under ac voltage were also studied;
- Based on the Obenaus concept for flashover on polluted surfaces, and on the experimental results as obtained in the present research, a mathematical model was developed to analyze the flashover on snow-covered insulator surfaces under AC voltages;
- To validate the proposed static arc model, flashover tests on the simplified physical model as well as on actual outdoor insulators were carried out according to standard methods. Good agreement between the experimental results and calculated results was obtained.

## 1-4 Structure of the Thesis

This dissertation introduces and discusses the different aspects of snow-covered insulator flashover, as follows:

Chapter 2 qualitatively reviews natural snow characteristics and snow-covered insulators' flashover processes after a short review of the flashover mechanisms of the snow-covered insulator. This chapter is completed by an insight into the state of the art concerning the static models developed for insulator surface flashover;

Chapter 3 analyses the DC conductivity of snow as a function of various parameters; moreover, conductivity of water melted from snow for a large number of snow samples are examined to derive relationship between the observed conductivity and snow temperature;

Chapter 4 summarizes the investigations performed to determine the snow residual resistance from a large number of snow samples and Voltage-Current characteristics of snow under H.V;

Chapter 5 describes the investigations performed on a great number of snow samples, to determine static arc characteristics in the case of snow-covered insulator flashover. Using regressions, the arc parameters are derived both for snow and air gap media;

Chapter 6 focuses on the validation of the derived static model to predict snow-covered insulator flashover voltage. To validate the simulation results, the need for several series of flashover tests is justified in this chapter;

Chapter 7 concludes this work and also highlights recommendations and future directions for the follow-up of this project.

# CHAPTER 2:

# LITERATURE REVIEW OF SNOW CHARACTERISTICS AND ITS INFLUENCE ON OUTDOOR INSULATORS

## 2-1 Introduction

The influence of snow accretion on flashovers occurring on HV insulators is still a challenging subject in many cold climate countries.

In order to understand the flashover processes of snow-covered insulators and to establish design criteria for outdoor insulators, the electrical characteristics of natural snow should first be investigated. In the present chapter, before proceeding to the discussion of snow physics, a short review of the flashover mechanisms of snow-covered insulators will be presented. All snow parameters are important, but some have special merit in the characterization of snow's electrical properties. The important ones are those that are likely to vary significantly with snow impurity and composition as well as with external parameters, such as temperature, impurities and electric field. The most important overall are the volume resistivity and density, followed by the liquid water content and the conductivity of water melted from snow. Finally, to complete this review, the parameters affecting the electrical performance of snow-covered insulators will be discussed.

## 2-2 Flashover Mechanism of Snow-covered Insulators

Outdoor insulators can be subjected to either wet or dry snow, depending on whether the air temperature is below or above freezing [2]. From a meteorological point of view, wet snow may be treated as 'ice' while dry snow is considered different [2]. It should be noted that practically no exploratory research work is available on the mechanisms of flashover occurrence involving snow-covered insulators. However, it is well-established that several parameters, including snow type and density, snow amount and distribution and melted water conductivity are major parameters affecting the withstand voltage characteristics of snow-covered insulators [2, 7]. It has also been established that the flashover performance of snow-covered insulators is affected by the height of snow and the ratio of the length of the snow cap to the insulator length [2, 7].

Snow-covered insulator flashover is not an instantaneous phenomenon, but results from the process outlined in Figure 2.1.

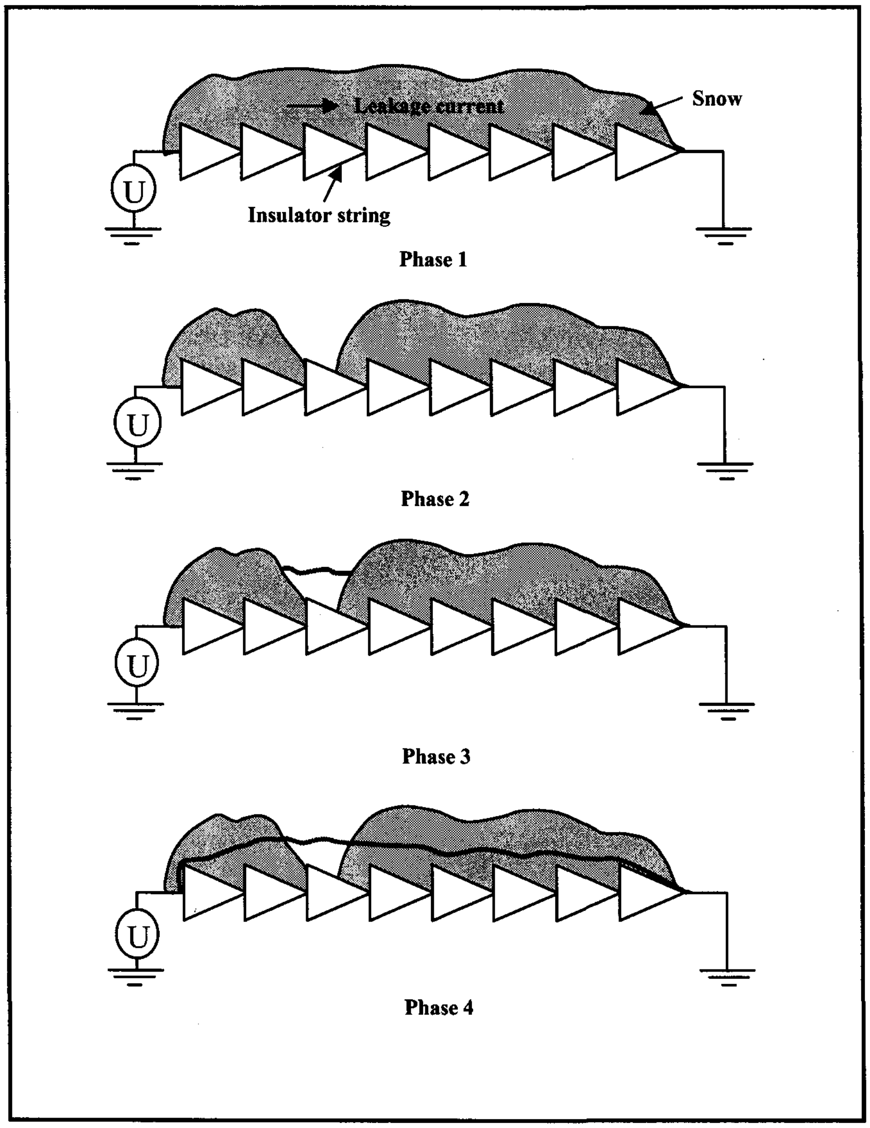



**Figure 2.1:** Flashover process of snow-covered insulator

- **Phase 1:** Leakage current flows through the wet snow covering the insulator. Unlike ice-covered insulators, the flashover characteristics of snow-covered insulators are mostly influenced by the volume conductivity and other volume characteristics of the snow. The characteristics of accumulated snow on an energized insulator change with time, mainly due to leakage current and ambient temperature [6]. The higher the conductivity, the higher the leakage current flowing through the snow. The leakage current also increases with the density and water content of the snow [7].
- **Phase 2:** As a result of the increase in leakage current, part of the snow exposed to high current density may melt prematurely through Joule heating. Due to gravity, the melted water flows downwards and collects at the bottom of the accumulated snow bed covering the insulator. Segments of that snow may then drop off the insulator string. Shedding of snow also depends on the adhesive and thermal properties of the insulator surface material (glass, porcelain, composite, steel, etc.). The resulting air gaps have a tendency to extend until complete interruption of the leakage current occurs.
- **Phase 3:** This non-uniform snow distribution results in a strongly non-linear voltage distribution along the insulator string. If the electric field across the air gap is high enough, corona discharges are initiated. Transition from corona discharges to partial arc is similar to the breakdown process in air that occurs when the conditions required for the stem to evolve into an arc channel are attained [5]. Depending on the electric conductivity of the remaining snow and the length of the snow-free gaps over the string, partial arcs may bridge these gaps, causing a substantial increase in leakage current and a concomitant melting of snow.
- **Phase 4:** From this stage, the evolution of the discharge can take different courses: the

local arc can die out, or it can lengthen to reach the electrodes leading to the total flashover.

## 2-3 Review of snow physics

Falling snow may be dry or wet, depending on whether the air temperature is below or above freezing. Snow can therefore be considered an insulator made of air and ice [19] and the actual ice in a snow crystal is not different from that in an ordinary ice cube; it is a two-component system. When wet, it becomes a three-component system composed of air, ice and water. Wet snow is treated as a three-phase mixture, considering the ice and water particles to be inclusions embedded in the air that is the background material, as shown in Figure 2.2.

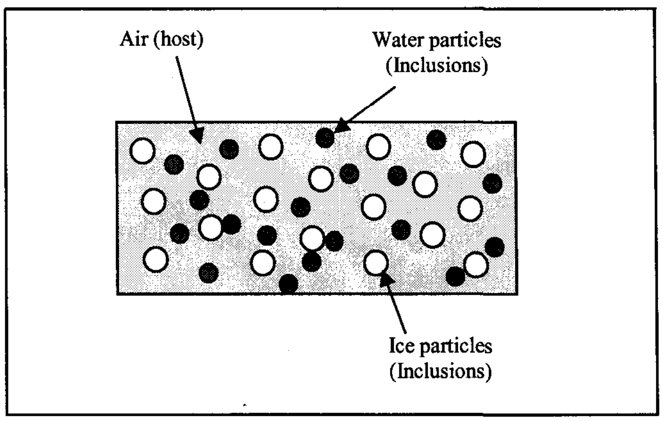



**Figure 2.2:** Wet Snow as a three-phase mixture

Ice bonding between the grains is observed in most, but not all, types of snow. In studying the electrical properties of snow, it must be recognized from the start that wet and dry snow are fundamentally two different materials, since liquid water causes major changes in the configuration of both grains and bonds. In fact, the geometries and electrical properties of wet and dry snow are markedly different [20, 27].

Wet snow is categorized by its liquid content level (high or low), while dry snow is categorized by its growth rate (high or low). Wet snow with high liquid water content is slushy and less cohesive because the grain boundaries are unstable against (pressure melting.

During its "formative" stage in the atmosphere, snow can be defined simply as particles of ice formed in a cloud which have grown large enough to fall to the ground with a measurable velocity.

The formation of snow in the atmosphere depends on many variables. The most important is that the ambient temperature should be less than 0°C. Figure 2.3 shows the flow diagram of different types of snow formation.

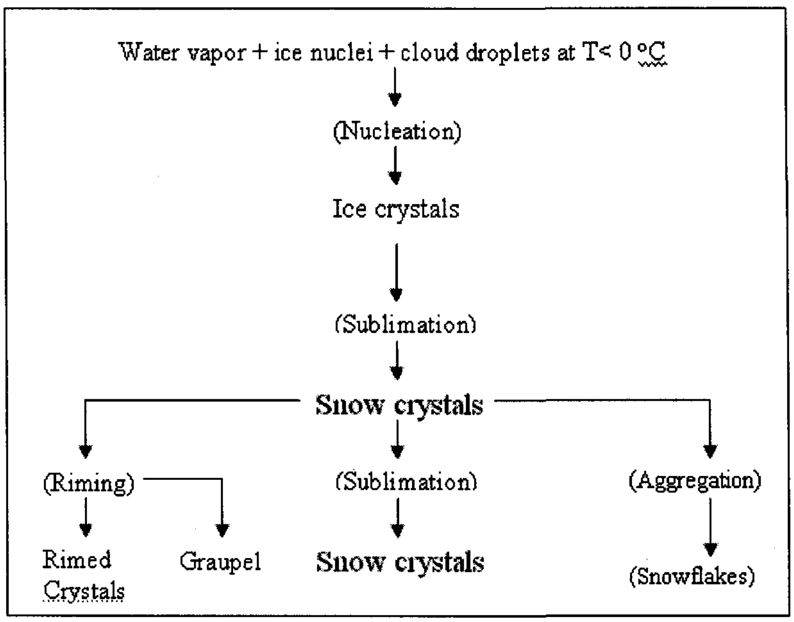



**Figure 2.3:** Flow diagram of the formation of different types of Snow

Initially, a cloud is formed by condensation of the water vapor in an ascending region of warm moist air. When the cloud temperatures go below freezing, conditions are suitable for the formation of snow. At about –5°C the nuclei in the atmosphere form tiny crystals through the process of ice nucleation. The ice crystal is the initial step in the formation of the snow particle, having a small size, a diameter usually less than 75-micrometer with a very low fall velocity, typically less than 5 cm/s often a hexagonal plate. As shown in Figure 2.3, if the ice crystal continues to grow by sublimation, a snow crystal is formed. This is a large individual particle, often having a very intricate shape, and of such a size that it is readily visible to the naked eye. A snowflake is an aggregation of snow crystals. Figure 2.4 shows the formation of a snowflake from the nucleation stage to the final shape of formation [28].

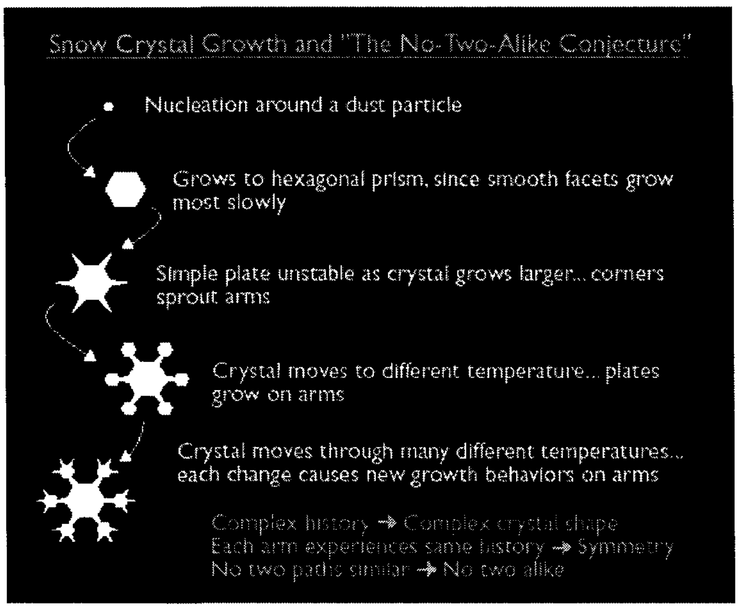



**Figure 2.4:** Growth of a Snowflake

Snowflakes are made from between two and several hundred snow crystals joined together. Generally, for snowflakes to form, a series of crystals should be joined together at different velocities at air temperatures slightly lower than 0 °C.

The physical properties of snow on the ground may differ greatly from the ice crystals in a snowfall. Ice particles that form in the atmosphere have a large variety of crystal shapes and sizes. By the time these ice crystals reach the ground, they have already undergone a number of changes resulting from growth, disintegration, or agglomeration. The properties and characteristics of fallen snow change constantly as a function of energy fluxes, wind, moisture, water vapor, temperature and pressure.

One of the snow characteristics that is strongly affected by external conditions is snow density. There are some investigations of snow density; for example, the results of Nakamura and Magono (1965) showed that the density of a snowflake decreases in size according to the equation [28]:

$$R \cdot d^2 = 2 \times 10^{-2} \quad (2.1)$$

where R is the density in $g/cm^3$ and d is snow crystal diameter in cm. Snow crystal size can change because of all parameters mentioned above.

Snow density can also change because of presence of the wind. It moves snow crystals, changing their physical shape and properties. For example, Church (1941) found that fresh snow with densities of 36 and 56 $kg/m^3$ increased in density to 176 $kg/m^3$ within 24 hours of being subjected to wind action [28]. Gray et al. (1971) found similar results; the density increased from 45 to 230 $kg/m^3$ within 24 hours due to wind action. Although initiated by wind action, this time-densification of snow is also influenced by condensation, melting and other processes. Table 2.1 lists the densities of snow cover subjected to different levels of wind action [28].

**Table 2.1:** Densities of Snow cover

| **Snow type** | **Density** ($kg/m^3$) |
|---|---|
| Natural Snow | 10-30 |
| Ordinary wet snow immediately after falling in the still air | 50-65 |
| Settling Snow | 70-90 |
| Very slightly toughened by wind immediately after falling | 63-80 |
| Average wind-toughened Snow | 280 |
| Hard wind slab | 350 |
| New firm Snow | 400-550 |
| Advanced firm Snow | 550-650 |
| Thawing firm Snow | 600-700 |

The density of snow covers is not uniform in depth. According to the Bogorodskii's observations the increase is two times greater at a depth of 3 m from 0.22 to 0.45 g/cm$^3$ (Figure 2.5), the growth in density occurring exponentially [29].

$$d = 0.11 h^{0.213} \tag{2.2}$$

where, d is snow density in g/cm$^3$, and h is the depth in cm.

The snow cover compacts rapidly as wind speed grows (Table 2.2); temperature has little effect on snow cover compaction: at –2 °C the density of freshly fallen snow is 0.1-0.11 g/cm$^3$, while at –10 °C density is 0.07-0.08 g/cm$^3$.

**Table 2.2:** Density of freshly fallen Snow depending on wind speed [30]

| Snowfall condition | Wind speed (m/s) | Density (g/cm$^3$) |
|---|---|---|
| Calm weather | 0-2 | 0.05 – 0.06 |
| Moderate wind | 3-7 | 0.14 – 0.17 |
| Strong wind | 8-15 | 0.18 –0.22 |
| storm | >=16 | 0.23 – 0.33 |

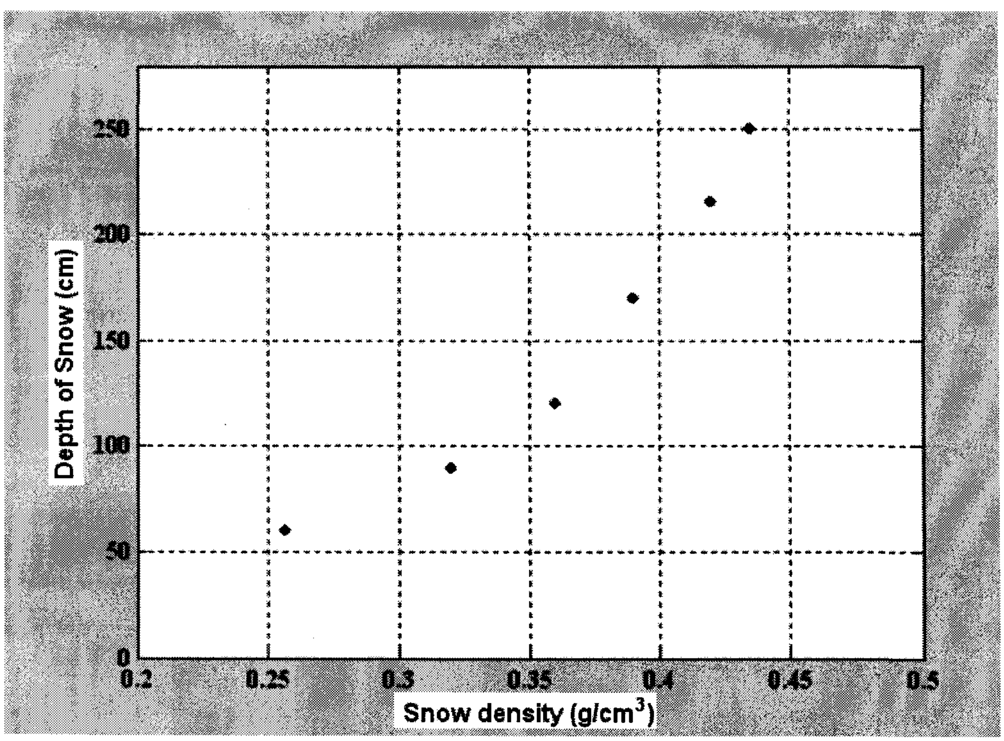



**Figure 2.5:** Change in Snow cover density with depth depending upon depth.

## 2-4 Parameters affecting the dielectric performance of snow-covered insulators

It should be noted that, so far, there is almost no exploratory research work available on the mechanisms of flashover occurrence on snow-covered insulators. However, it is well-established that several snow parameters, including type and density, amount, distribution and conductivity of the water melted form snow are the major parameters which affect the AC withstand voltage characteristics of an insulator assembly covered with dry snow [2, 7]. The electric properties of snow which is accumulated on an energized insulator surface also depend on geometric factors and on the nature and quality of its contact with the electrodes. Among those parameters, however, volume conductivity seems to be the most important one for determining the electrical characteristics of snow. In turn, this parameter is largely influenced by snow volume density, as well as by liquid water and salt content [2, 19].

### 2-4-1 Liquid water content

In studying the electrical properties of snow, it must be recognized from the start that wet and dry snow, fundamentally, are two different materials, since liquid water causes major changes in the configuration of both grains and bonds. In fact, the geometries and electrical properties of wet and dry snow are markedly different [41].

Wet snow is categorized by its liquid content level (high or low), while dry snow by its growth rate (high or low). Wet snow with high liquid water content is slushy and less cohesive because the gra54in boundaries are unstable against pressure melting.

At temperatures above -21.2°C, ice crystals and water drops can still co-exist in salt solution. Hollstein [31] has investigated the super-cooling of common salt solutions of various concentrations contained in small glass ampoules of about 1 $cm^3$ capacity. The super-cooled state is metastable and its existence implies the absence of suitable nuclei to initiate freezing. The eutectic temperature (-21.2°C) is commonly regarded as being the lowest temperature at which sodium chloride solutions can exist; below that point ice and salt crystallize out.

It is agreed that the precise determination of the liquid water content (LWC) of wet snow is not an easy matter. This parameter is defined as the ratio of the weight of water contained in a given quantity of snow to the total weight of the sample. However, its measurement is made possible by separating water from snow using a motor-driven centrifuge [2]. The measurement procedure will be detailed in Chapter 3.

There is not much data on the influence of the liquid water content of snow on the flashover voltage of snow-covered insulator strings. Although the reduction of withstand voltage with increased water content can be seen in Figure 2.6 [2], this tendency is not observed in every test.

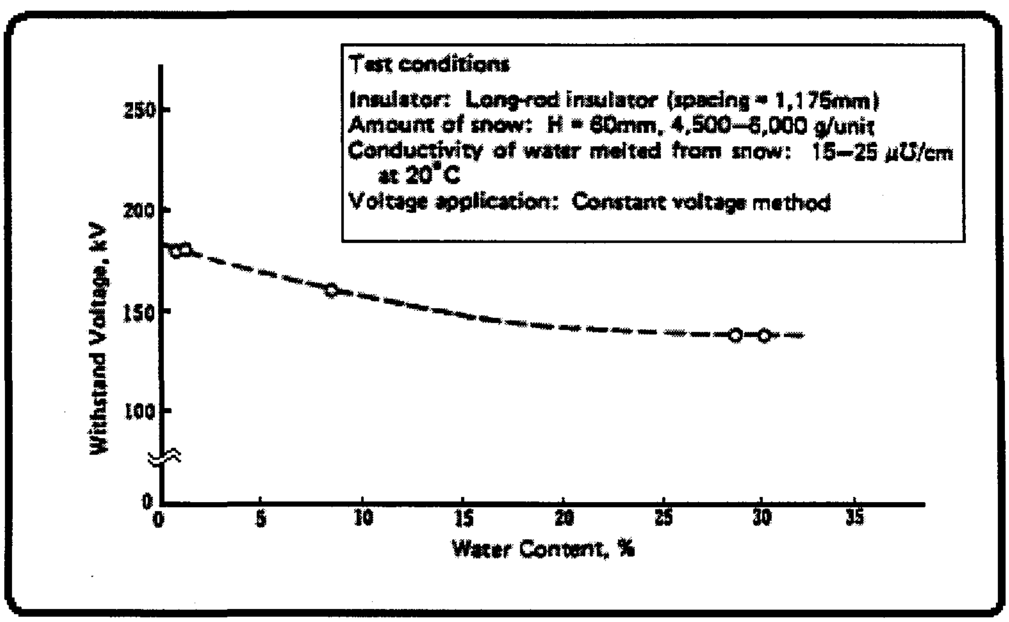



**Figure 2.6:** Effect of the liquid water content of snow on the withstand voltage

### 2-4-2 Conductivity of water melted from snow

The salt content of snow is determined by measuring the conductivity of the water melted from this snow at 20°C. Indeed, chemical analysis of snow collected from various locations has shown that the conductivity of water melted from snow is mainly due to the presence of NaCl [19]. In addition, acids, as well as neutralized fallouts, contribute to the conductivity of melted snow [32].

The flashover performance of snow-covered insulator strings worsens as melted snow conductivity increases [2]. The effect of the conductivity of water melted from snow on withstand stress in the case of the clean insulators naturally covered with contaminated or clean snow, is shown in Figure 2.7 [2]. The withstand voltage of the insulator assembly covered with snow decreases as the conductivity of water melted from snow becomes higher.

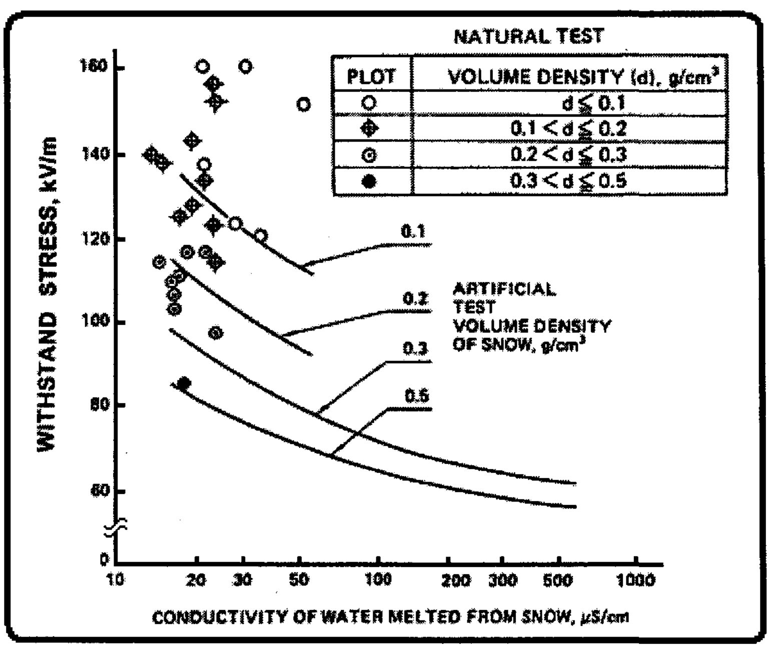


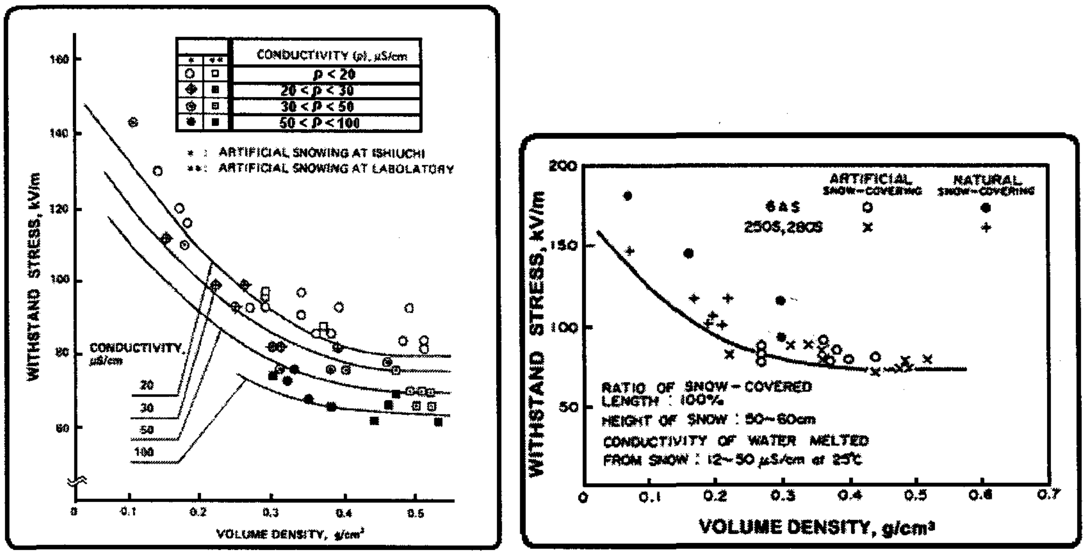

**Figure 2.7:** Effect of conductivity of water melted from snow on the withstand stress

### 2-4-3 Volume density

As natural snow is made up of three basic components, air, ice grains, and liquid water, its density will be markedly influenced by their relative proportions. Water freezes when the motion of its molecules has slowed down enough to allow for the development of bonds upon collision. The rate at which freezing occurs is governed by nucleation, the formation of small solids in a liquid, and growth. The growth rate of ice structures is density dependent. Many parameters, including temperature, air pressure, snowstorm type, geographic location and altitude, may affect the density of snow [33]. In practice, each snowstorm produces snow of a different density. For example, some types of snow may be very dense, which means that they contain a relatively larger quantity of liquid water and/or ice grains [19].

The ice grains within a mass of snow are subjected to an electric force which can be different from the external one applied to that mass [33]. The later force could be modified within snow by the electric interactions which that force induces between one part of the ice network and another. The ice in snow responds to this modified electric force. The electric properties of snow are simply the combination of such responses occurring in every part of the ice network. In this way, snow of the same density generally shows different dielectric properties depending on its ice network structure.

The electric properties of snow are altered according to its ice content, i.e. according to its density. Recent investigations [34] clearly show that the higher the density, the higher the dc conductivity of snow. Figure 2.8-a and 2.8-b show the relationship between the volume density of snow and the AC withstand stress of a tension insulator assembly artificially covered with snow. The electrical performance of a snow-covered insulator string deteriorates as the volume density of snow increases [2].




**a)** Artificial snow covering **b)** Artificial and Natural snow covering

**Figure 2.8:** Effect of density of snow on the withstand stress

The AC withstand stress of the insulator assembly covered with snow decreases as the volume density of snow increases.

Although the range of the volume density of the snow was as low 0.2 to 0.3 g/cm$^3$, it can be seen from this Figure that the AC withstand voltages of an artificial and a natural snow cover are very close to each other.

### 2-4-4 Height of snow

The relation between the height of snow on the insulator assembly and withstand stress is shown in Figure 2.9. The withstand stress of an insulator covered with snow becomes lower as the height (or weight) of snow increases. The stress levels off at a snow height of more than 40-50 cm and weight of more than 10 kg per insulator unit [2, 7].

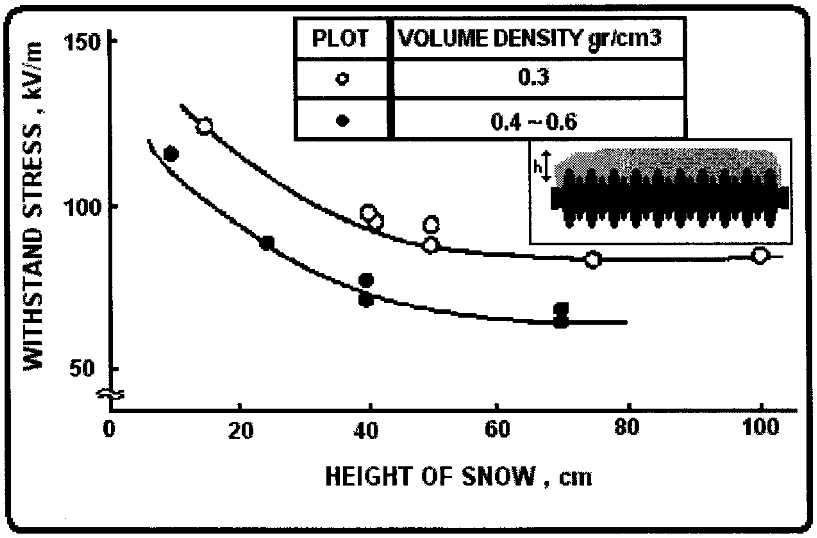



**Figure 2.9:** Effect of Height of snow on the withstand stress

### 2-4-5 Length of Snow

According to field observations made on a tension insulator assembly, snow on the line side insulator units is apt to fall down more in comparison to the Earth side, due to the higher electric field. There is a significant possibility of longitudinally non-uniform coverage [7]. Figure 2.10 shows the relationship between the ratio of snow-covered length from the Earth side and the withstand voltage. The withstand voltage of the insulator assembly covered with snow decreases as the ratio of the snow covered length increases, and it levels off at the ratio of more than 80%.

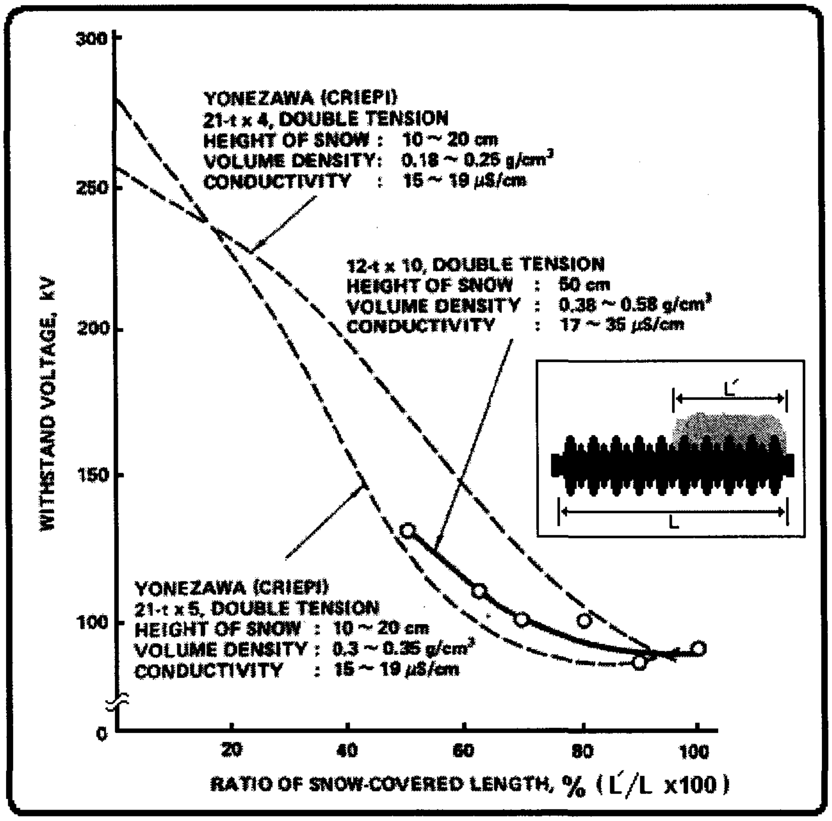



**Figure 2.10:** Effect of ratio of snow covered length on the withstand stress

## 2-5 Modeling of flashover

Numerous experimental and theoretical studies have been carried out over the years to investigate the flashover phenomenon of insulator surfaces covered by a conductive layer [35]. The pollution and ice surface process has been simulated and studied in many laboratories by using some simplified models [21, 23, 35, 36, 37].

Electric arcs tend to occur under certain conditions and to develop on/over the conductive layer covering the insulator up to the point of causing the total flashover. With the aim of improving insulator design, considerable work has already been or will be accomplished towards determining insulator behavior and the flashover process under contaminated conditions [38].

In this chapter, an overview of the different mathematical models for flashover on an insulator surface has been provided. Most of these models are the static models describing DC flashover phenomena. Most of the electrical energy transfer in high voltage networks takes place under AC applied voltage. AC static modeling is also being carried out under the same assumptions as DC modeling, with the addition of re-ignition conditions under polluted and ice surfaces [39]. Obenaus was a pioneer in the field who carried out quantitative analyses of the arc phenomenon on the surface of insulators covered with a conductive layer [40, 41]. He proceeded by considering an equivalent electrical circuit, constituted of an arc of axial length $x$ in series with a resistance, $R_p$, then obtained the arc current using the Kirchoff Voltage Loop. In Figure 2.11, L represents the total length of the insulator.

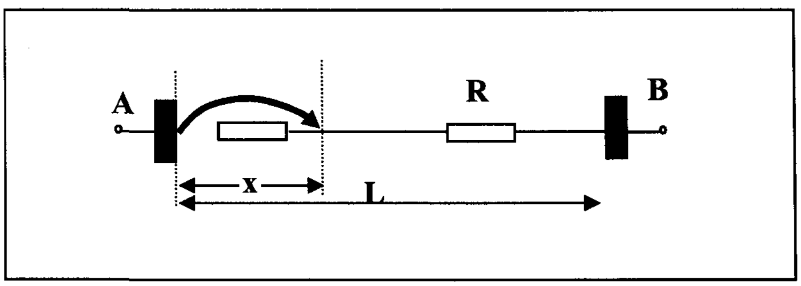



**Figure 2.11:** The Obenaus model

It was assumed that the same current which passes through the arc also passes through the resistive layer. It is necessary to obtain the appropriate equations calculating the arc potential and resistance of the non-bridged part of the conductive layer in order to solve the circuit. The circuit relationship needs to be accompanied by a physical theory so as to complete the model. This simple model became the basis of nearly all later works.

There are numerous arc models to substitute of arc model in the electric circuit equations. Some of these models are listed as follows:

- Ayrton's Equation [39, 42]
- The Rao and Gopal Model [43]
- The Cassie-Francis and Mayr Equations [44, 45]
- LTE and Saha's Equation [48]
- The Elenbaas-Heller Equation [46, 47, 48]
- Numerical Solution [45]

Many researchers have used Ayrton's arc gradient equation to model the arc [49]:

$$E_{arc} = AI_{arc}^{-n} \qquad (2.3)$$

where $I_{arc}$ is the leakage current, and $A$ and $n$ are arc constants. These constants may vary in accordance with the arc medium material and ambient conditions. A survey of the literature shows that the values of $A$ and $n$, as measured or utilized by different investigators, vary over a wide range for different types of arc (see Table 2.3) [3, 21, 23, 38, 40, 41, 50, 51, 52, 53]. These values depend not only on the arc medium but also on the electrolyte used to form the resistive layer. It is therefore foreseen that arc constants in a combined air and snow multimedia should be different from those obtained in the flashover on polluted/ice surfaces.

**Table 2.3:** Constants and exponents used by different investigators

| | Investigator | Current (A) | *A* | *n* | Excitation | Medium |
|---|---|---|---|---|---|---|
| 1 | C. G. Suits (1939) | 1-10 | 65<br>220<br>81 | 0.6<br>0.6<br>0.6 | NS<br>NS<br>NS | air<br>stem<br>nitrogen |
| 2 | Obenaus *et al.* (1959) | 0.1-2 | 100 | 0.7 | ac | air |
| 3 | L. Alston *et al.* (1963) | 0.1-15 | 63 | 0.76 | ac | air |
| 1 | E. Nasser *et al.*(1963) | 0.1-1.0 | 63 | 0.76 | dc | air |
| 5 | Hampton *et al.*(1964) | 0.1-0.5 | 65<br>52 | 0.8<br>0.1 | NS<br>NS | air<br>steam |
| 6 | E. Los *et al.*(1971) | 1-3 | 52 | 0.43 | dc | air |
| 7 | Nottingham (1973) | NS | 44<br>310<br>39.2<br>203 | 0.67<br>0.985<br>0.67<br>1.38 | dc | air |
| 8 | P. Claverie *et al.*(1973) | 1-2 | 113<br>98.99 | 0.5<br>0.5 | ac | air |
| 9 | D. C. Jolly *et al.* (1974) | 1-3 | 296 | 0.397 | ac | air |
| 10 | El-Arbaty *et al.* (1979) | NS | 40 | 0.8 | ac | air |
| 11 | F. A. M. Rizk (1981) | 0.05-2.0 | 130<br>210.6 | 0.45 to<br>1.3 | dc | air |
| 12 | Gers *et al.* (1981) | 0.1-5 | 46.05<br>44.77<br>43.80<br>59.64 | 0.91<br>0.822<br>0.822<br>0.773 | dc<br>impulse<br>dc<br>dc | air |
| 13 | M. P. Varma (1981) | NS | 53.45 | 0.5 | ac | air |
| 14 | Mayr *et al.* (1986) | NS | 40.6<br>50.20<br>114 | 0.724<br>0.708<br>0.714 | dc | air<br>helium<br>nitrogen |
| 15 | D. A. Swift (1989) | 1-3 | 80<br>60 | 0.5 | dc | air |
| 16 | G. Zhicheng *et al.* (1990) | 0.1-1.0 | 138<br>140 | 0.69<br>0.67 | dc<br>ac | air |
| 17 | F. L. Topalis (1992) | NS | 131.5 | 0.374 | NS | air |
| 18 | R. Sundararajan *et al.* (1993) | NS | 60<br>63 | 0.8<br>0.5 | dc | air |
| 19 | R. O. Sing *et al.* (1993) | NS | 31 to<br>100 | 0.43 to<br>0.98 | ac | air |
| 20 | N. Chatterjee *et al.* (1995) | NS | NS | 0.7 | ac | air |
| 21 | H. G. Gopal *et al.* (1995) | NS | 60<br>100 | 0.25<br>1.20 | NS | air |
| 22 | D. C. Chaurasia *et al.* (1996) | 0.01-1.2 | 50<br>100 | 0.25 to<br>1.1 | ac | air |
| 23 | A. S. Farag *et al.* (1997) | NS | 530 | 0.24 | ac | air |
| 25 | M. Farzaneh *et al.* (2000) | NS | 84<br>209<br>205 | 0.77<br>0.45<br>0.56 | dc-<br>dc+<br>ac | air, on the ice |
| 24 | J. P. Holtzhausen (2001) | NS | 59 | 0.53 | ac | air |

It has also been acknowledged in that the flashover performance of snow-covered insulators is affected by the height of the snow and the ratio of snow-covered length over total length [2]. In the case of snow-covered insulators, the accumulation is generally non-uniform. Those zones without snow are referred as air gaps. Because arc constants are greatly affected by the propagation medium, Ayrton's arc gradient equation will be used to model the arc, and constants will be derived for arc in airgap and arc inside snow.

## 2-6 Static Arc Models

### 2-6-1 DC Static Model

Based on the model of the simple circuit shown in Figure 2.11, as proposed by Obenaus, the governing equation of this circuit leads to:

$$V=V_{ap}-V_e=V_{arc}+R_pI_{arc} \tag{2.4}$$

where $V_{ap}$ is the voltage applied to the circuit, and $V_e$ is the total electrode voltage drop. Glow-to-arc transitions were observed for currents of the order of 100 A only, therefore $V_e$ may be considered as a constant [54]. In this equation, $I_{arc}$ represents the arc current, while the circuit implies that the same current which passes through the arc will also pass through the conductive layer. Thus, the DC flashover voltage of an insulator may be obtained when both of the following equations are satisfied:

$$\frac{\partial V}{\partial I_{arc}}=0 \tag{2.5}$$

$$\frac{\partial V_m}{\partial x}=0 \tag{2.6}$$

where $V_m$ is the solution to the first equation as a function of length. The solution to the second equation provides the critical voltage, $V_c$, and the length, $x_c$, corresponding to this critical voltage. At this point, the value of the critical current, $I_c$, may be obtained using the circuit equations. In order to solve the aforementioned equations, appropriate relationships for the calculation of arc voltage and the resistance of the conductive layer are required.

Obenaus developed these equations using Ayrton's equation for the arc and a fixed resistance for a polluted surface, $R_p$, so as to obtain the appropriate relationship for critical arc length [41].

His research was later developed further by Boehme who found an expression for the minimum critical voltage, $V_c$, which is able to sustain an arc over a certain length, $x$ [55].

The equations were subsequently developed even further by Neumärker [56], Alston [50] using the same concept and applying a uniform pollution resistance per unit of length, $r_p$, thereby obtaining the closed form of a set of equations with which to calculate critical values of voltage, length and current.

A visual illustration of the aforementioned solution may be seen in Figures 2.12 to 2.14.

Figure 2.12 shows the arc and pollution voltages for a certain length of arc, $x$, followed by the sum of these two resistances. In this Figure, $V_m$ is the minimum voltage which is necessary to sustain an arc along $x$. Similar curves for different lengths of the arc are illustrated in Figure 2.13 while Figure 2.14 shows the $V_m$ curve for the different values of $x$, as obtained from Figure 2.13. It will be observed that, for a certain arc length, $x_c$, the necessary applied voltage able to sustain the arc length along this length, $V_c$, is the maximum when compared to the other values of $V_m$, even for greater $x$ lengths. The values of $V_c$ and $x_c$ are called the critical flashover voltage and the critical arc length, respectively. Thus, it may be concluded that: if the relationships that govern the arc phenomenon are such as shown in Figure 2.12, then a critical arc length exists, and if the applied voltage is high enough to sustain the arc along this length, then no further voltage is required to reach the flashover point, and therefore flashover will inevitably occur under this voltage.

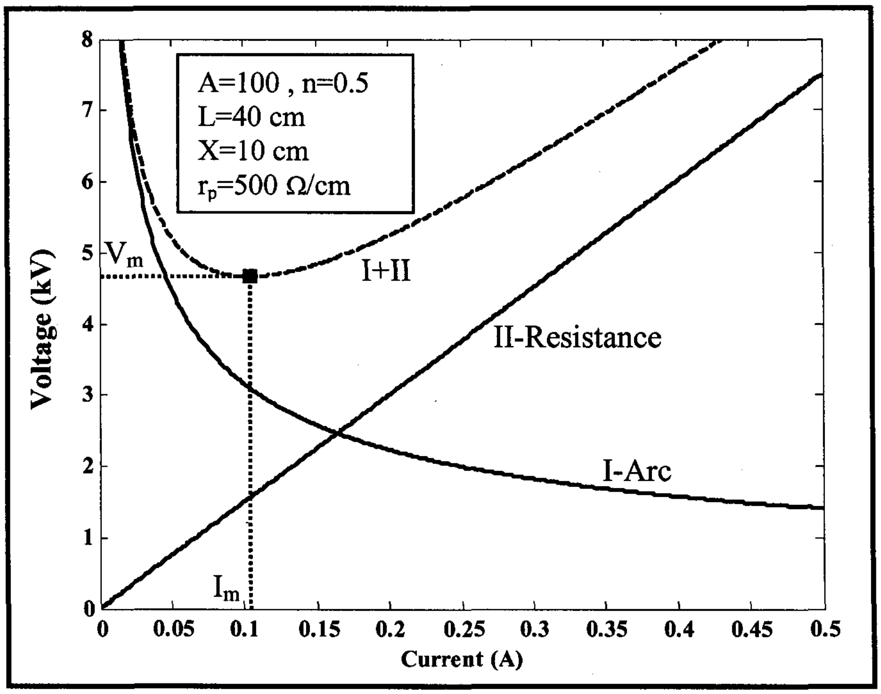



**Figure 2.12:** Typical arc and uniform conductive layer resistances in a given arc length.

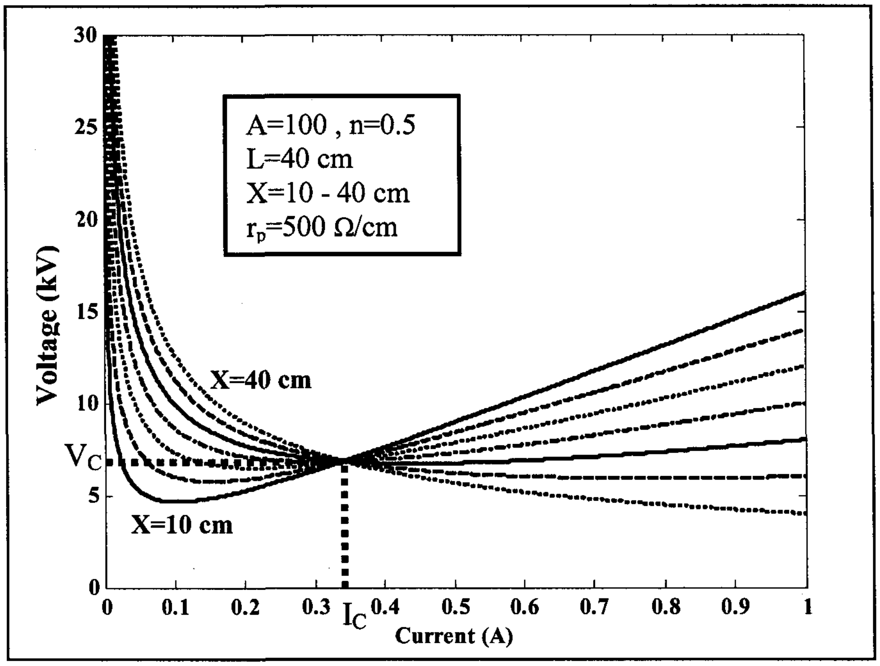



**Figure 2.13:** Typical arc and uniform conductive layer resistances for a variety of arc lengths

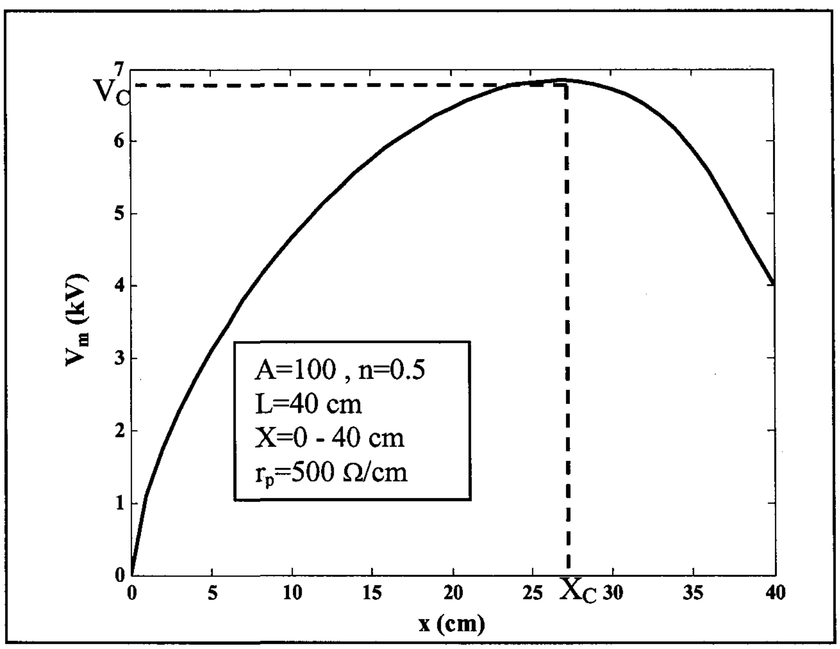



**Figure 2.14:** Critical arc voltage and length

Static modeling does not take into consideration the physical mechanism involved in arc phenomena. It will be observed, from Figure 2.13, that at any arc length, when the voltage applied to the insulator is higher than $V_m$, the arc may or may not be sustained along this length, and thus the arc elongation from each length to a new greater length is not certain for lengths less or greater than critical length. Theoretically speaking, even applying voltages which are higher than the critical voltage, does not ensure that the arc will propagate to the next electrode and thus lead to flashover; therefore the arc may be considered stationary at any given length for any undefined time period.

### 2-6-2 AC Static Model

Since, under AC applied voltages, flashover occurs around the peak value of the applied voltage, the same analysis of DC applied voltage is used to calculate the AC minimum flashover voltage. On the other hand, during the voltage cycles before the last propagating cycle is reached, the arc current drops to zero, and the arc voltage required to re-ignite the arc depends on the initial arc characteristics and the remaining polluted conditions.

In order to take into account the effects of arc re-ignition, an experimentally based relationship was proposed and used by Claverie to calculate the minimum voltage, $V_{peak}$, able to re-ignite the arc which carries the current, $I_{peak}$, along the length $x$, as follows [39]:

$$V_{peak} = \frac{Kx}{I_{peak}^{b}} \qquad (2.7)$$

where $K$ and $b$ are constants. Different authors based their calculations on different values for $K$ and $b$, but these were generally set at 800 and 0.5 respectively, for polluted insulators [21], and 1118 and 0.53 respectively, for iced insulators [3]. Thus it was considered that, when an arc occurs under AC voltage, the current and the voltage are calculated using DC relationships (Equations 2.5 and 2.6). If the aforementioned condition (Equation 2.7) is not satisfied, however, the arc will not be able to stabilize or to extend.

This type of model is considered to be experimental, since it does not refer to any specific physical mechanism by which the AC arc is maintained, and it is based solely on experimental results. By using a heat transfer equation in the arc channel, Rizk obtained an equation for calculating the critical voltage, $U_c$, necessary to sustain an arc at any position along an insulator of length, $L$, covered with a pollution layer of a resistance per unit, $r_p$, as follows [21]:

$$\frac{U_c}{L}=23r_p^{0.4} \qquad (2.8)$$

It should be noted that this relationship was obtained using a combination of experimental results and analytical evaluation.

## 2-7 Summary

From this literature review, it can be seen that very few investigations have been focused on arc modeling inside or in presence of snow. Concerning the parameters that influence the dielectric performance of snow-covered insulators, it was found that two parameters of snow are important; that is, its density and impurity of snow or its conductivity.

Because flashover on snow-covered insulator surfaces can be considered a special type of pollution/icing flashover, models developed to predict insulator pollution/icing flashover have been reviewed.

Farzaneh et al. [25] developed a model for predicting the flashover voltage of ice-covered insulators energized with an ac voltage. The model takes into account the variation of ice surface conductivity as a function of the freezing water conductivity. They also determined the effects of the length of the arc on its own characteristics, as well as an ac arc reignition condition, in a laboratory investigation using triangular ice samples.

Despite numerous investigations in ice covered surface and polluted surface, little information is applicable to the present study. The review of the available literature illustrates that electrical discharge phenomena inside wet snow are very complex when compared to ice or polluted surfaces.

# CHAPTER 3:

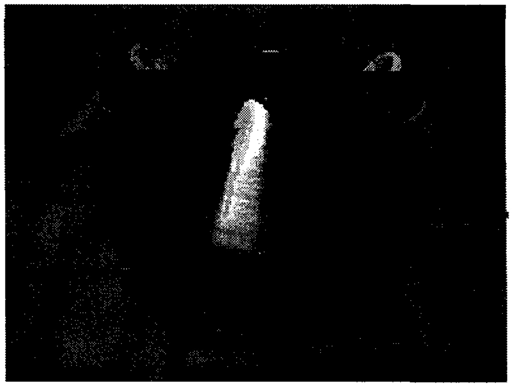
# PARAMETERS AFFECTING THE DC CONDUCTIVITY OF SNOW

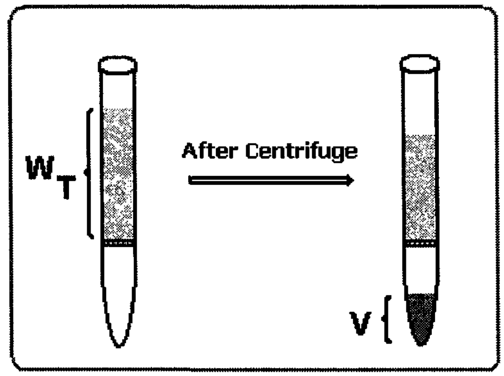
## 3-1 Introduction

Several major parameters affecting the electrical behavior of natural snow, namely volume conductivity and density, liquid water content and conductivity of water melted from snow, are crucial for the characterization of the electrical performance of snow-covered HV insulators. However, little study has been devoted to this subject, despite its importance. These parameters are found to vary significantly with snow composition and purity as well as with other parameters, such as temperature, airborne pollutants, electric field strength and polarity. In this chapter, the determination of the liquid water content and the dc conductivity of snow are analyzed as a function of its density. Moreover, conductivity of water melted from snow for a large number of snow samples are examined to find out whether any relationship exists between the observed conductivity and snow temperature.

## 3-2 Determination of the liquid water content

It is not generally an easy matter to determine the liquid water content or free water content, $\eta_E$, of wet snow. The free water content is defined as the ratio of the amount of water contained to the total weight of the wet snow. The free water content $\eta_E$ is determined by separating the water from the snow by a motor-driven centrifuge (Figure 3.1-a). Two test tubes containing filters were especially designed for this purpose. These filters separate dry snow from the liquid water contained in the snow sample as depicted in Figure 3.1-b. The water separated from the snow by centrifugal force was gathered into the bottom of the tube to be measured by the graduated scale. The rotating speed of the centrifuge was 1700 rpm. The time of rotation was half a minute in order to prevent the wet snow in the glass tube from melting while the centrifuge was rotating.






**(a)** **(b)**

**Figure 3.1:** Centrifugal Machine.

**a)** Photograph of the centrifugal machine used to quantify the water content of a snow sample.

**b)** Drawing of a test-tube before and after the utilization of the centrifugal machine.

After each test of the water percentage in the snow, the test tubes are cleaned and dried in order to avoid any deposits that could influence further measurements. The test tubes are also kept in a cold chamber at the same temperature as the snow sample in order to avoid substantial melting of snow during measurement with the centrifugal machine. The temperature inside the snow sample is measured before and after the test using thermocouples to consider an average value. The weight of water ($W_E$) dripped from the snow sample is then calculated:

$$W_E = \rho \upsilon \qquad (3.1)$$

Where $\rho$ (in g/cm$^3$) corresponds to the density of water dripping from snow sample and $\upsilon$ indicates the water volume contained in the snow.

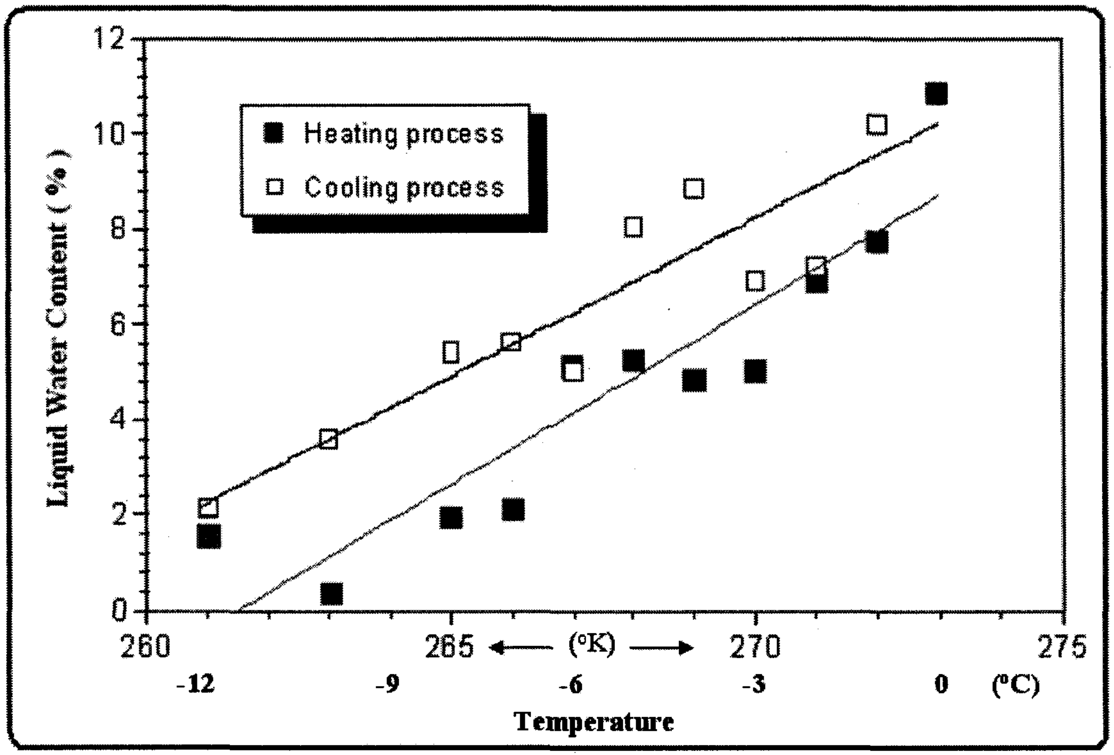



**Figure 3.2:** Liquid Water Content according to temperature.

Water content in the snow sample is then expressed as percentage of the total mass:

$$\eta_E = \frac{W_E}{W_T} \times 100 \qquad (3.2)$$

Figure 3.2 depicts the results of some investigations performed using snow samples having a density between 0.35 and 0.4 kg/m$^3$.

As shown in Figure 3.2, the liquid water content (LWC) increases with the temperature. A mathematical approach to the data suggests the existence of some kind of relationship between the LWC and the snow sample temperature ($T_S$). Indeed, the LWC ($\eta_E$) can be described as a mathematical function of the temperature $T_S$ representing the solid-line curves, which fit the experimental data plotted in Figure 3.2.

For heating process:

$$LWC_1\,(\%) = 0.76T(^{o}K) - 200 \qquad (3.3)$$

For cooling process:

$$LWC_2(\%) = 0.662T(^{o}K) - 170.5 \qquad (3.4)$$

## 3-3 The DC conductivity of snow

The dc conductivity of snow is difficult to measure and, consequently, different values have been reported in the literature [19, 24, 25, 32]. Apart from errors arising from snow impurities, there are two main sources of error: electrode polarization and surface conduction [25]. At higher temperatures, surface conduction through a snow specimen may completely neutralize volume conductivity. Surface conductivity can be largely eliminated by protecting the electrodes or probes with guard rings [1, 2]. DC volume conductivity can be determined by measuring the bulk current under a given applied voltage. Snow volume conductivity is known to depend on the density of the sample. Therefore, any desired snow density is obtainable by packing the snow in the capacitive structure shown in Figure 3.3.

This capacitive structure, of volume, V, equals to 188.4 $cm^3$, is comprised of a driven and a sensing electrode. Underneath the sensing electrode lies a guard electrode driven by a buffer amplifier staged to always be at the same potential as the sensing electrode. The latter is surrounded by a ring electrode, which is connected to the guard electrode. In addition to shielding the sensing electrode from external electric fields, the guard electrode serves to eliminate all parallel parasitic capacitances and resistances from the surrounding medium, which might otherwise affect the sensing electrode. Another advantage to having a guard ring around the sensing electrode is that the resulting electric field is highly uniform, with essentially no fringing fields associated with that electrode.

The material sample is larger than the sensing electrode, thus letting almost all field lines pass through the material sample. Teflon was chosen as the insulating material because of its excellent thermal properties.

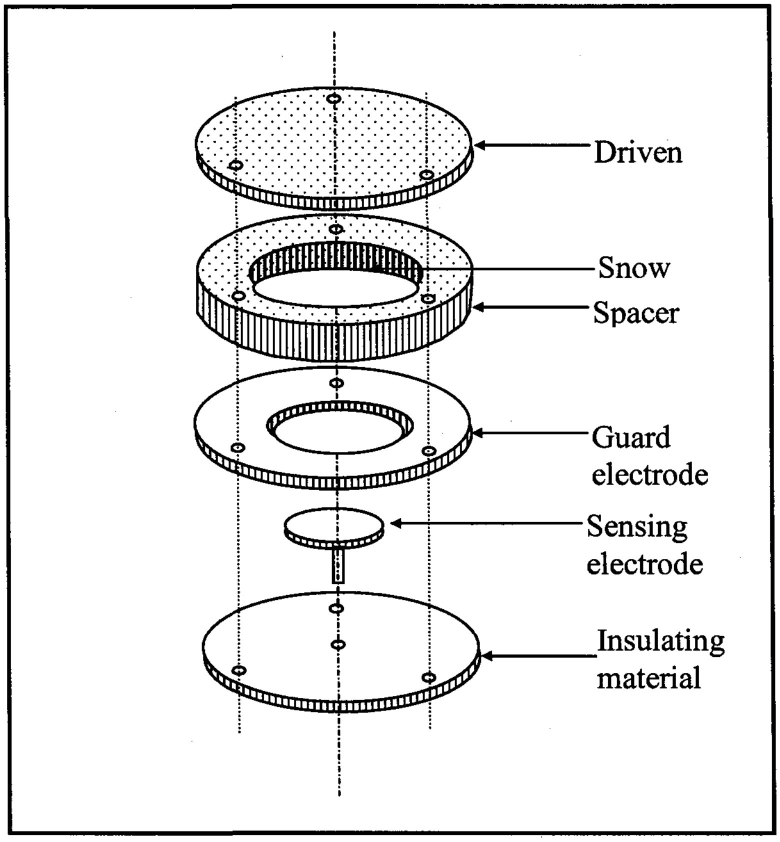



**Figure 3.3:** Capacitive structure used to determine the conductivity of snow samples.

Figure 3.4 depicts the experimental setup used for snow sample conductivity measurements. As shown in this figure, in the case of short circuit of snow sample, two resisences ($R_1$ and $R_2$) have been used. For all the measurements, samples of natural snow, kept in a freezer at –20°C after collection, were used.

The capacitive structure is cooled down to the desired temperature, $T_S$, inside an Envirotronics EH40-2-3 cold chamber, before measurement. The cold chamber temperature is monitored by a microprocessor-based temperature/humidity controller with a ± 0.1 °C accuracy. During the experiments, both the temperatures inside the cold room and snow sample are recorded.

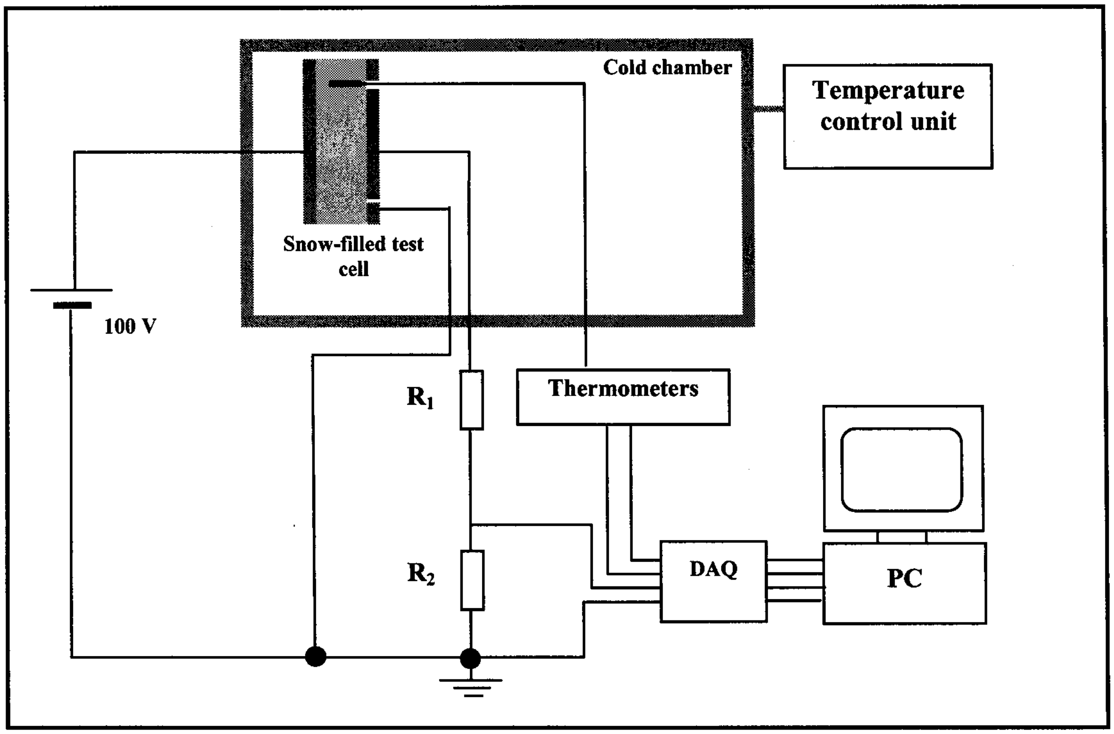



**Figure 3.4:** Experimental setup used to determine the conductivity of snow

Snow sample conductivity, $\sigma_S$, is calculated from the direct current flowing through a sample, 2.4 cm in length (l) and 78.5 $cm^2$ in normal sections (A), submitted to a 100 V dc voltage. This corresponds to an average field of 41.25 V/cm across the snow sample.

The current is sampled at a rate of 1200 samples/s, transferred to a data buffer and stored. The main components of the data acquisition system are a National Instrument DAQ plug-in board, installed in a PC, and the LabVIEW™ application software. The data are stored both as ASCII text files and binary files. This ensures that the LabVIEW™ acquired data could also be analyzed further using other software applications, like MATLAB™.

Resistance of the snow in the circuit is calculated using the following basic relation:

$$R_S = \frac{V}{I} = \frac{l}{\sigma A} \qquad (3.5)$$

This leads to snow sample conductivity ( $\sigma$ ).

In addition to conductivity, snow samples densities are calculated by dividing the mass of the snow sample, m, packed in the capacitive cell (Figure 3.4) by its volume, V. Finally, the chemical purity of the snow samples is quantified by measuring the conductivity of the water that is melted from it.

In order to have various kinds of snow density, the snow sample was compressed manually therefore controlling the snow density. Table 3.1 summarizes the values of the investigated parameters. The density values ($0.187 < \delta < 0.55$) were selected so as to cover a wide range of different types of natural snow (fresh, collapsing, compressed, grainy, etc.) [19].

**Table 3.1:** Snow parameters used in the experiments

| | **Low σ** | **Medium σ** | **High σ** |
|---|---|---|---|
| **Low δ** | σ=39.5 μS/cm<br>δ=0.187 g.cm$^{-3}$ | σ=81.7 μS/cm<br>δ=0.26 g.cm$^{-3}$ | σ=131 μS/cm<br>δ=0.265 g.cm$^{-3}$ |
| **Medium δ** | σ=33 μS/cm<br>δ=0.286 g.cm$^{-3}$ | σ=80 μS/cm<br>δ=0.431 g.cm$^{-3}$ | σ=142 μS/cm<br>δ=0.33 g.cm$^{-3}$ |
| **High δ** | σ=38 μS/cm<br>δ=0.426 g.cm$^{-3}$ | σ=93 μS/cm<br>δ=0.551 g.cm$^{-3}$ | σ=146 μS/cm<br>δ=0.546 g.cm$^{-3}$ |

During these investigations, the temperature varied between -12 to 0°C. The process involving the decrease in temperature from 0 to -12°C will referenced as cooling, while the one involving the increase in temperature will be referenced as heating process.

### 3-3-1 Results and Discussions

#### 3-3-1-1 Effect of snow crystals

Snow crystal growth is quite sensitive to small changes in temperature, super-saturation and other factors [57]. Snow crystals, also called snowflakes, are single crystals of ice that grow from water vapor. While the physics of snow crystal formation deals with crystal growth problems, it also touches on several environmental and meteorological issues, simply because ice crystals often play a major role in atmospheric phenomena. Snow crystal growth dynamics is typically dominated by attachment kinetics in combination with two transport effects: particle diffusion, which carries water molecules to the growing crystal, and heat diffusion, which removes latent heat generated by solidification. The interplay of these three processes is ultimately responsible for the vast diversity of snow crystal morphologies [57-59].

A wide range of chemical impurities, such as vapors from many alcohols, acids, hydrocarbons, sodium chloride, etc, even at low concentrations, affect both crystal morphologies and growth rates. Their presence in water lowers the freezing temperature, which is a consequence of the second law of thermodynamics. Ice crystals are essentially pure water so the chemical-water mixture separates during freezing. Since this separation lowers the mixture's entropy, an additional source of energy is needed to satisfy the second law, which is provided by freezing the mixture below the normal freezing temperature of water.

Wet snow is well-bonded at low liquid water content levels where ice-bonded clusters form. It should be noted that a transitional form of snow, melt–freeze grains, can be either wet or dry. These amorphous, multi-crystalline particles arise from melt–freeze cycles. They are solid within and well-bonded to their neighbors.

During the heating process, where temperature is increased from -12 to 0°C, a portion of the snow crystals can melt. The resulting reorganization of the water molecules changes the microstructure of the snow sample, considerably affecting snow sample properties. This phenomenon is shown by the experimental results summarized in Figure 3.5.

The snow sample under consideration was investigated using the following sequence of processes: i) heating from -12°C to 0°C; ii) cooling from 0°C to -12°C; iii) re-heating from -12°C to 0°C; and iv) re-cooling from 0°C to -12°C. Any heat transferred to ice goes into melting more ice, not into raising its temperature. Any heat removed from the ice comes from freezing more water, not from lowering its temperature. Melting is a phase transition, a transformation from the ordered solid phase to the disordered liquid phase. Heat goes into breaking bonds and converting ice into water. This process is accompanied by energy absorbed by the liquid water and, so to speak, towards an increase in temperature. Sublimation of ice particles and surface diffusion of water molecules are active in snow near the melting temperature [60]. This transfer of water molecules can change the microstructure of snow [61]. In the cooling process, contacts may be reconstructed by the condensation process at the sites of the broken bonds and contacts. Tight bonds between ice particles grow due to vapor and surface diffusion near the melting temperature [61].

Figure 3.5 shows that during the first heating process, the sample conductivity increases as temperature increases from -12°C to around -2°C, and then decreases as the temperature increases from -2°C to 0°C. The peak in conductivity is observed at a temperature close to -2°C, which will be discussed.

During the first heating process, from -12°C to 0°C, the original snow sample melts, then transforms into ice, when brought back to -12°C, during process (ii). When heated again from -12°C to 0°C, conductivity remains almost constant and equal to that of ice crystals. Indeed, bulk dc conductivity of pure polycrystalline ice was found to be $(1.1 \pm 0.5) \times 10^{-4}$ μS/cm at -10°C, as reported by Hobbs [40]. The repetition of process (iv) shows no change in the dc conductivity of snow. This sequential experiment shows the important role played by free water and/or ice crystals in the dc conductivity of natural snow.

When increasing the snow sample temperature, (from -12°C to around -2°C), the quantity of melted water increases too (equations 3.3 and 3.4).

From Figure 3.5, it may be observed that, in the heating process, sample conductivity increases with an increase in temperature from -12°C to around -2°C, reaching a peak at that point. It then decreases from there to the melting temperature. This peak in conductivity is observed in both the heating and the cooling processes (see Figures 3.6 to 3.17). This is curious and unexpected behaviour because dc conductivity of ice generally increases with increasing temperature [19]. This apparently odd behaviour has been already observed in our previous investigation [34] and by Takei et al. [61] as well. This phenomenon seems to indicate that important changes in the texture of snow are taking place nearing the melting temperature. This temperature to peak conductivity appears to be very important for outdoor insulation. In effect, it indicates that the probability of snow-covered insulator flashover is higher at temperatures around -2°C, because of a much-increased conductivity.

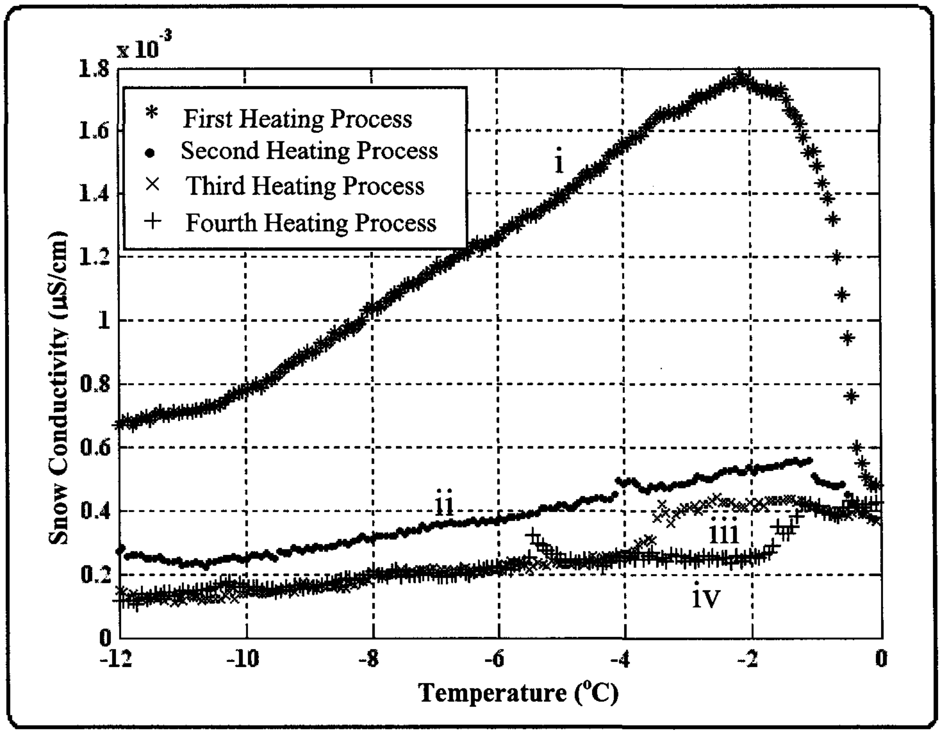



**Figure 3.5:** Temperature dependence of the dc conductivity of a snow sample undergoing four heating process sequences with same snow condition.

Snow crystal growth is quite sensitive to small changes in various parameters such as temperature and super-saturation. The variety of snow crystal forms seen in Bentley's photographs prompted physicist U. Nakaya to perform the first in-depth laboratory study of snow crystal growth in the 1930s [59]. These observations revealed a surprisingly complex dependence of crystal morphology on temperature and super-saturation. Temperature mainly determines whether snow crystals will grow into plates or columns, while higher super-saturations produce more complex structures. The morphology switches from plates to columns (at T≈-2°C) to plates (at T≈-15°C) to predominantly columns (at T≈-30°C) as temperature is decreased [57]. Little progress has been made, however, in explaining their diversity and how their external morphology is related to the crystalline structure and to the conditions of growth. Crystal growth depends on exactly how water vapour molecules are incorporated into the growing ice crystal, and the physics behind this is quite complex and not understood very well. Exactly how and why snow crystals form is still something of a mystery to physicists [57, 58, 62].

The primary habits exhibited by snow crystals growth (plates and columns, etc) determined by the temperature, could be a straightforward explanation for the peak in the conductivity at temperature around -2°C [57].

### 3-3-1-2 Effect of snow density

Figures 3.6 to 3.11 are summarized results obtained for different kinds of snow density samples under the heating and cooling processes. From these Figures, it is evident that snow sample density plays a major role in dc conductivity. Compressing snow breaks its structure, thereby increasing its density and the contact surfaces between its ice crystals. Because of the likelihood that dc conduction of snow is predominantly due to the presence of impurities held outside individual grains, Shabtaie and Bentley [63] concluded that electrical transport must take place at the surface of the ice crystals.

Increasing of density causes surface contacts, and, as shown in the Figures 3.6 to 3.11, when density increases the snow conductivity decreases. In section 3-3-2 the effect of density on the snow conductivity will be explained and its role will be presented mathematically in the model.

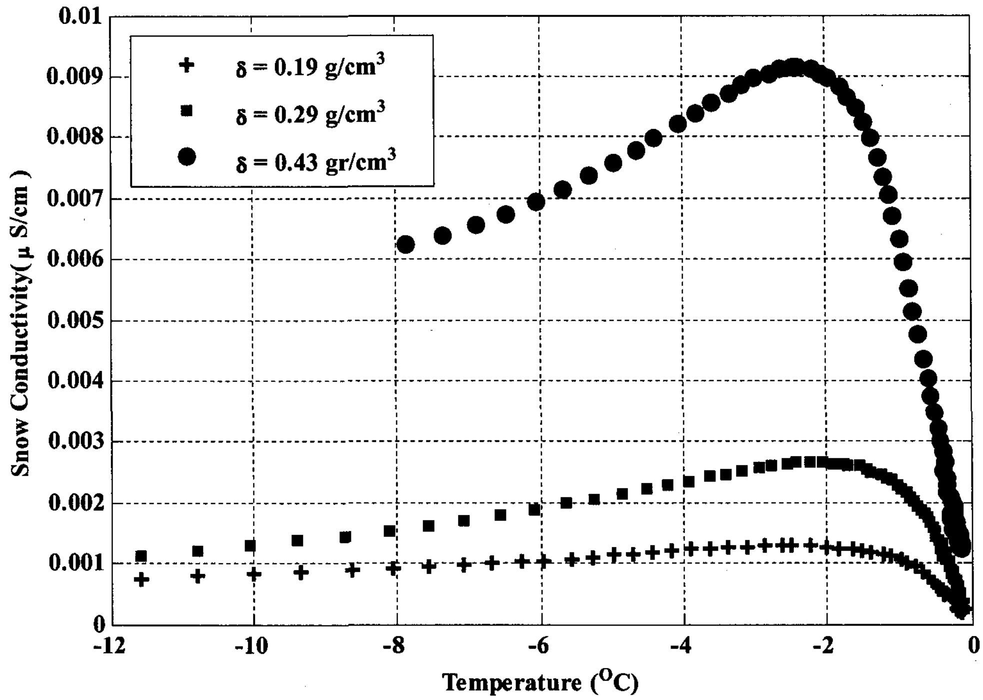



**Figure 3.6:** Variation of dc conductivity as a function of temperature and density under the heating process applied to a snow sample with melted snow conductivity of $\sigma$ =36.8 μS/cm.

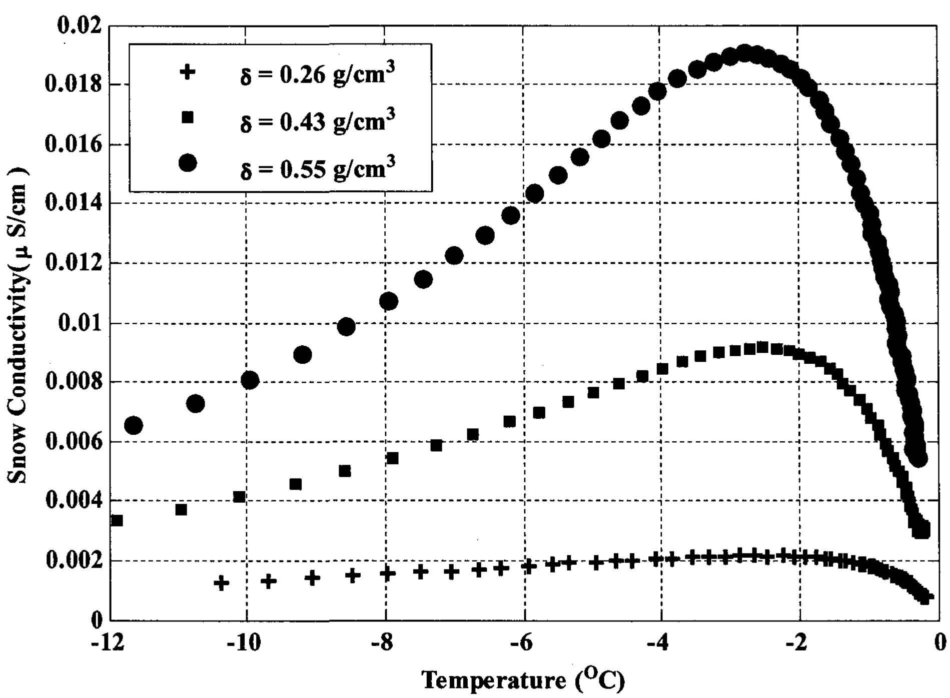



**Figure 3.7:** Variation of dc conductivity as a function of temperature and density under the heating process applied to a snow sample with melted snow conductivity of $\sigma$ =85 μS/cm.

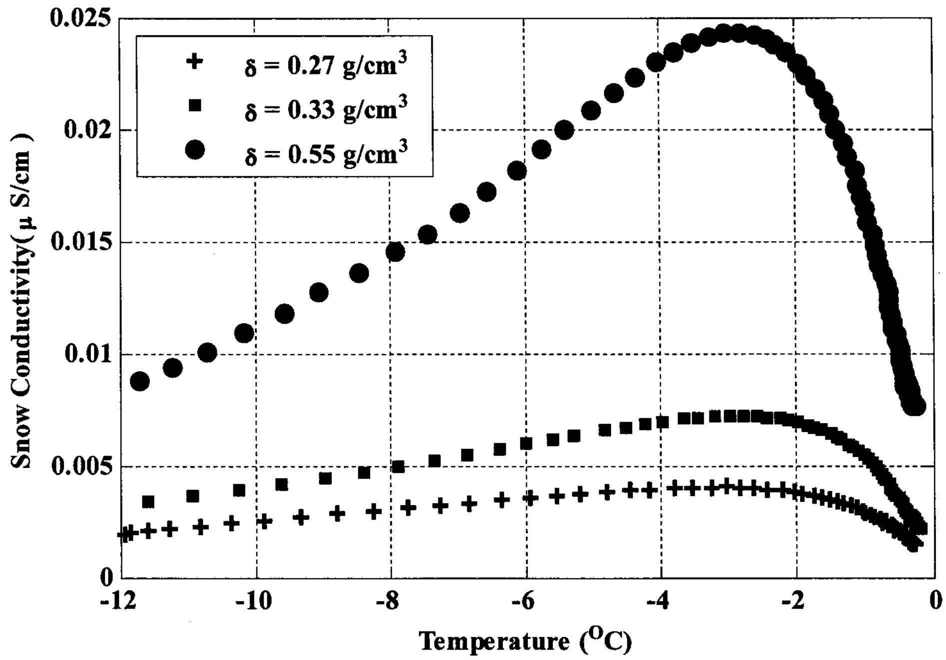



**Figure 3.8:** Variation of dc conductivity as a function of temperature and density under the heating process applied to a snow sample with melted snow conductivity of $\sigma$=139.6 μS/cm.

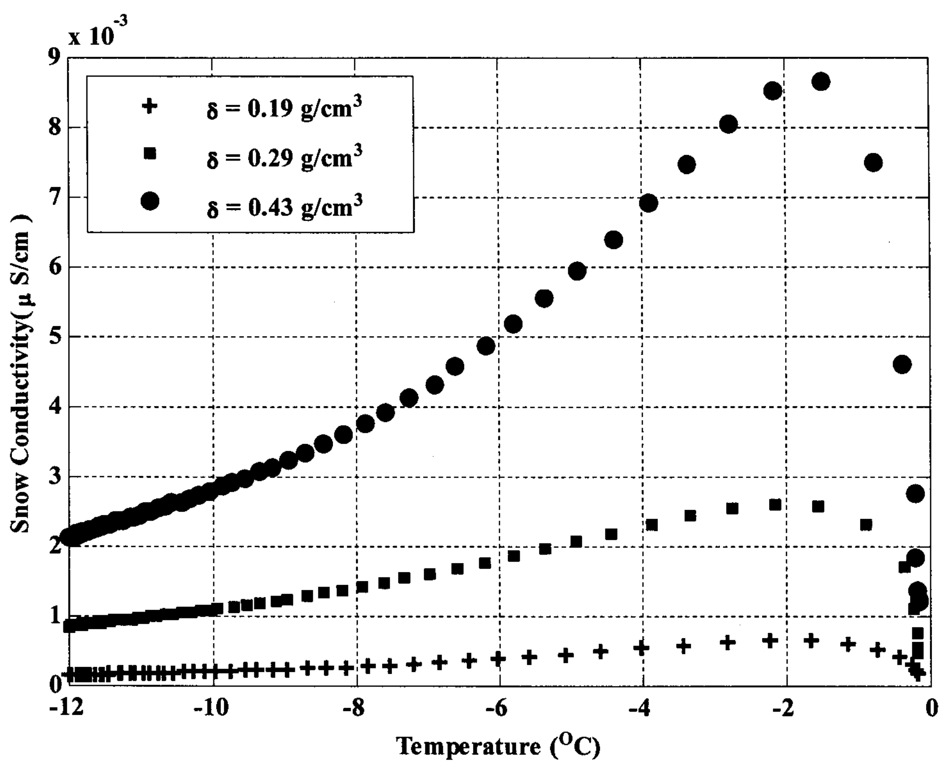



**Figure 3.9:** Variation of dc conductivity as a function of temperature and density under the cooling process applied to a snow sample with melted snow conductivity of $\sigma$ =36.8 μS/cm.

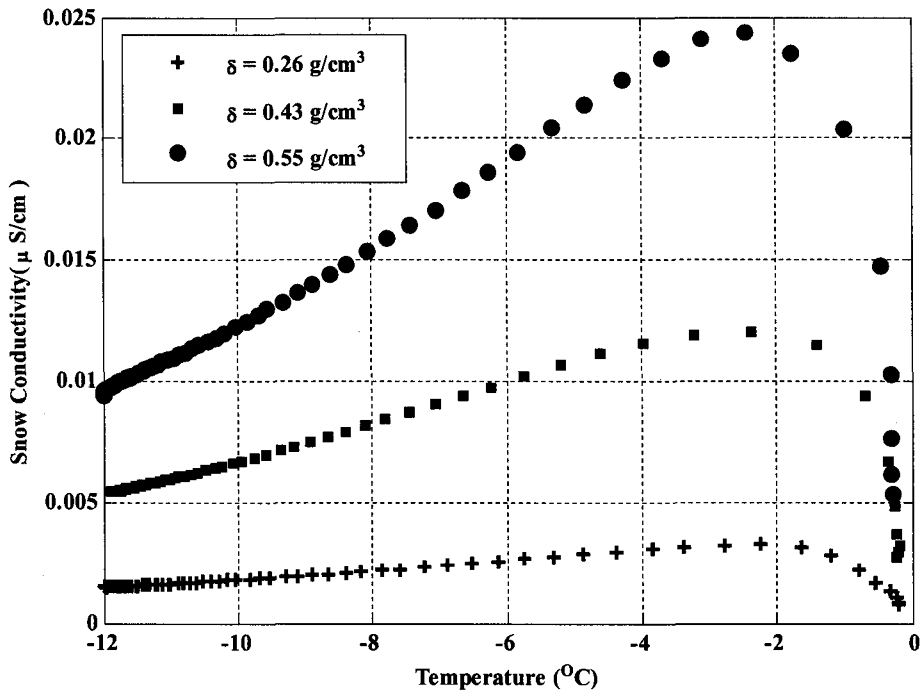



**Figure 3.10:** Variation of dc conductivity as a function of temperature and density under the cooling process applied to a snow sample with melted snow conductivity of $\sigma$ =85 $\mu$S/cm.

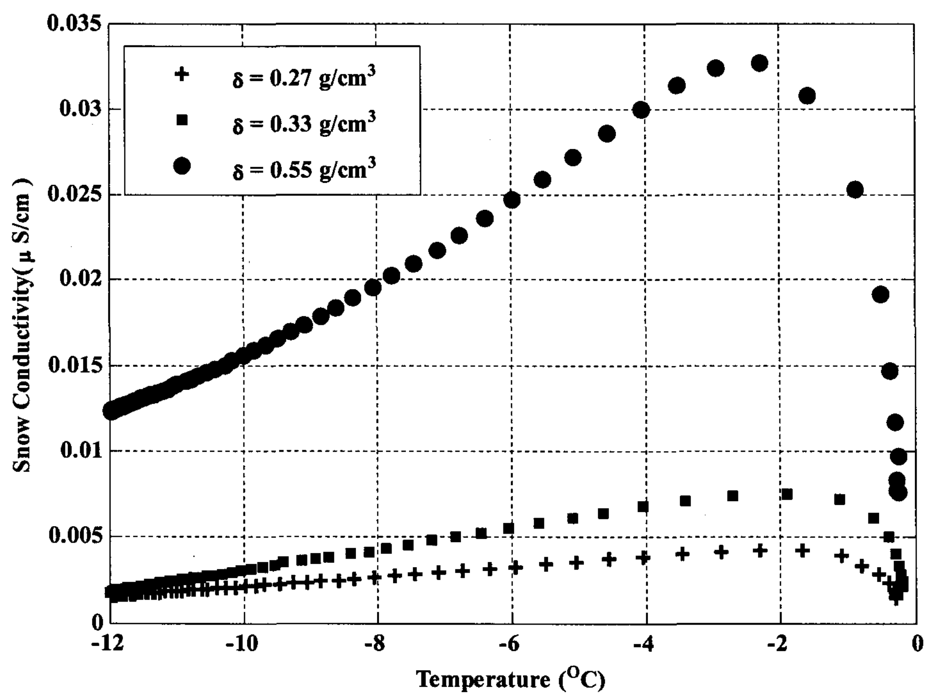



**Figure 3.11:** Variation of dc conductivity as a function of temperature and density under the cooling process applied to a snow sample with melted snow conductivity of $\sigma$ =139.6 $\mu$S/cm.

### 3-3-1-3 Effect of salt and/or impurity content

Figures 3.12 to 3.17 depict the dc conductivity variation as a function of temperature for different samples of snow having different melted snow conductivity under heating and cooling process. Each Figure shows the effect of salt and/or impurity content on the snow conductivity. These Figures clearly show that, when melted snow conductivity increases, dc conductivity increases.

The presence of water in the liquid phase causes electric conductivity to increase. Although pure water is a poor conductor of electricity, many chemicals, such as salt, dissolve in it due to its polar nature. In the process of water dissolution, the splitting molecules of the dissolving chemical become caught up in the loops and chains of water molecules. Not everything dissolves in water. Materials that dissolve best, however, contain atoms, molecules, or other particles that bind strongly to water molecules, more strongly, in fact, than they did in the original material. There are also a few gases that dissolve well in water because they bind with water molecules [64]. Some gases dissolve in water and then rearrange into ions. Complete chemical analyses [64] performed on a number of natural snow samples showed that substances such as calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), iron ($Fe^{+}$), carbonate ($C0_3^{2-}$), and nitrate ($N0_3^{2-}$) were almost always absent. Potassium ($K^{+}$) and sodium ($Na^{+}$) were the most frequently represented cations. The most common anions were bicarbonate ($HCO_3^{-}$), sulphate ($SO_4^{2-}$), and chloride ($Cl^{-}$). The higher the concentration of impurities dissolved in water, the higher is its electrical conductivity [65].

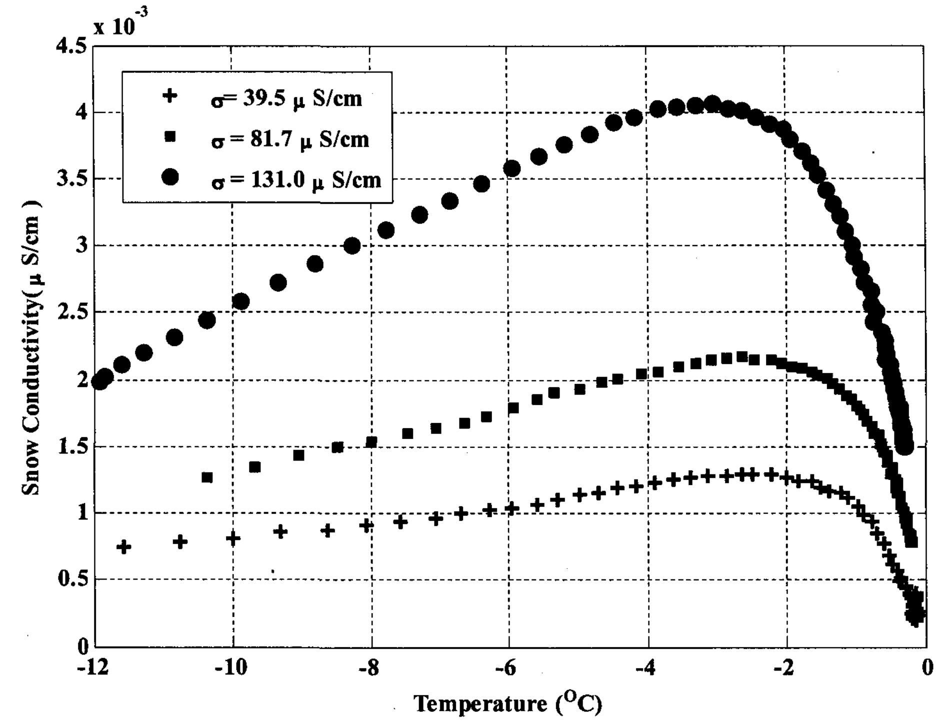



**Figure 3.12:** Variation of dc conductivity as a function of temperature and melted snow conductivity under the heating process of snow samples with snow density of $\delta = 0.24$ g/cm$^3$.

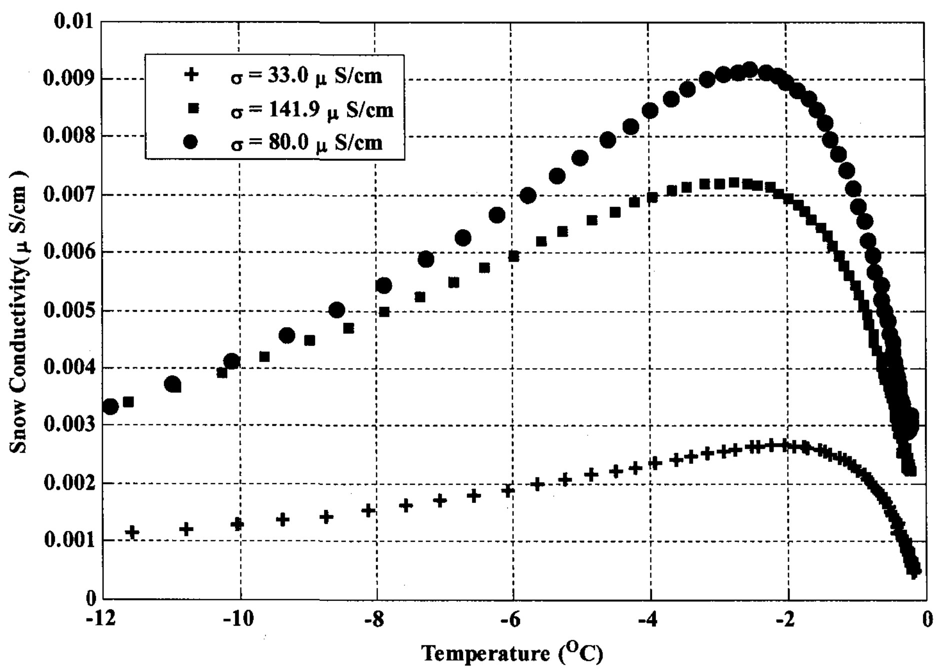



**Figure 3.13:** Variation of dc conductivity as a function of temperature and melted snow conductivity under the heating process of snow samples with snow density of $\delta = 0.35$ g/cm$^3$.

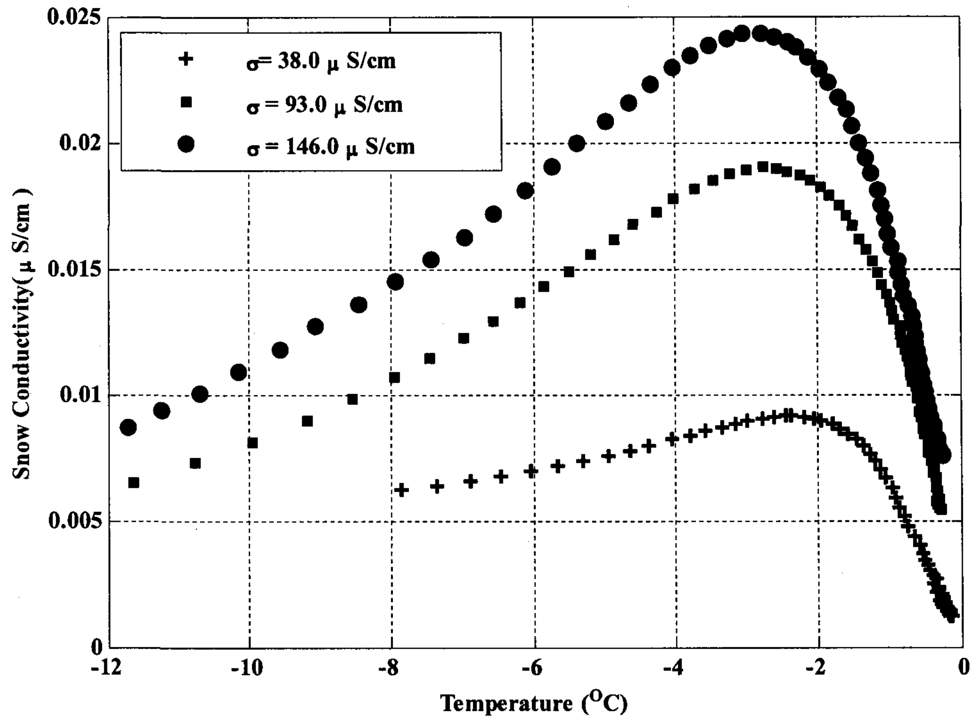



**Figure 3.14:** Variation of dc conductivity as a function of temperature and melted snow conductivity under the heating process of snow samples with snow density of $\delta = 0.51$ g/cm$^3$.

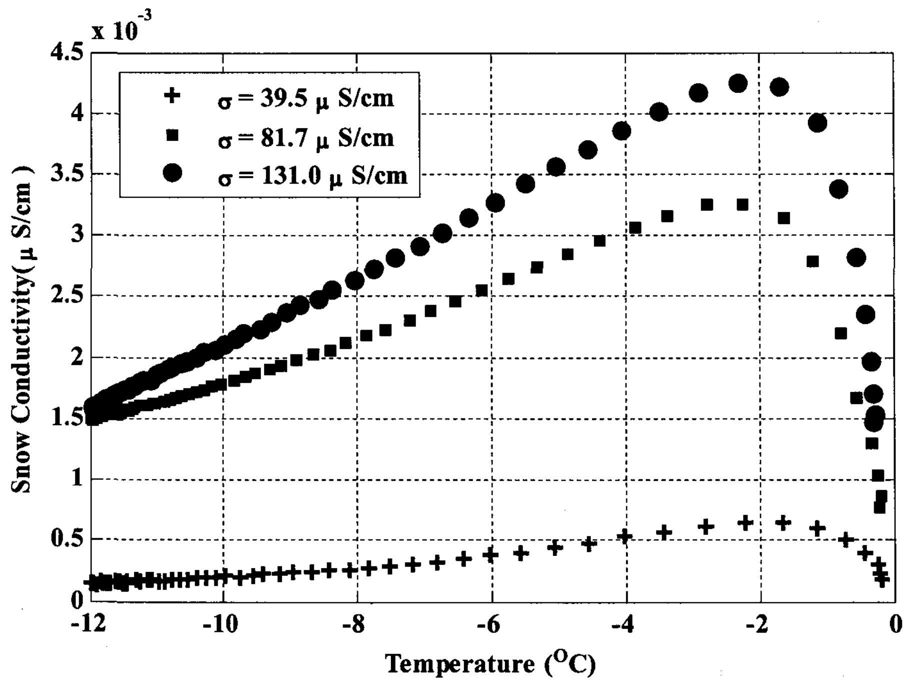



**Figure 3.15:** Variation of dc conductivity as a function of temperature and melted snow conductivity under the cooling process of snow samples with snow density of $\delta = 0.24$ g/cm$^3$.

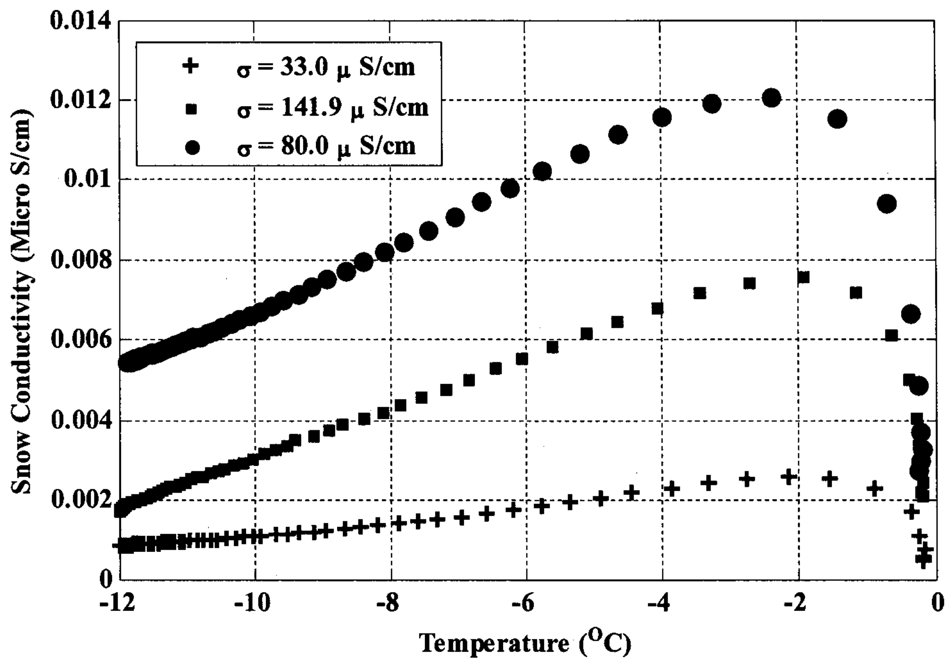



**Figure 3.16:** Variation of dc conductivity as a function of temperature and melted snow conductivity under the cooling process of snow samples with snow density of δ = 0.35 g/cm$^3$.

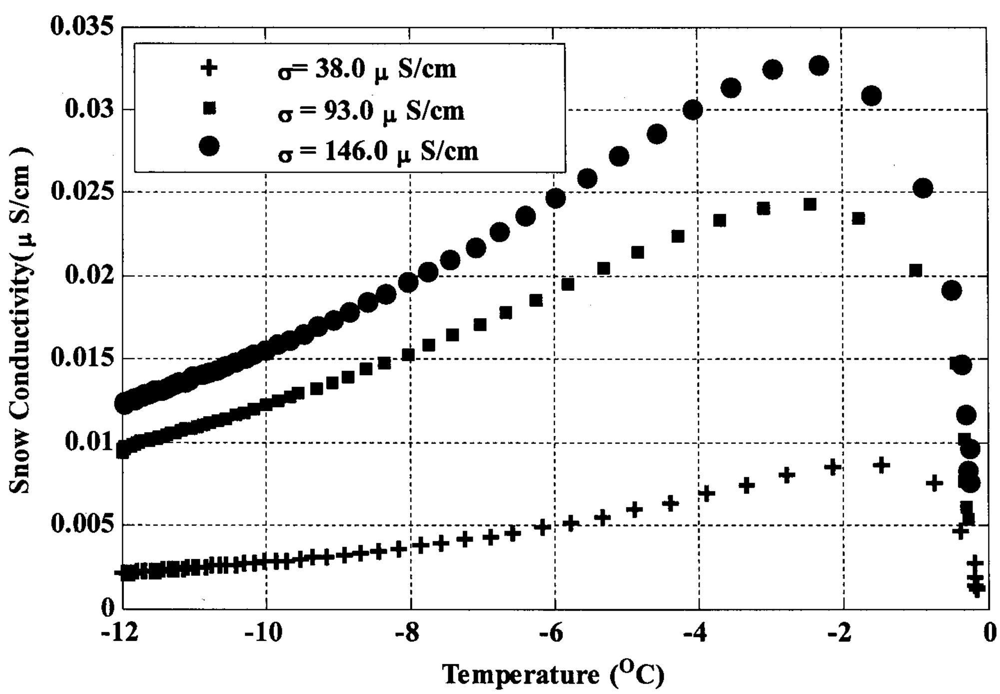



**Figure 3.17:** Variation of dc conductivity as a function of temperature and melted snow conductivity under the cooling process of snow samples with snow density of δ = 0.51 g/cm$^3$.

### 3-3-2 Proposed mathematical model to predict snow DC conductivity behavior

In this section, the various models for predicting the dc conductivity of snow are summarized, and their predictive capacity discussed. The relationship between the dc conductivity, $\sigma_{dc}$, and the sample temperature is obviously not linear and the models that best fit the data suggest that conduction-enhancing impurities in the snow are contributing to the direct current component of total conductivity.

Multiple regression analysis was used to determine dc conductivity as a function of temperature, and it was found that the dc conductivity, $\sigma_{dc}$, can be predicted using a bi-exponential impulse shape for $-15 < T < 0$ °C:

$$\sigma_{dc}(T) = K\left(e^{K_1 T} - e^{K_2 T}\right) \tag{3.6}$$

This set of parameters needs to be determined for both the heating and cooling processes, while the parameters K, $K_1$ and $K_2$ depend on snow characteristics such as density, nature and level of chemical impurities.

Figures 3.18 to 3.29 illustrate some curves resulting from the model and predicting dc conductivity of various snow samples as a function of temperature under heating and cooling processes.

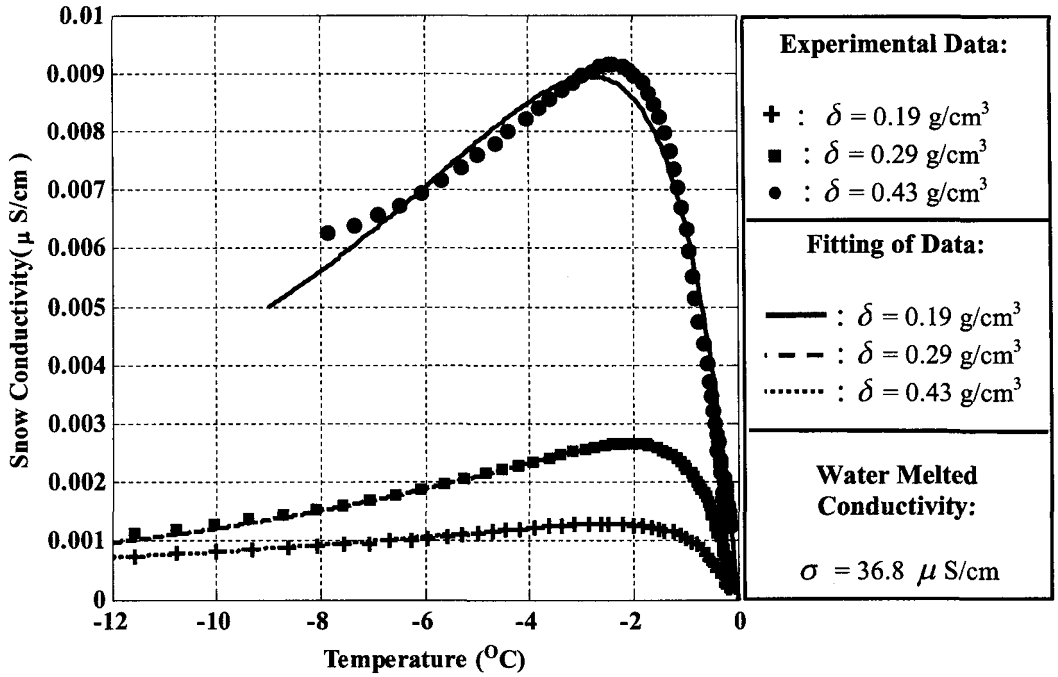



**Figure 3.18:** Variation of dc conductivity by using of regression method of experimental data under heating process and $\sigma$ = 36.8 $\mu$ S/cm

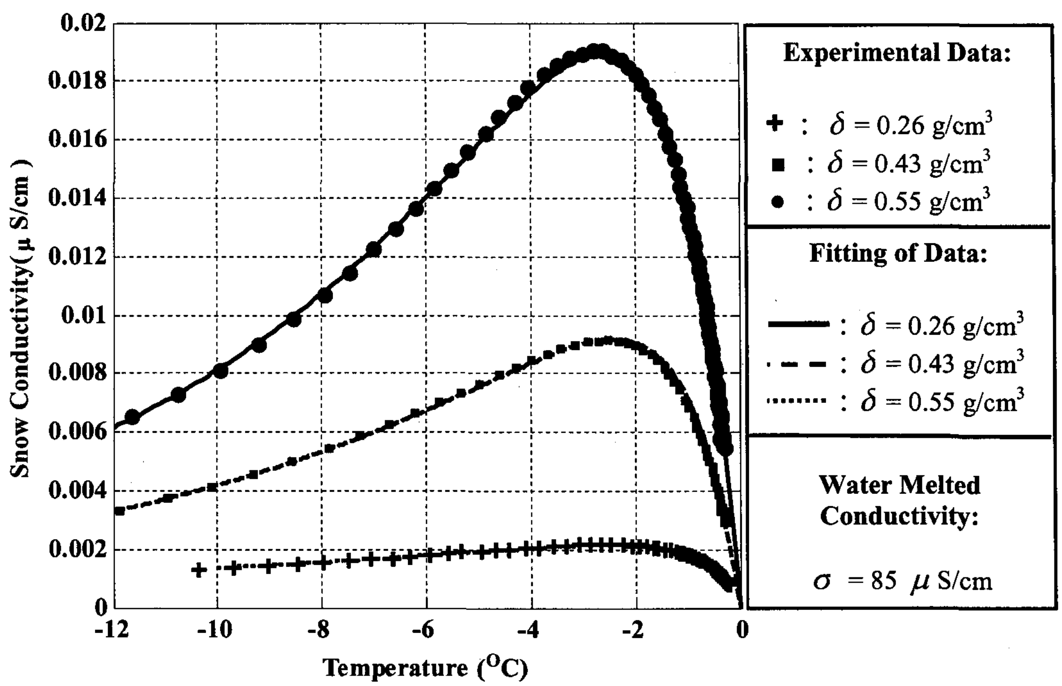



**Figure 3.19:** Variation of dc conductivity by using of regression method of experimental data under heating process and $\sigma$ = 85 $\mu$ S/cm

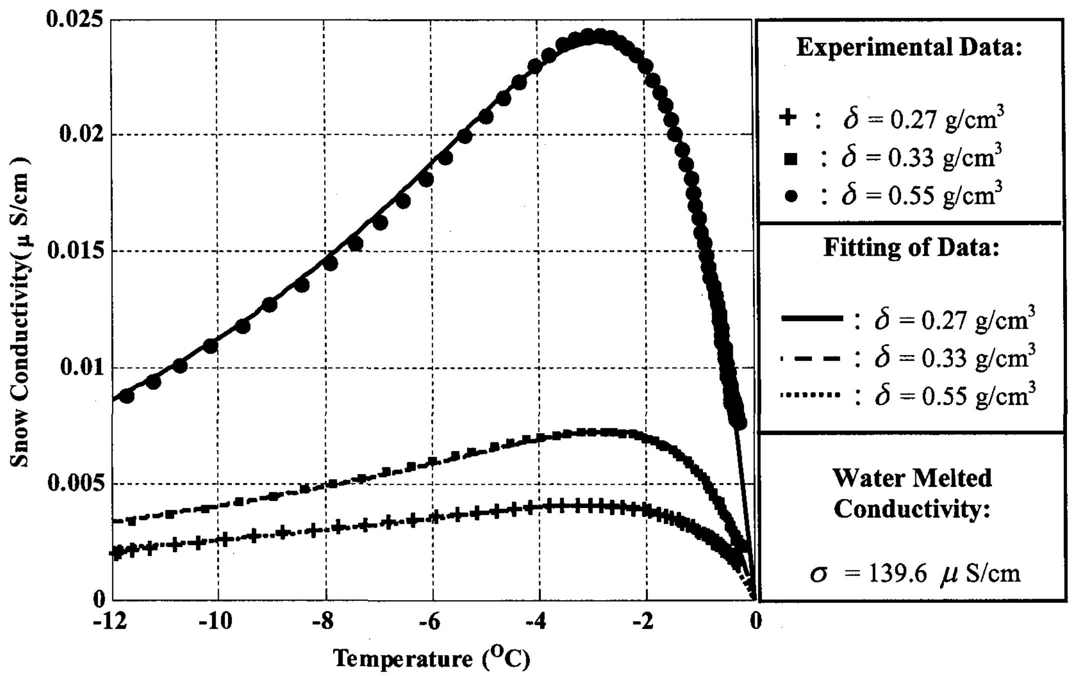



**Figure 3.20:** Variation of dc conductivity by using of regression method of experimental data under heating process and $\sigma$ = 139.6 $\mu$ S/cm

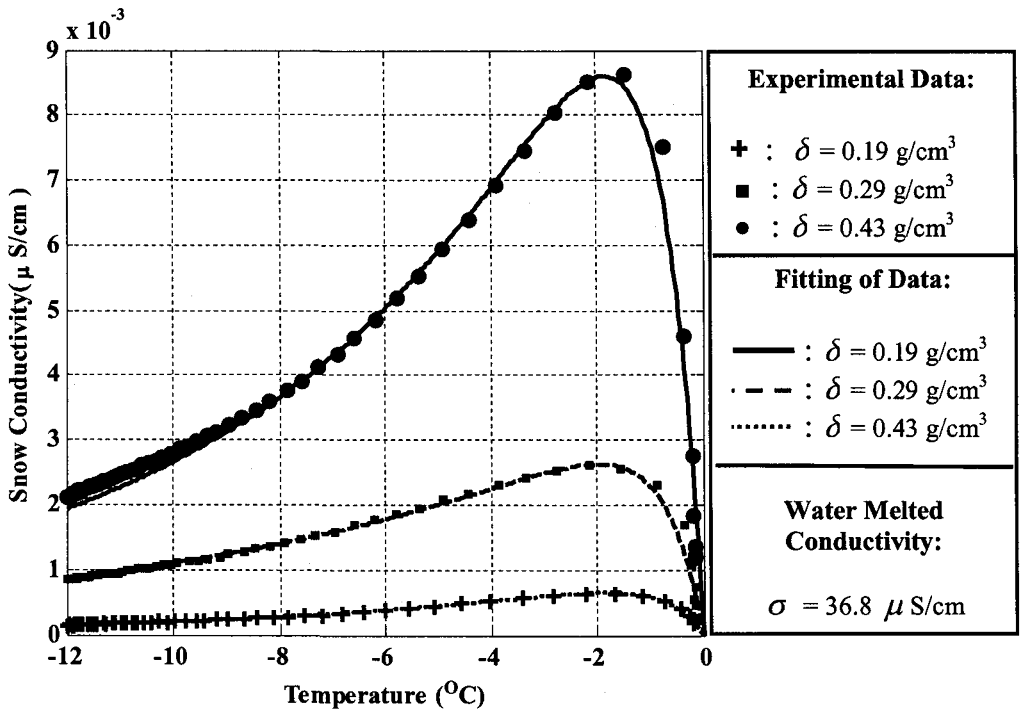



**Figure 3.21:** Variation of dc conductivity by using of regression method of experimental data under cooling process and $\sigma$ = 36.8 $\mu$ S/cm

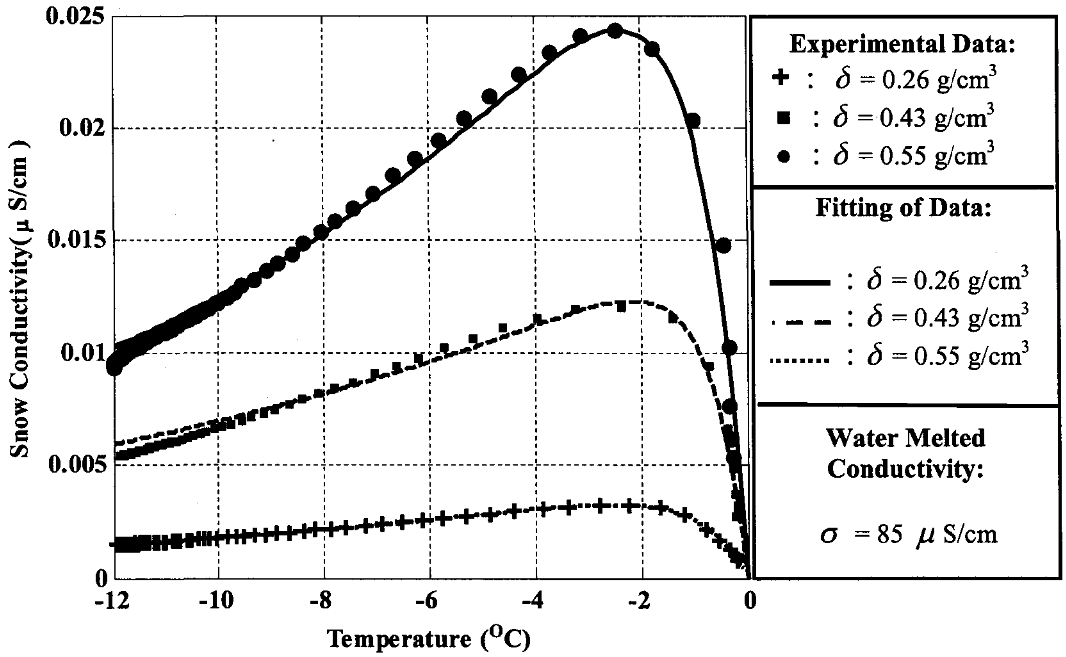



**Figure 3.22:** Variation of dc conductivity by using of regression method of experimental data under cooling process and $\sigma$ = 85 $\mu$ S/cm

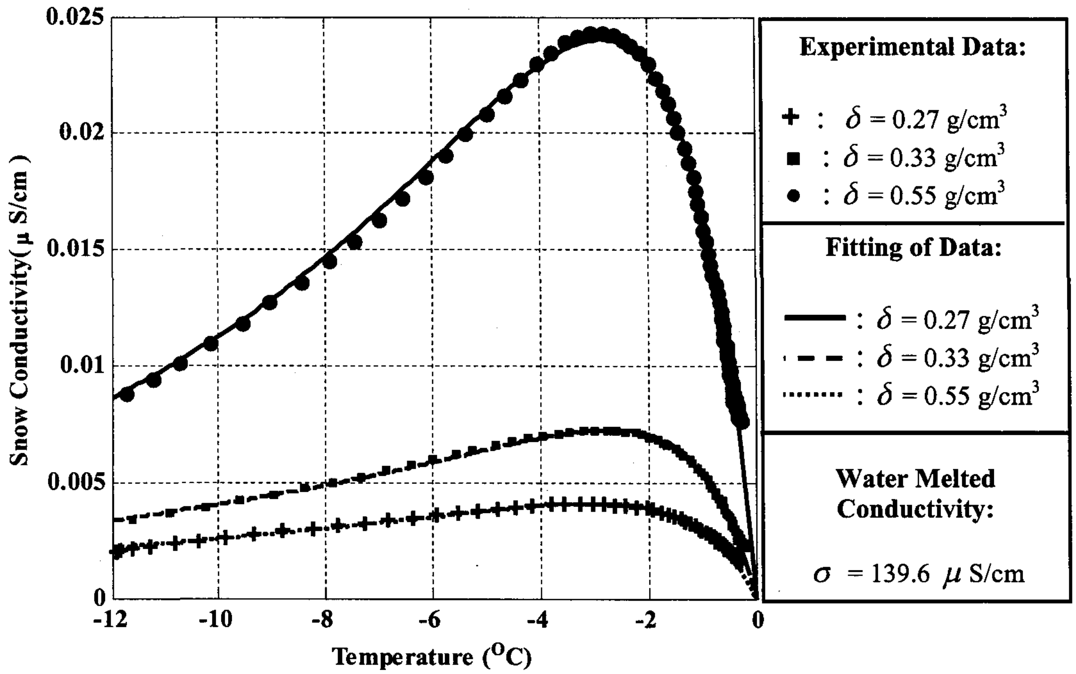



**Figure 3.23:** Variation of dc conductivity by using of regression method of experimental data under cooling process and $\sigma$ = 139.6 $\mu$ S/cm

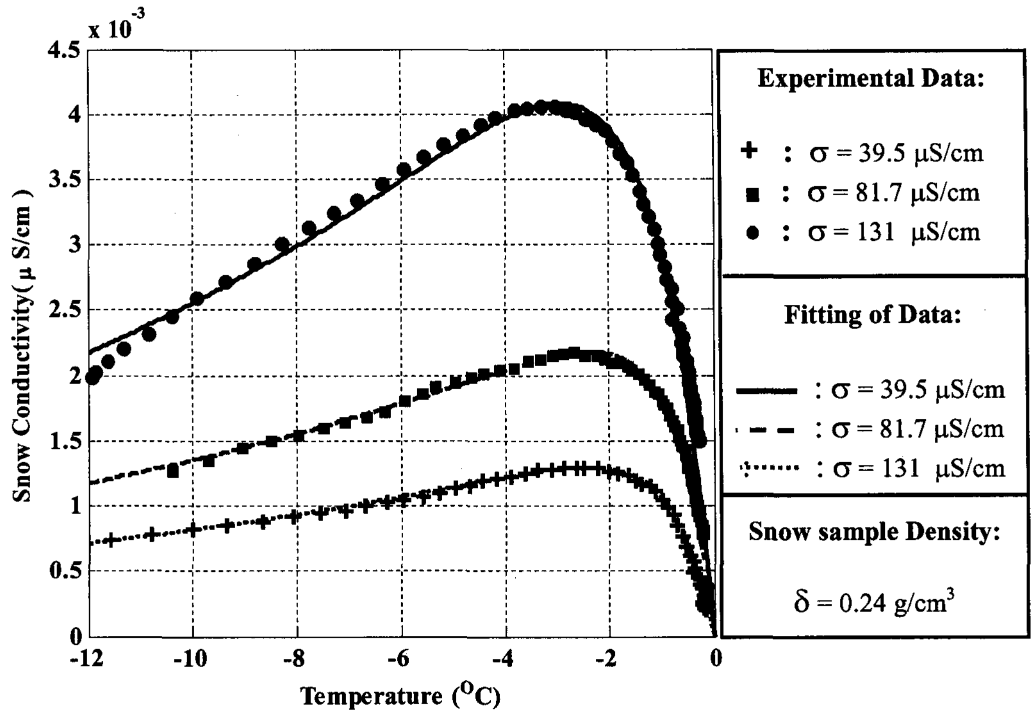



**Figure 3.24:** Variation of dc conductivity by using of regression method of experimental data under heating process and $\boldsymbol{\delta} = 0.24$ g/cm$^3$

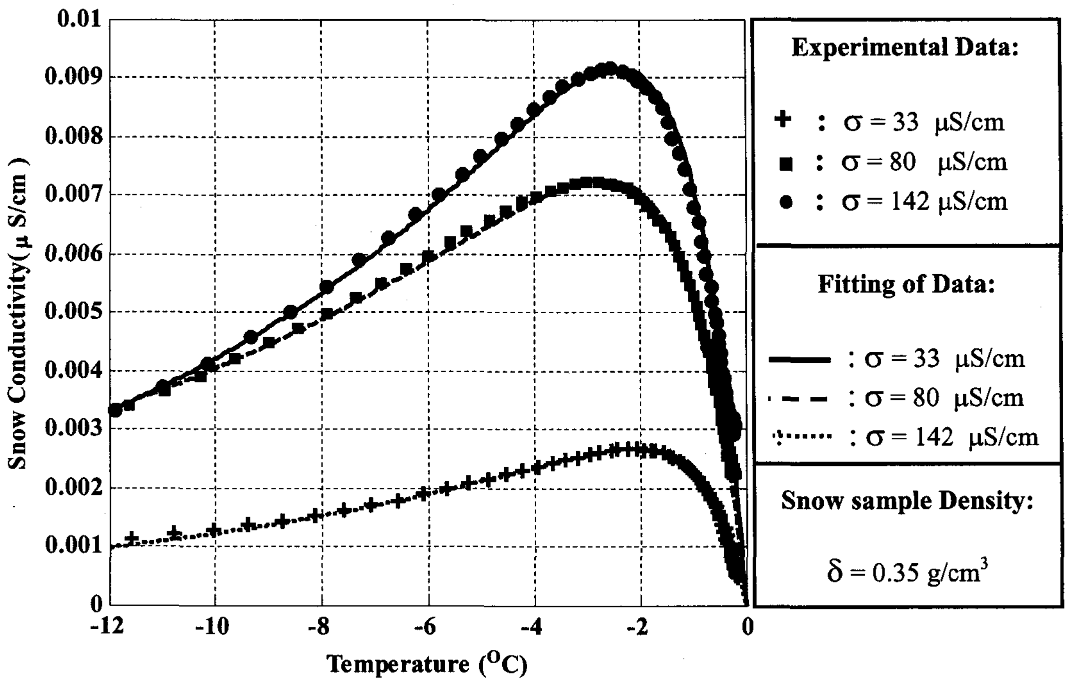



**Figure 3.25:** Variation of dc conductivity by using of regression method of experimental data under heating process and $\boldsymbol{\delta} = 0.35$ g/cm$^3$

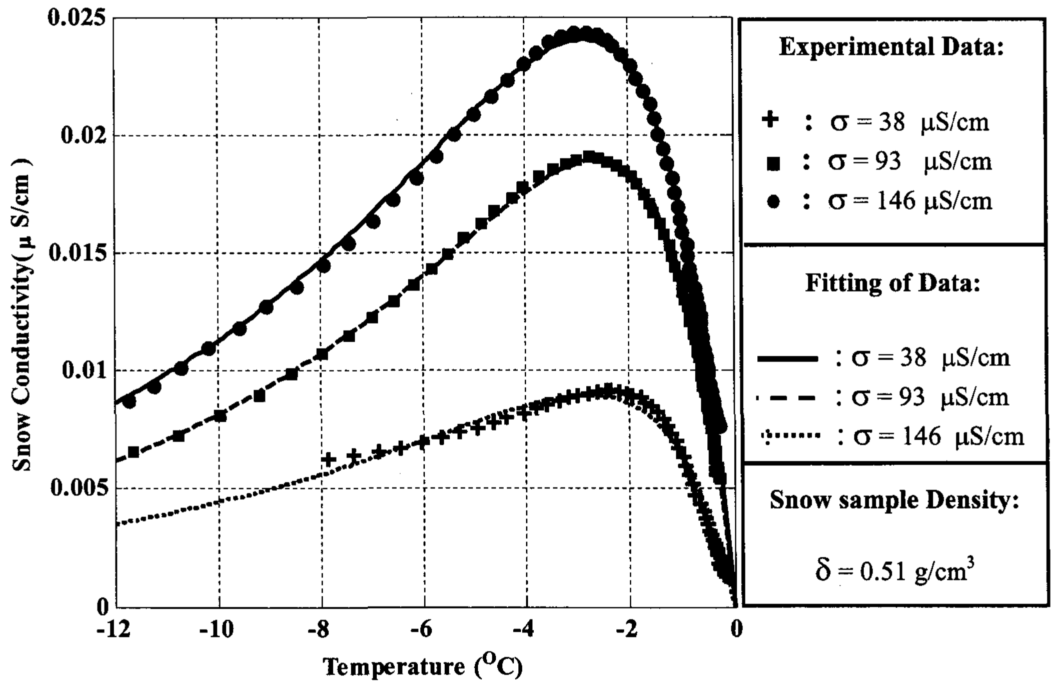



**Figure 3.26:** Variation of dc conductivity by using of regression method of experimental data under heating process and **δ** = 0.51 g/cm³

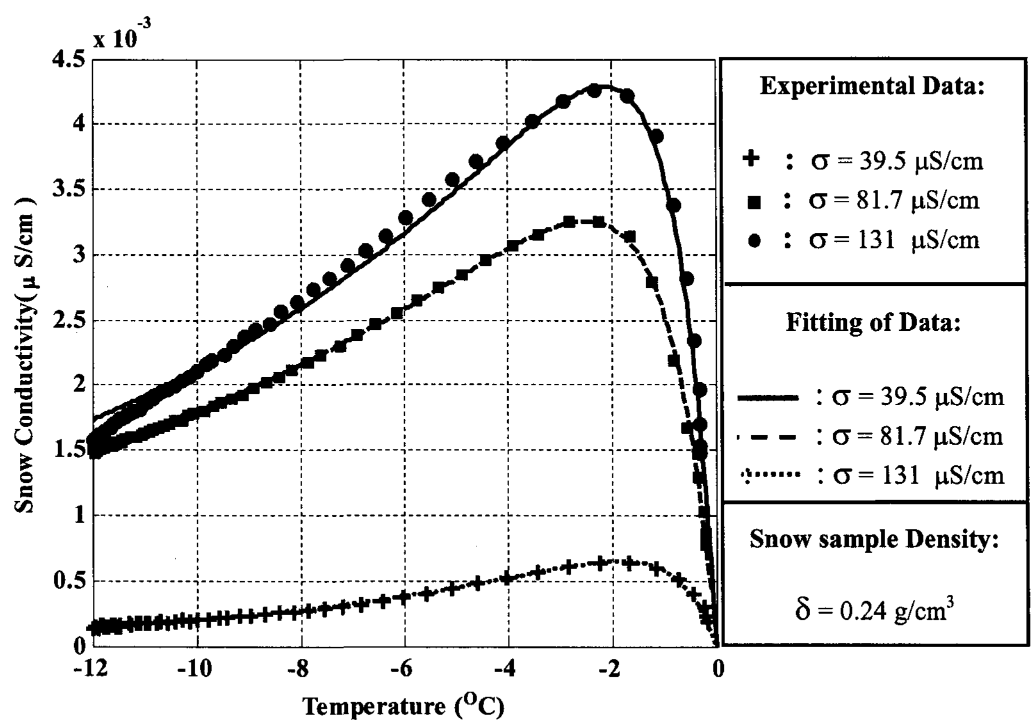



**Figure 3.27:** Variation of dc conductivity by using of regression method of experimental data under cooling process and **δ** = 0.24 g/cm³

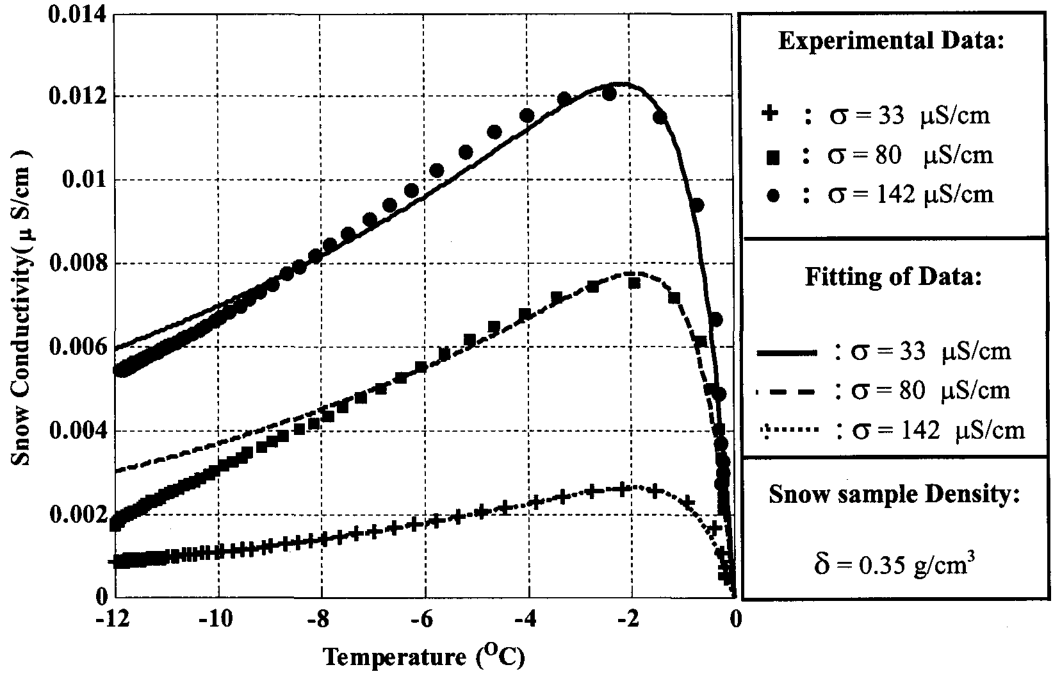



**Figure 3.28:** Variation of dc conductivity by using of regression method of experimental data under cooling process and $\boldsymbol{\delta} = 0.35$ g/cm$^3$

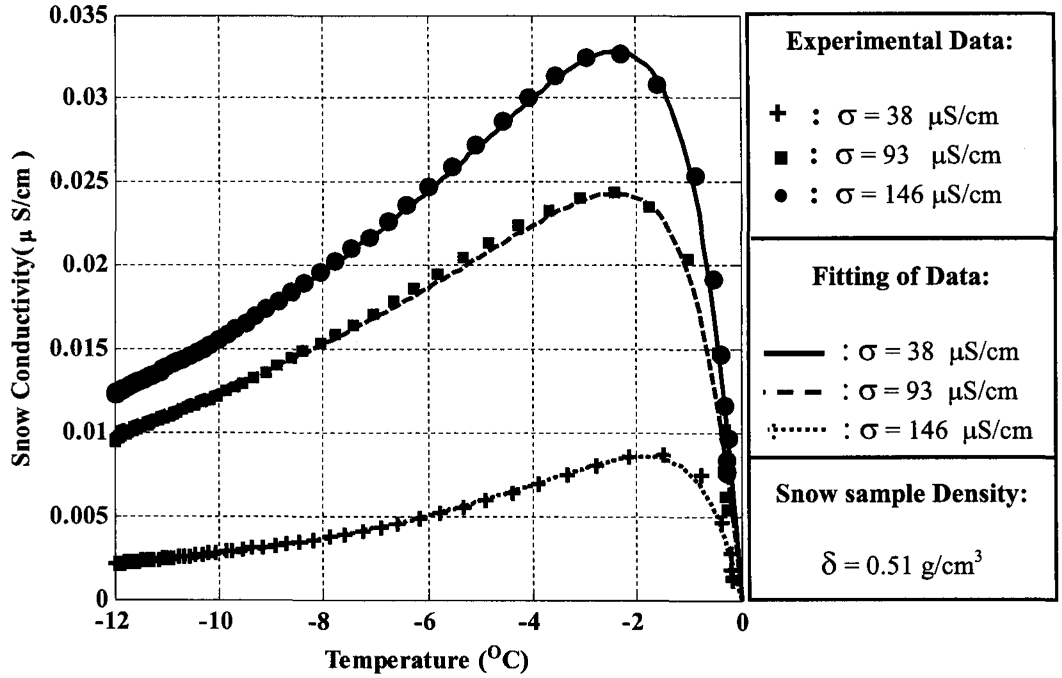



**Figure 3.29:** Variation of dc conductivity by using of regression method of experimental data under cooling process and $\boldsymbol{\delta} = 0.51$ g/cm$^3$.

The parameters $K_1$, $K_2$ and K were determined using regression on the test results for several snow densities and conductivities according to Table 3.1.

### 3-3-2-1 Heating process

Table 3.2 summarizes the values of the K, $K_1$ and $K_2$ parameters obtained from all the test results in the heating process by using regression on the data.

**Table 3.2:** Parameters K (μS/cm), $K_1$ (°C$^{-1}$) and $K_2$ (°C$^{-1}$), obtained using regression on the test results under heating process

| | Low σ | Medium σ | High σ |
|---|---|---|---|
| Low δ | K = 0.00161<br>$K_1$ = 0.068<br>$K_2$ = 1.3 | K = 0.00271<br>$K_1$ = 0.072<br>$K_2$ = 1.3 | K = 0.00567<br>$K_1$ = 0.095<br>$K_2$ = 0.9 |
| Medium δ | K = 0.00365<br>$K_1$ = 0.11<br>$K_2$ = 1.3 | K = 0.0106<br>$K_1$ = 0.118<br>$K_2$ = 1.01 | K = 0.0138<br>$K_1$ = 0.094<br>$K_2$ = 0.947 |
| High δ | K = 0.0147<br>$K_1$ = 0.12<br>$K_2$ = 0.8 | K = 0.033<br>$K_1$ = 0.158<br>$K_2$ = 0.7 | K = 0.0435<br>$K_1$ = 0.14<br>$K_2$ = 0.72 |

As shown in the Table 3.2, the values of coefficient $K_1$ are constrained between 0.068 and 0.158 with the most likely value being around 0.107 °C$^{-1}$; those of $K_2$ vary between 0.7 and 1.3 with a mean value around 0.9967 °C$^{-1}$.

There is a relationship between those parameters and the snow parameters, namely the conductivity of water melted from snow (σ) and the snow density (δ). Indeed, K, $K_1$ and $K_2$ may be expressed as a mathematical function of σ and δ, represented by the solid-line curves that fit the experimental data.

To determine the effect of the parameters K, $K_1$ and $K_2$ on the snow conductivity (see equation 3.6), the maximum, average and minimum value of each one of those parameters was considered. When calculating each one of those parameters, provided the other parameters listed in the Table 3.2 are kept constant, the derived error can be evaluated as follows:

$$Error_{Average} = \left\{ Average \left( \frac{\left| \sigma(Max \quad K_i) - \sigma(Min \quad K_i) \right|}{\sigma(Mean \quad K_i)} \right) \right\} \times 100 \tag{3.7}$$

The computation of relation 3.7 allows the determination of the average value of errors. The obtained results are summarized in Table 3.3.

**Table 3.3:** Mean Value and Error after calculating of snow conductivity for all parameters under heating process.

| Parameter | Mean value | Mean Value of Error (%) |
|---|---|---|
| $K_1$ | 0.1087 | 5.08 |
| $K_2$ | 0.9967 | 8.54 |
| K | 0.01436 | 99.84 |

In the Table 3.3, it can be seen that $K_1$ and $K_2$ parameters do not seriously affect the conductivity of snow. Considering the mean value of these parameters in Equation 3.7, will induce errors less than 9%. However, for K parameter, the necessity of determining a relation between K and snow parameters is of prime importance.

Figures 3.30, 3.31 and 3.32 shows the effect of these parameters on the snow conductivity under the heating process for a high snow density sample and high water melted conductivity. There, the difference is clear between snow conductivity using the maximum, average and minimum values of each of parameters.

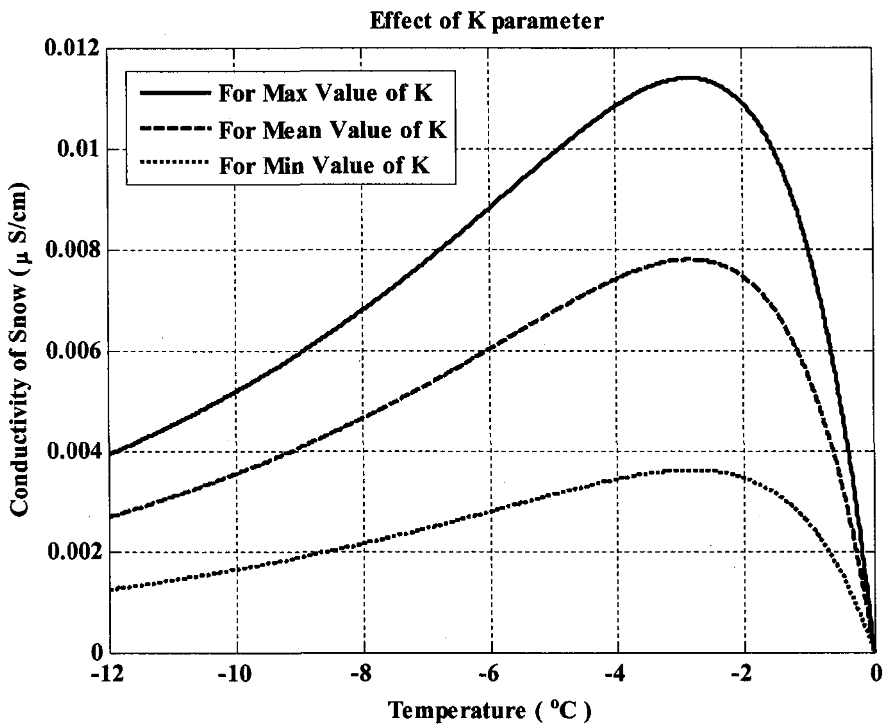



**Figure 3.30:** Effect of K on the snow conductivity under heating process for snow sample of $\delta = 0.55$ g/cm$^3$, $\sigma = 146$ μS/cm, $K_1 = 0.14$ °C$^{-1}$ and $K_2 = 0.72$ °C$^{-1}$

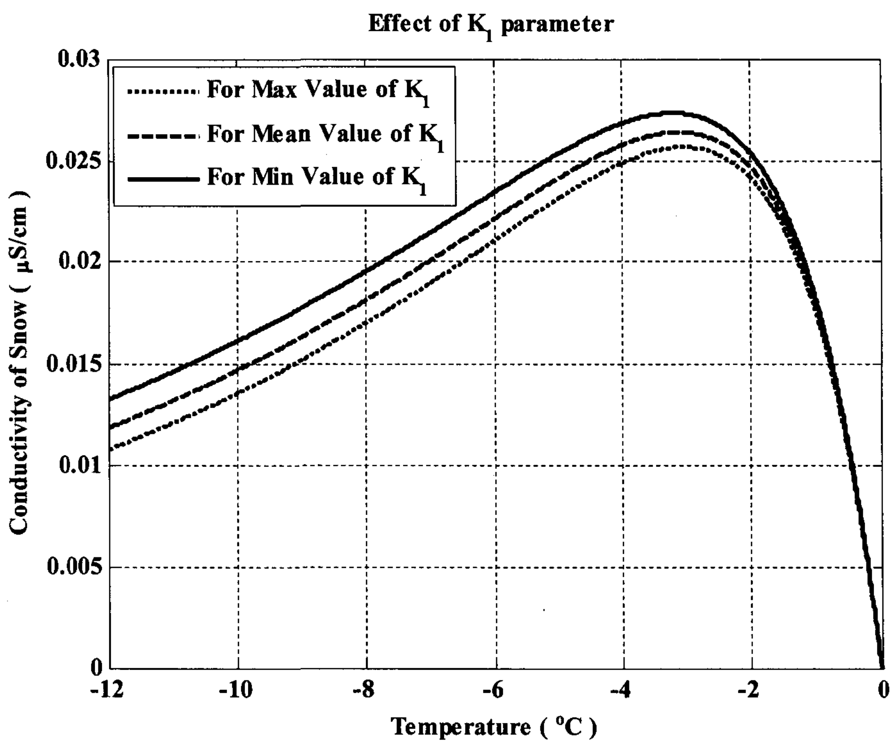



**Figure 3.31:** Effect of $K_1$ on the snow conductivity under heating process for snow sample of $\delta = 0.55$ g/cm$^3$, $\sigma = 146$ μS/cm, $K_2 = 0.72$ °C$^{-1}$, K=0.0435 μS/cm

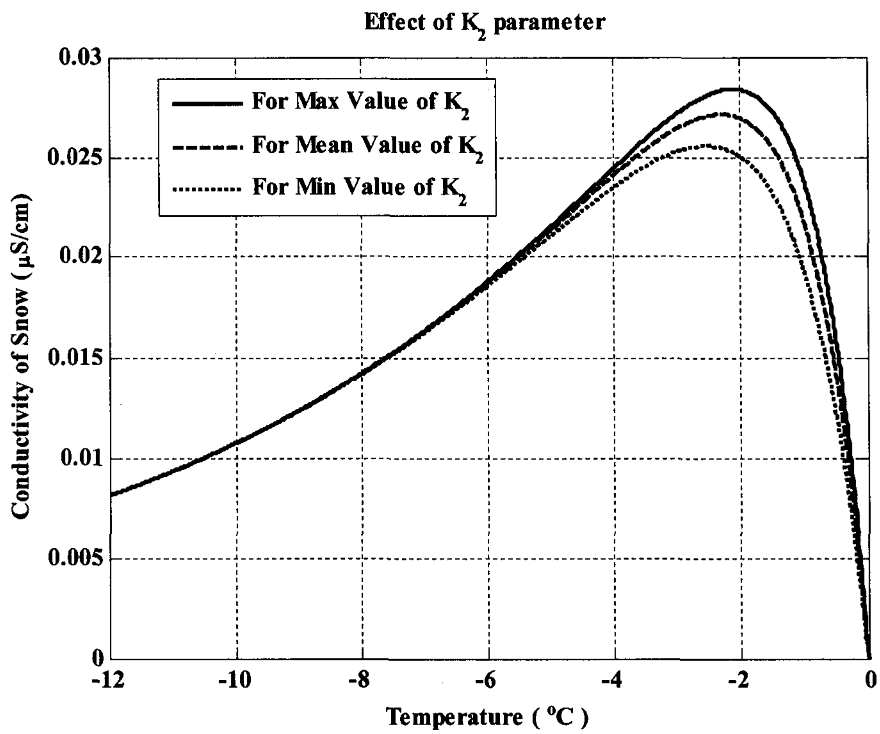



**Figure 3.32:** Effect of $K_2$ on the snow conductivity under heating process for snow sample of $\delta = 0.55$ g/cm$^3$, $\sigma = 146$ µS/cm, $K_1 = 0.14$ °C$^{-1}$ and K= 0.0435 µS/cm

As shown in Figures 3.33 and 3.34, the linear functions between K parameter and snow parameters may be used as the best fit for the results obtained for the heating process. Figure 3.33 shows the linear relationship between K parameter and water melted from snow conductivity for different snow density values, and Figure 3.34 shows the linear relationship between K parameter and snow density for different water melted conductivity values.

From regression methods, the linear relation can be expressed as:

- For Figure 3.33

For $\delta = 0.24$ g/cm$^3$ : $K=0.000045\,\sigma -0.00044$ (3.8)

For $\delta = 0.35$ g/cm$^3$ : $K=0.000091\,\sigma +0.0016$ (3.9)

For $\delta = 0.51$ g/cm$^3$ : $K=0.00027\,\sigma +0.0057$ (3.10)

By applying the regression method to the above equations again, the coefficient K is determined as a function of δ and σ:

$$K(\sigma, \delta) = (0.00085\,\delta - 0.00017)\,\sigma + (0.023\,\delta - 0.006) \qquad (3.11)$$

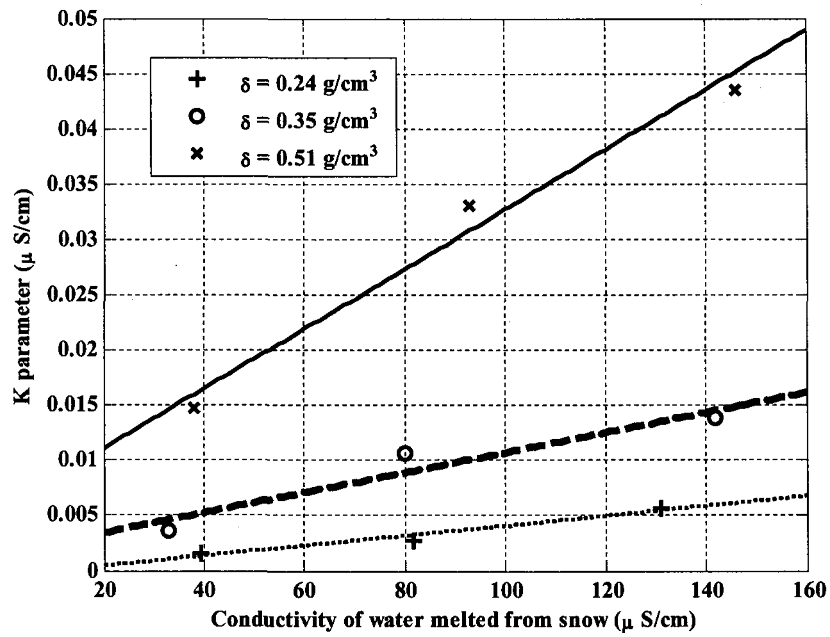



**Figure 3.33:** Parameter K for the heating process versus conductivity of water melted from snow (σ) for different density values (δ)

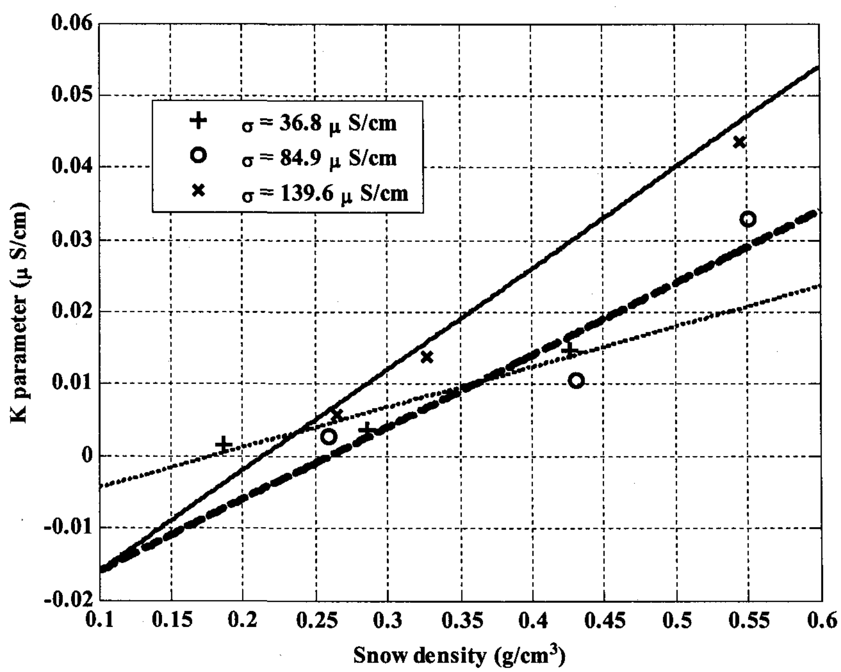



**Figure 3.34:** Parameter K for the heating process versus density values (δ) for different conductivity of water melted from snow (σ)

- For Figure 3.34

For $\sigma = 36.8\ \mu$ S/cm : $K=0.056\ \delta - 0.01$ (3.12)

For $\sigma = 85\ \mu$ S/cm : $K=0.1\ \delta - 0.026$ (3.13)

For $\sigma = 139.6\ \mu$ S/cm : $K=0.14\ \delta - 0.03$ (3.14)

By applying the regression methods to the above equations again, the coefficient K is determined as a function of $\delta$ and $\sigma$:

$$K(\sigma,\delta)=(0.00082\ \sigma + 0.028)\ \delta + (-0.00019\ \sigma - 0.0053) \qquad (3.15)$$

When comparing the equations 3.11 and 3.15, it is evident that there is good correlation between them. In order to obtain a precise mathematical model with taking the average values for the coefficients, the final relation between K parameter and snow parameters under the heating process can be expressed as follows:

$$K(\sigma, \delta)=0.000835\ \sigma\ \delta + 0.0255\ \delta + 0.00018\ \sigma - 0.00565 \qquad (3.16)$$

where K is expressed in $\mu$S/cm, $\delta$ in g/cm$^3$ and $\sigma$ in $\mu$S/cm.

### 3-3-2-2 Cooling process

Table 3.4 summarizes the values of the K, $K_1$ and $K_2$ parameters obtained from all the test results in the cooling process by using regression on the data.

**Table 3.4:** Parameters K ($\mu$S/cm), $K_1$ ($^oC^{-1}$) and $K_2$ ($^oC^{-1}$), obtained using regression on the test results under cooling process

| | Low $\sigma$ | Medium $\sigma$ | High $\sigma$ |
|---|---|---|---|
| Low $\delta$ | $K = 0.000995$<br>$K_1 = 0.1$<br>$K_2 = 1.3$ | $K = 0.00443$<br>$K_1 = 0.09$<br>$K_2 = 1.1$ | $K = 0.00575$<br>$K_1 = 0.1$<br>$K_2 = 1.3$ |
| Medium $\delta$ | $K = 0.00365$<br>$K_1 = 0.12$<br>$K_2 = 1.35$ | $K = 0.011$<br>$K_1 = 0.085$<br>$K_2 = 1.45$ | $K = 0.0157$<br>$K_1 = 0.1$<br>$K_2 = 1.51$ |
| High $\delta$ | $K = 0.01315$<br>$K_1 = 0.16$<br>$K_2 = 1.3$ | $K = 0.034$<br>$K_1 = 0.1$<br>$K_2 = 1.1$ | $K = 0.048$<br>$K_1 = 0.112$<br>$K_2 = 1.05$ |

The values of the coefficient $K_1$ is constrained between 0.08 and 0.16, with the most likely value being around 0.1136; while those of $K_2$ vary between 1.05 and 1.55 with a mean value of 1.272.

For the same reasons mentioned in the heating process, in order to see the effect of these K parameters of the conductivity of snow we will find errors for average values of k parameters as shown in Table 3.5.

**Table 3.5:** Mean Value and Error after calculating of snow conductivity for all parameters under cooling process

| Parameter | Mean value | Mean Value of Error (%) |
|---|---|---|
| $K_1$ | 0.1002 | 4.0 |
| $K_2$ | 1.2722 | 2.2 |
| K | 0.0152 | 113.38 |

As shown in the Table 3.5 for the parameter K, the error is very large when considering a mean value in equation 3.7, but for others ($K_1$ and $K_2$), the mean values can be considered, since it will induce a maximum error of 4%.

Figures 3.35, 3.36 and 3.37 show the effect of these parameters on the snow conductivity under the cooling process; as shown there, the difference between snow conductivity using the maximum, average and minimum values of each of the parameters under the cooling process is clear.

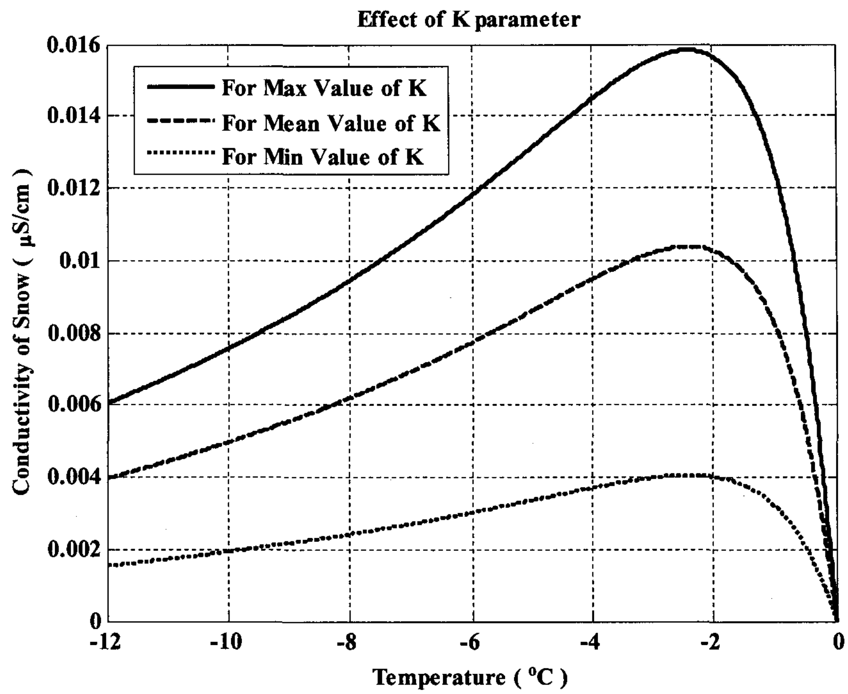



**Figure 3.35:** Effect of K on the snow conductivity under heating process for snow sample of $\delta = 0.55$ g/cm$^3$, $\sigma = 146$ μS/cm, $K_1 = 0.112$ °C$^{-1}$ and $K_2 = 1.05$ °C$^{-1}$

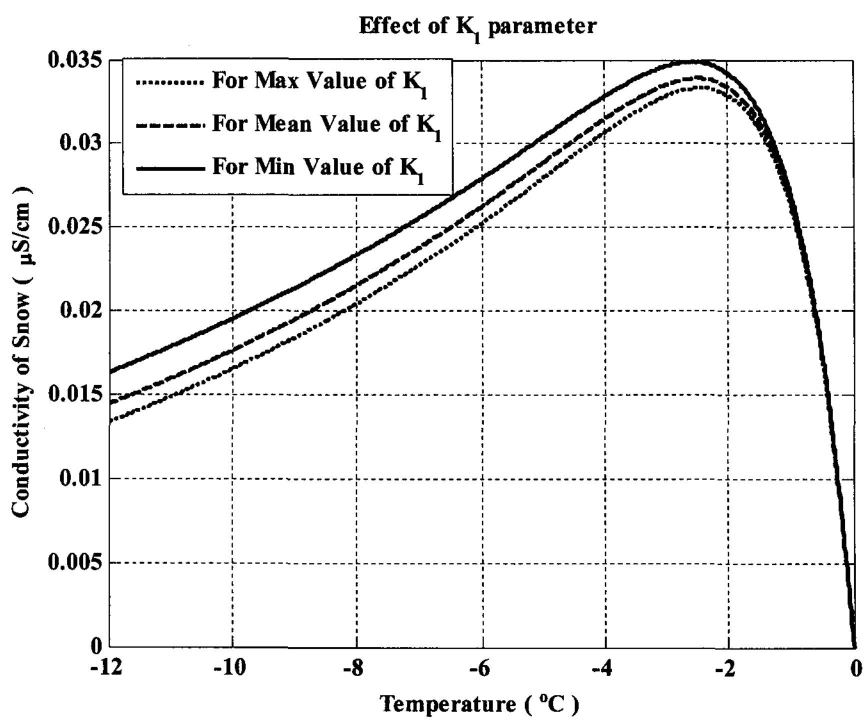



**Figure 3.36:** Effect of $K_1$ on the snow conductivity under heating process for snow sample of $\delta = 0.55$ g/cm$^3$, $\sigma = 146$ μS/cm, $K_2 = 1.05$ °C$^{-1}$, K=0.048 μS/cm

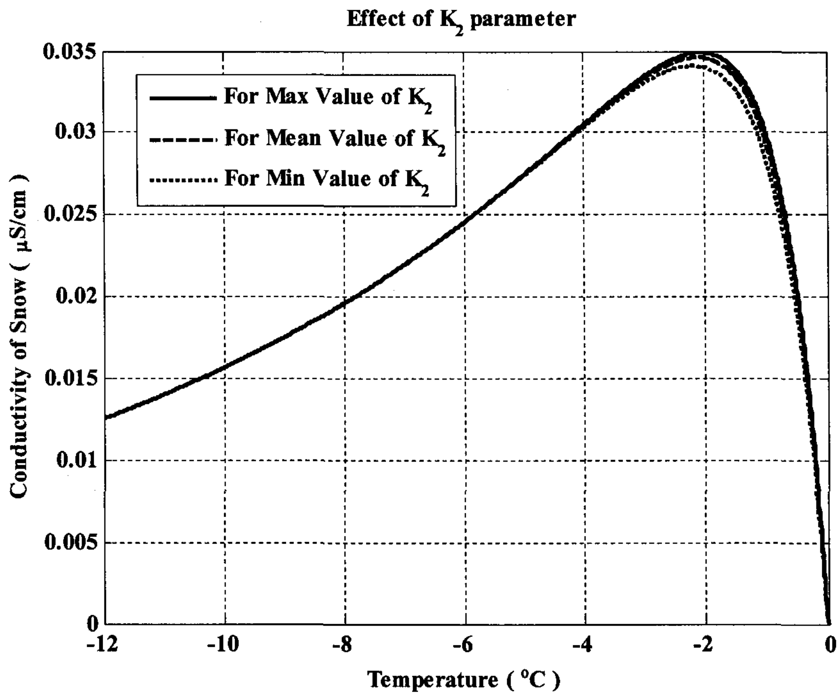



**Figure 3.37:** Effect of $K_2$ on the snow conductivity under heating process for snow sample of $\delta = 0.55$ g/cm$^3$, $\sigma = 146$ μS/cm, $K_1 = 0.112$ °C$^{-1}$ and K= 0.048 μS/cm

As shown in Figures 3.38 and 3.39, the linear functions between K and snow parameters may be used as the best fit of the results obtained for cooling process. Figure 3.38 shows the linear relationship between K parameter and water melted conductivity for different snow density values, and Figure 3.39 shows the linear relationship between K parameter and snow density for different water melted conductivity values.

From the regression method the linear relation can be expressed as:

- For Figure 3.38

For $\delta = 0.24$ g/cm$^3$ : $K=0.000051\,\sigma - 0.00058$ (3.17)

For $\delta = 0.35$ g/cm$^3$ : $K=0.00011\,\sigma + 0.00087$ (3.18)

For $\delta = 0.51$ g/cm$^3$ : $K=0.00032\,\sigma + 0.0019$ (3.19)

By applying the regression methods to the above equations, the relation between K and snow parameters can be shown as:

$$K(\sigma,\delta)=(0.001\,\delta - 0.00021)\,\sigma + (0.009\,\delta - 0.0025) \quad (3.20)$$

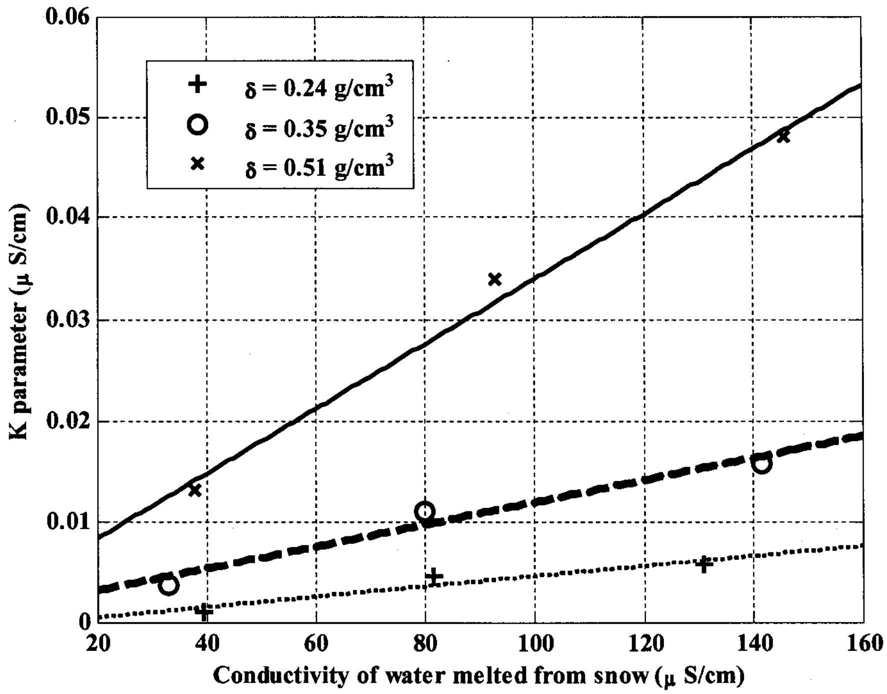



**Figure 3.38:** Parameter K for the heating process versus conductivity of water melted from snow (σ) for different density values (δ).

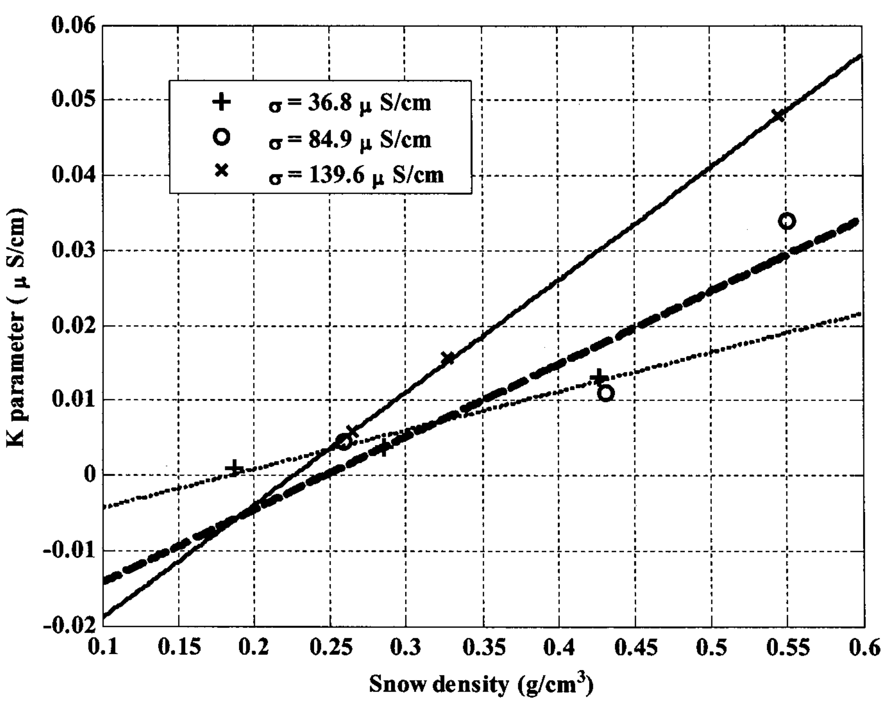



**Figure 3.39:** Parameter K for the heating process versus density values (δ) for different conductivity of water melted from snow (σ).

- For Figure 3.39

For $\sigma = 36.8\ \mu$ S/cm : K=0.052 δ - 0.0096 (3.21)

For $\sigma = 85\ \mu$ S/cm : K=0.097 δ - 0.024 (3.22)

For $\sigma = 139.6\ \mu$ S/cm : K=0.15 δ - 0.034 (3.23)

By applying the regression methods to the above equations once again, the relationship between K and snow parameters can be shown as:

$$K(\sigma,\delta)=(0.00095\ \sigma + 0.007)\ \delta + (-0.00024\ \sigma - 0.002) \quad (3.24)$$

For the equations 3.20 and 3.24 when considering the average values for the coefficients the final relation between K parameter and snow parameters under heating process can be expressed as equation 3.25:

$$K(\sigma,\delta)=0.000975\ \sigma\ \delta + 0.008\ \delta - 0.000225\ \sigma - 0.00225 \quad (3.25)$$

where K is expressed in μS/cm, δ in $g/cm^3$ and σ in μS/cm.

The insertion of the equations 3.16 and 3.25 into the relation 3.7 when considering the mean values for $K_1$ and $K_2$ parameters, leads to a relation between snow conductivity and its parameters as a function of temperature, both for the heating and cooling processes as follows:

For the heating process:

$$\sigma_{dc}(T,\sigma,\delta)=\left[0.000835\ \sigma\delta + 0.0255\ \delta + 0.00018\ \sigma - 0.00565\right]\cdot\left(e^{0.1087.T} - e^{0.9967.T}\right) \quad (3.26)$$

and for the cooling process:

$$\sigma_{dc}(T,\sigma,\delta)=\left[0.000975\ \sigma\delta + 0.008\ \delta - 0.000225\ \sigma - 0.00225\right]\cdot\left(e^{0.1002.T} - e^{1.2722.T}\right) \quad (3.27)$$

These relationships are of prime importance since they allow the prediction of $\sigma_{dc}$ under the selected conditions under consideration (temperature, density and water melted from snow conductivity ranges).

## 3-4 Summary

The electrical characteristics of some major natural snow parameters affecting the electrical performance of HV snow-covered insulators were investigated. From these investigations, the following conclusions may be drawn:

DC conductivity of snow was found to be a function of snow temperature and density, as well as of the conductivity of water melted from snow.

The apparently curious behavior of the dc conductivity of snow near the melting temperature, where peak conductivity is reached, seems to be directly related to the sensitivity of snow crystal growth to temperature and humidity. The existence of the peak may be related to the dynamics of disappearance and reconstruction of weak bonds and contacts in the snow. Indeed, this phenomenon would indicate that peak temperatures constitute a limiting factor for snow-covered insulator flashover performance, because the highest conductivity is observed at that peak temperature (near -2°C).

Empirical relationship between the density and conductivity of water melted from snow, on one hand, and snow dc conductivity, on the other hand, was proposed. Even though the obtained relationships cannot yet be considered universally well established for natural snow, because of the limited number of samples tested, this result, however, is of primary importance since it allows predicting $\sigma_{dc}$ under the selected conditions under consideration.

# CHAPTER 4:

# SNOW RESIDUAL RESISTANCE CALCULATION

## 4-1 Introduction

The residual resistance R(x) is perhaps one of the most important parameters influencing arc propagation inside wet snow. R(x) of the snow during the development of the flashover arc is influenced not only by the volume conductivity but also by many other factors, such as temperature, density, partial arc occurring during flashover, liquid water content, etc. Therefore, in the present study, R(x) was measured specifically during the development of the flashover arc instead of in a low-voltage steady condition.

Several authors have studied the residual resistance in polluted or ice-covered insulators flashover processes [e.g. 25, 66]. In the case of snow-covered insulator flashover the calculation/measurement should be different since arcs propagate inside the wet snow. The difficulty is further increased because an arc propagating inside snow cannot be photographed for the purpose of studying the processes involved. Given that a snow-covered insulator has a complex shape, a simplified physical model was considered. This physical model consisted of a cylindrical tube half-filled with wet snow. The residual resistance R(x) of a cylinder model filled with wet snow samples with different density ($\delta$) and snow conductivity, $\sigma$ (that is the conductivity of water melted from snow) were measured.

## 4-2 Developed Model to estimate arc progress inside wet snow

In some previous studies, a static model of the arc as it occurs on ice-covered insulator surfaces was presented [24, 25, 67-69]. The model for flashover on snow-covered insulator surfaces is still a challenge in the study of outdoor insulation. This situation arises from the complexity of the phenomena depending on a great number of parameters including temperature, contamination, volume conductivity, density, liquid water content, and conductivity of water melted from snow [2, 67, 70, 71].

It should be noted that practically no exploratory research work is available on the mechanisms of flashover occurrence on snow-covered insulators.

The elaboration of a mathematical model could be very helpful in optimizing experiments and in the interpretation and presentation of some test results. However, it is well established that several parameters, including snow type, density, amount and distribution, as well as melted-water conductivity are of major importance in affecting the withstand voltage characteristics of snow-covered insulators [2,7]. It has also been established that flashover performance of snow-covered insulators is affected by the height of snow and the ratio of snow-covered length over the total length of insulator [2, 7, 70].

## 4-3 Calculating arc constants and arc re-ignition constants

Recent studies [3, 24, 25, 68, 69] have confirmed that the flashover voltage of ice-covered insulator surfaces can be predicted using a method based on Obenaus' concepts [41], which have largely been used for modeling polluted insulator surfaces [e.g. 36, 38]. The same assumption is considered in the mathematical modeling of snow-covered insulators.

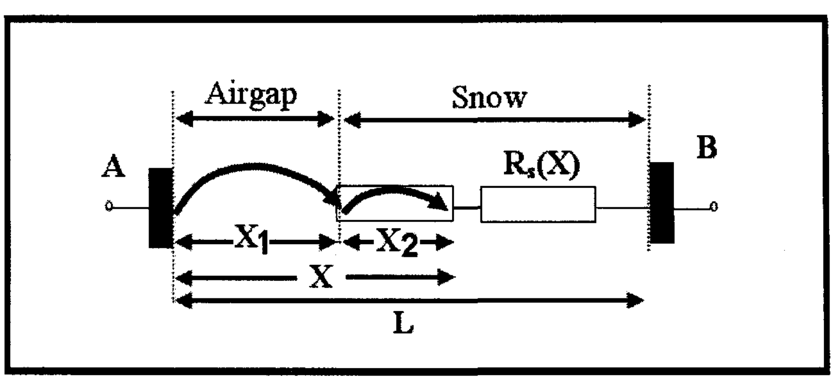



**Figure 4.1:** The Obenaus model used for partially snow covered insulator

This model is presented in Figure 4.1 and the equation for the flashover process under AC voltage is expressed as follows [21]:

$$V_m = A_a x_1 I_m^{-n_a} + A_s x_2 I_m^{-n_s} + I_m R_s(x) \tag{4.1}$$

where $V_m$ (in V) and $I_m$ (in A) are the peak value of the applied voltage and leakage current inside wet snow, respectively; $A_a$, $n_a$, $A_s$ and $n_s$ are the arc constants in airgap and snow respectively; $x_1$, $x_2$ (in cm) are the length of the arc in airgap and inside snow respectively and $x=x_1+x_2$ is total arc length and $R_s(x)$ (in Ω) is the residual snow resistance: the resistance of the non-bridged snow layer. Constants $A_a$, $n_a$, $A_s$ and $n_s$ may vary in accordance with the arc medium material and the ambient conditions [21, 35, 42].

For the modeling purposes of an arc burning inside wet snow, it is not only Equation 4.1 that is considered, but the arc re-ignition condition as well; under AC [21, 25, 38]. The arc re-ignition condition can be explained by [25]:

$$V_m \geq \frac{k_{as} x}{I_m^{b_{as}}} \tag{4.2}$$

where, $k_{as}$ and $b_{as}$ are the arc re-ignition constants. In the critical case of the re-ignition condition, Equation 4.2 can be rewritten as:

$$V_m = \frac{k_{as} x}{I_m^{b_{as}}} \tag{4.3}$$

or:

$$I_m = \left( \frac{k_{as} x}{V_m} \right)^{\frac{1}{b_{as}}} \tag{4.4}$$

Combining equations 4.1 and 4.4 yields:

$$V_m = A_a x_1 \left( \frac{k_{as} x}{V_m} \right)^{\frac{-n_a}{b_{as}}} + A_s x_2 \left( \frac{k_{as} x}{V_m} \right)^{\frac{-n_s}{b_{as}}} + R(x) \left( \frac{k_{as} x}{V_m} \right)^{\frac{1}{b_{as}}} \quad (4.5)$$

This equation shows a relationship between the peak value of alternating applied voltage ($V_m$) and the length of arc ($x$). If the constants $A_a$, $n_a$, $A_s$, $n_s$, $k_{as}$ and $b_{as}$ are known, $V_m$ is uniquely determined by arc lengths.

$A_a$, $n_a$, $A_s$ and $n_s$ are the arc constants, while $k_{as}$ and $b_{as}$ are referred to the re-ignition constants. It should be noted that the indexes "*a*" and "*s*" are used to specify the relevancy of those parameters with regards to airgap and snow respectively and index "*as*" is used to specify the relevancy of those parameters with regards to airgap and snow at the same time.

## 4-4 Equivalent conductivity

The residual resistance R(x) of the cylinder snow model was measured for different conditions of snow samples, which allowed various equivalent volume conductivities. For the cylinder model as shown in Figure 4.2, the residual resistance of snow can be calculated as:

$$\mathrm{R(x)} = \int_{X_2}^{L} \frac{1}{\pi \gamma_e R_y^2} dy \quad (4.6)$$

After solving this integration equation and considering Figure 4.2, the equivalent volume conductivity of snow sample can be expressed as follows:

$$\gamma_e = \frac{1}{\pi R_1 R_2 R(x)} (L - X_2) \quad (4.7)$$

where $X_2$ (in cm) the distance from the cylinder top surface to the measuring electrode, $\gamma_e$ (in μS/cm) is the equivalent volume conductivity of snow sample, $R_1$ and $R_2$ are electrode radii equal to 4 cm and R(x) is snow residual resistance for a given arc length which will be determined using the experimental data.

As shown in Figure 4.2, for various snow parameters $\sigma$ and $\delta$, R(x) can be determined from the knowledge of the voltage dropped across the residual (unbridged) part of snow and the measured leakage current.

To determine the equivalent conductivity of snow as a function of both snow parameters ($\sigma$ and $\delta$), two series of tests should be carried out, provided the other parameter is kept constant, in order to quantify the effect of each one separately. In the following two sections, the effect of the conductivity of water melted from snow ($\sigma$) and snow density ($\delta$) on the equivalent conductivity of snow will be investigated.

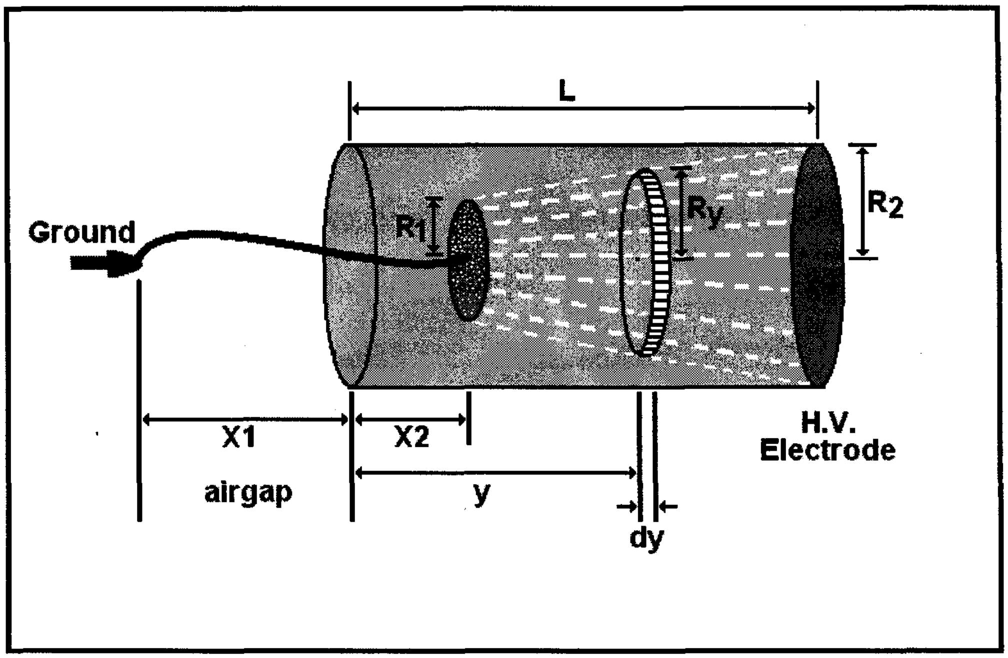



**Figure 4.2:** experimental setup for snow residual resistance calculation

### 4-4-1 Relationship with snow density

The control and adjustment of the conductivity of water melted from snow samples was not an easy matter. In order to overcome this, four typical ranges were considered for conductivity. These ranges can be found in Table 4.1.

**Table 4.1:** Ranges of conductivity of the water melted from snow used to determine the relationship between the snow equivalent conductivity and density.

| Group | Minimum Conductivity (μS/cm) | Maximum Conductivity (μS/cm) | Average conductivity (μS/cm) |
|---|---|---|---|
| $C_1$ | 215 | 284 | 243 |
| $C_2$ | 330 | 396 | 363 |
| $C_3$ | 421 | 476 | 444 |
| $C_4$ | 495 | 790 | 653 |

The results obtained are summarized in Figure 4.3. The mathematical processing of the data suggest some linear relationships between the equivalent volume conductivity of the wet snow sample, $\gamma_e$ and δ, for a given snow conductivity. At this time, the following equations may be used:

For: σ=243 μS/cm $\gamma_e = 2.493992\delta - 0.50196$ (4.8)

For: σ=363 μS/cm $\gamma_e = 3.378904\delta - 0.72769$ (4.9)

For: σ=444 μS/cm $\gamma_e = 4.397444\delta - 1.08333$ (4.10)

For: σ=653 μS/cm $\gamma_e = 4.888477\delta - 1.07885$ (4.11)

These equations are in the form of $\gamma_e = a\delta + b$ where the parameters a and b can be determined as a function of the conductivity of water melted from snow:

$$a = 0.0059\sigma + 1.2948 \quad (4.12)$$

$$b = -0.0014\sigma - 0.24 \quad (4.13)$$

That is:

$$\gamma_e = (0.0059\sigma + 1.2948)\delta + (-0.0014\sigma - 0.24) \qquad (4.14)$$

or:

$$\gamma_e = 0.0059\sigma\delta + 1.2948\delta - 0.0014\sigma - 0.24 \qquad (4.15)$$

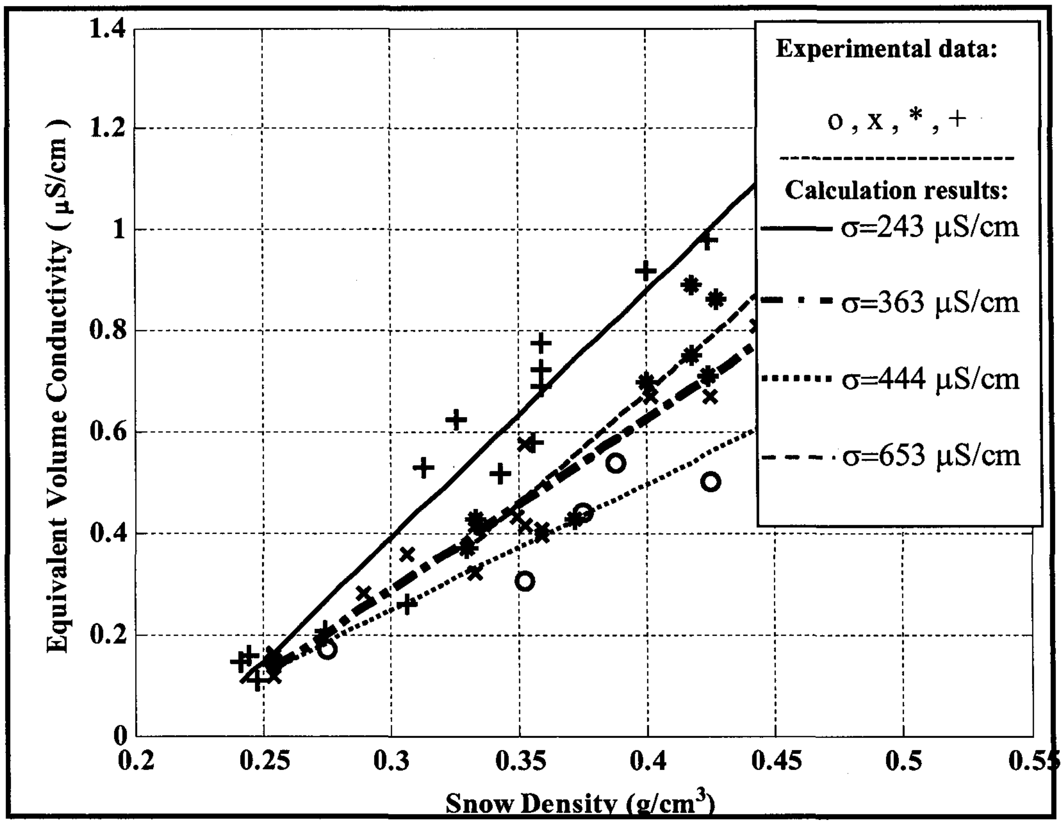



**Figure 4.3:** Relationship between $\gamma_e$ and the snow density ($\delta$)

### 4-4-2 Relation with water melted from snow conductivity

For the same reasons, as for conductivity, the control and adjustment of the density of snow samples is not an easy matter. In order to overcome this, four typical ranges were considered. These ranges can be found in Table 4.2.

**Table 4.2:** Ranges of snow density used to determine the relationship between the snow equivalent conductivity and water melted from snow conductivity

| Group | Minimum Density ($g/cm^3$) | Maximum Density ($g/cm^3$) | Average density ($g/cm^3$) |
|---|---|---|---|
| $D_1$ | 0.2221 | 0.2613 | 0.249 |
| $D_2$ | 0.3004 | 0.3592 | 0.332 |
| $D_3$ | 0.3723 | 0.4278 | 0.406 |
| $D_4$ | 0.4637 | 0.5095 | 0.490 |

The results obtained, which depict the equivalent conductivity of snow samples as a function of the conductivity of water melted from snow for different densities can be found in Figure 4.4. Regression processing of the data suggests some linear relationships between the equivalent volume conductivity of the wet snow sample, $\gamma_e$ and $\sigma$, for a given snow density $\delta$. At this time, the following equations may be used:

For: $\delta$=0.249 $g/cm^3$ $\gamma_e = 0.000208\sigma + 0.090325$ (4.16)

For: $\delta$=0.332 $g/cm^3$ $\gamma_e = 0.000309\sigma + 0.142102$ (4.17)

For: $\delta$=0.406 $g/cm^3$ $\gamma_e = 0.000779\sigma + 0.395574$ (4.18)

For: $\delta = 0.490$ $g/cm^3$ $\gamma_e = 0.00151\sigma + 0.351269$ (4.19)

These equations are in the form $\gamma_e = a\delta + b$ where the parameters a and b can be determined as a function of the snow density:

$$a = 0.0055\delta - 0.0013 \quad (4.20)$$

$$b = 1.2838\delta - 0.2292 \quad (4.21)$$

That is:

$$\gamma_e = (0.0055\delta - 0.0013)\sigma + (1.2838\delta - 0.2292) \quad (4.22)$$

or:

$$\gamma_e = 0.0055\delta\sigma - 0.0013\sigma + 1.2838\delta - 0.2292 \quad (4.23)$$

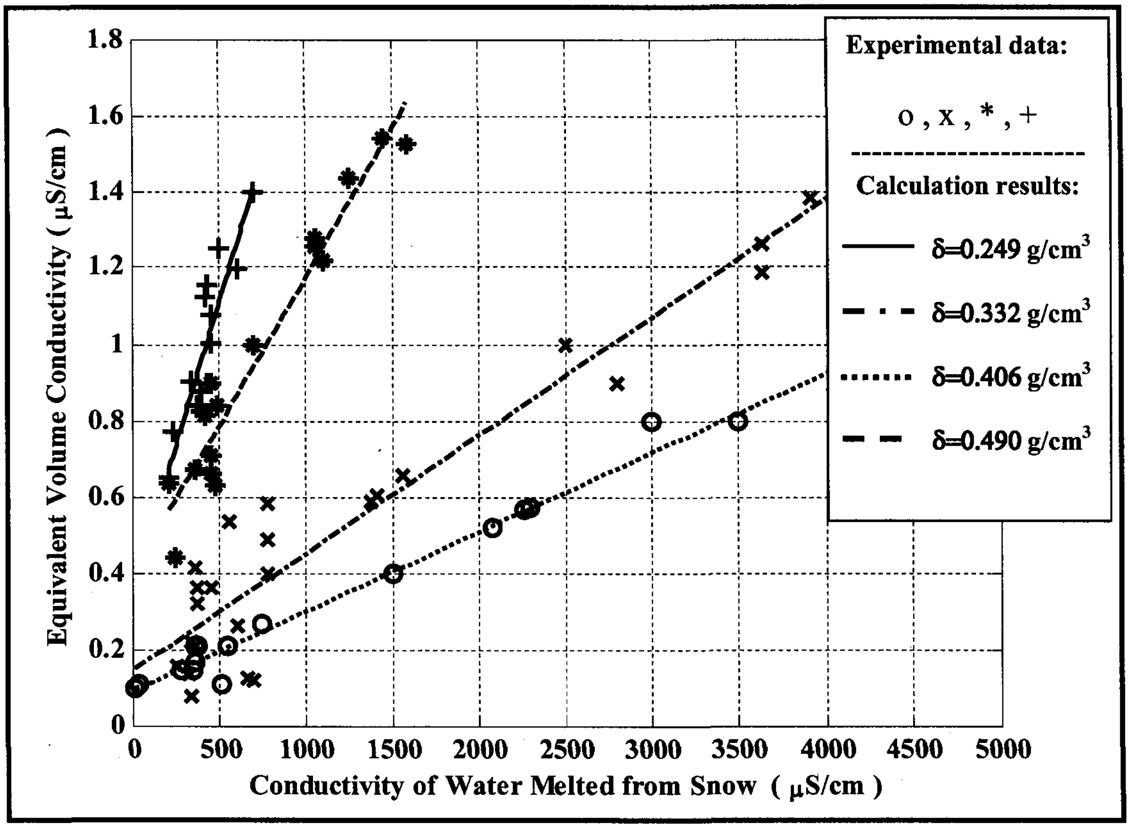



**Figure 4.4:** Relationship between $\gamma_e$ and the conductivity of water melted from snow ($\sigma$)

When comparing relations 4.15 and 4.23 a good concordance is found. Finally, by averaging all the coefficients involved in these two relations, the following relationship can be used:

$$\gamma_e = 0.0057\sigma\delta + 1.2893\delta - 0.00135\sigma - 0.2346 \qquad (4.24)$$

## 4-5 Voltage-Current characteristics of snow under H.V.

The main objective of this section is to determine an analytical model enabling a simulation of electrical characteristics, that is, the resistance and the leakage current of a snow-covered insulator. In this regard, a snow-covered insulator, the applied voltage and leakage current flowing through it were examined and monitored under high alternative voltage. From the voltage-current characteristics of snow, which were measured from several tests, it was found that the voltage across snow and the leakage current flowing through the snow-covered insulator are almost in the same phase. However, the resistance of snow is not linear, as it decreases with an increase in the voltage across snow. Based on experimental results, a precise mathematical model for simulating the leakage current was developed. This model shows that the leakage current through snow is in the form of an exponential function of the voltage across snow depending on the density and conductivity of the water melted from snow.

Figure 4.5 shows the electric circuit of the experimental setup, consisting of a 350 kV AC high voltage system rated at 2 A, and a climate room.

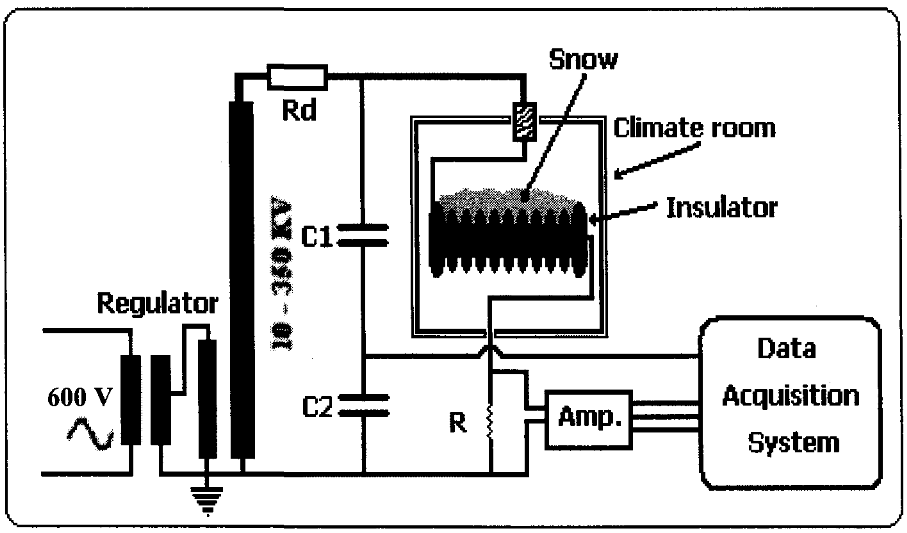



**Figure 4.5:** Circuit of the laboratory test setup for Voltage-Current characteristics of snow

A LabVIEW graphical software program was used to acquire high-quality data. The voltage signal was attenuated using a capacitive voltage divider with $C_1$ = 1200 pF and $C_2$ = 8890 nF. The current signal was transferred to a voltage signal using a low resistance shunt of 10.2 Ω. The test signals were connected to a measuring set through a conditioning box providing protection and insulation. A NI-DAQ device, model PCI-6035E, was used for this purpose.

The AC high voltage was applied to the test circuit (Figure 4.5) and raised linearly at the constant rate of about 5 kV/s using a 700 kVA regulator.

The current and voltage was sampled at a rate of 2400 – 7200 samples/s, transferred to a data buffer and stored. The main components of the data acquisition system are a National Instrument DAQ plug-in board, installed in a PC, and the LabVIEW™ application software. The data are stored both as ASCII text files and binary files. This ensures that the LabVIEW™ acquired data could also be analyzed further using other software applications, like MATLAB™. After each test, part of the snow sample collected on the test object was weighed to determine its density. Also, the conductivity of water melted from snow was measured, and the obtained value was corrected at +20°C.

Figures 4.6 and 4.7 depict some typical values obtained during the experiments. From these figures, it may be noted that during the linear increase in the voltage across snow, the leakage current flowing through snow increases exponentially. However, the voltage and the leakage current remain almost in the same phase, their phase difference being less than 2 degrees for all samples measured. This means that the insulator covered with snow acts as a pure resistance. Indeed, the capacitive impedance of the insulator in parallel with snow resistance at 60 Hz power frequency is very large, and may therefore be neglected. The current and voltage waveforms from each test present a smooth sinusoidal wave shape which only becomes deformed just as discharge occurs over the insulator.

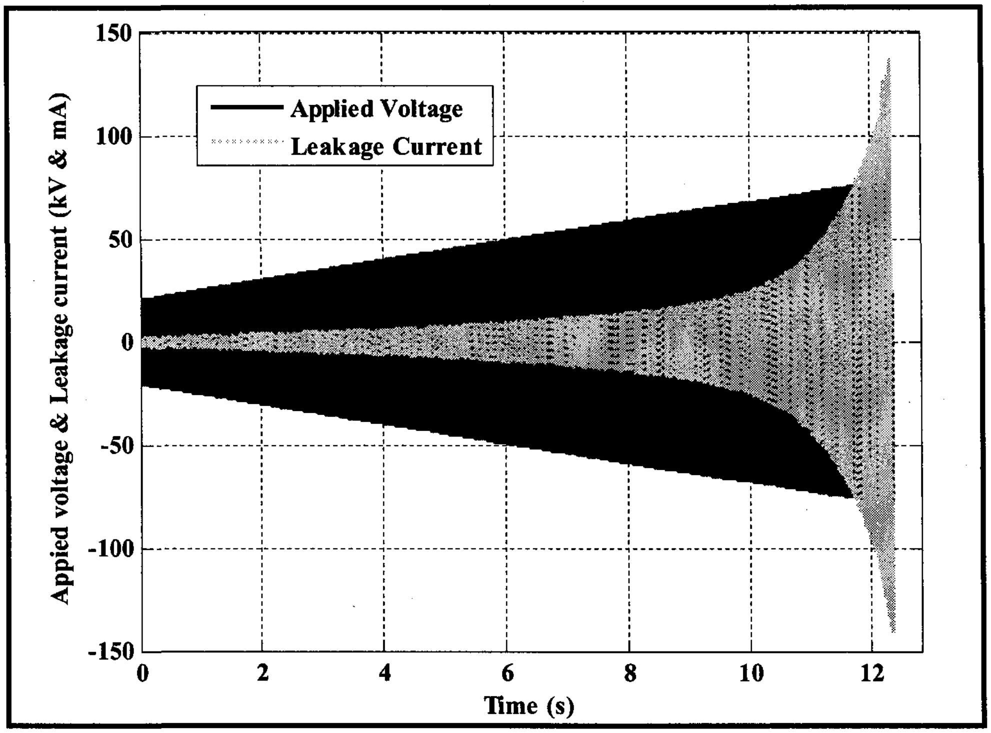



**Figure 4.6:** Evolution of the applied voltage and leakage current flowing through snow as a function of time

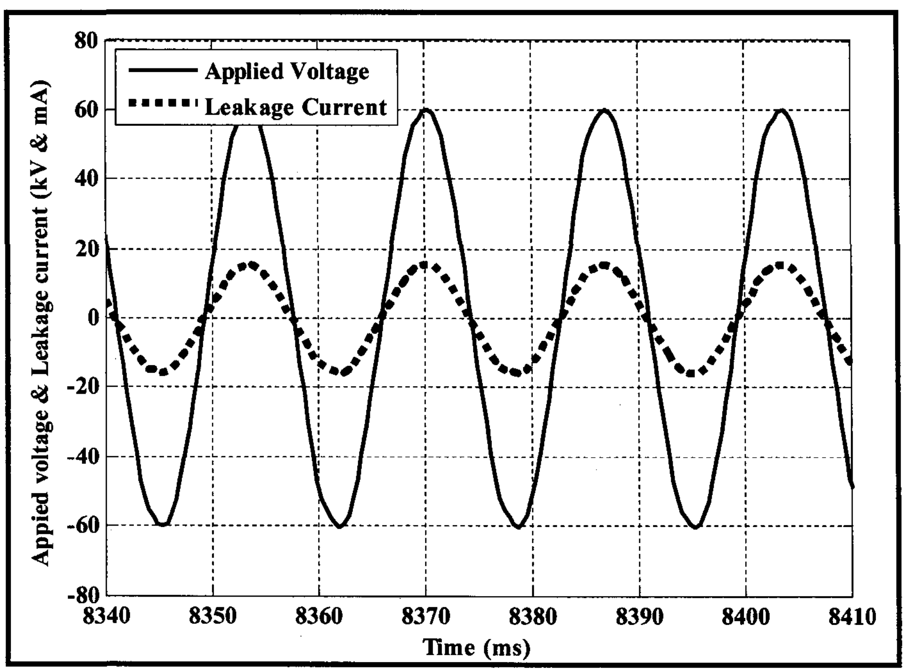



**Figure 4.7:** Close-up view of the evolution of the applied voltage and leakage current flowing through snow as a function of time.

### 4-5-1 Resistance of snow as function of the applied voltage

From all of the results obtained, it was found that snow presents a purely resistive medium depicting a non-linear voltage and current characteristics. A typical example can be found in Figure 4.8.

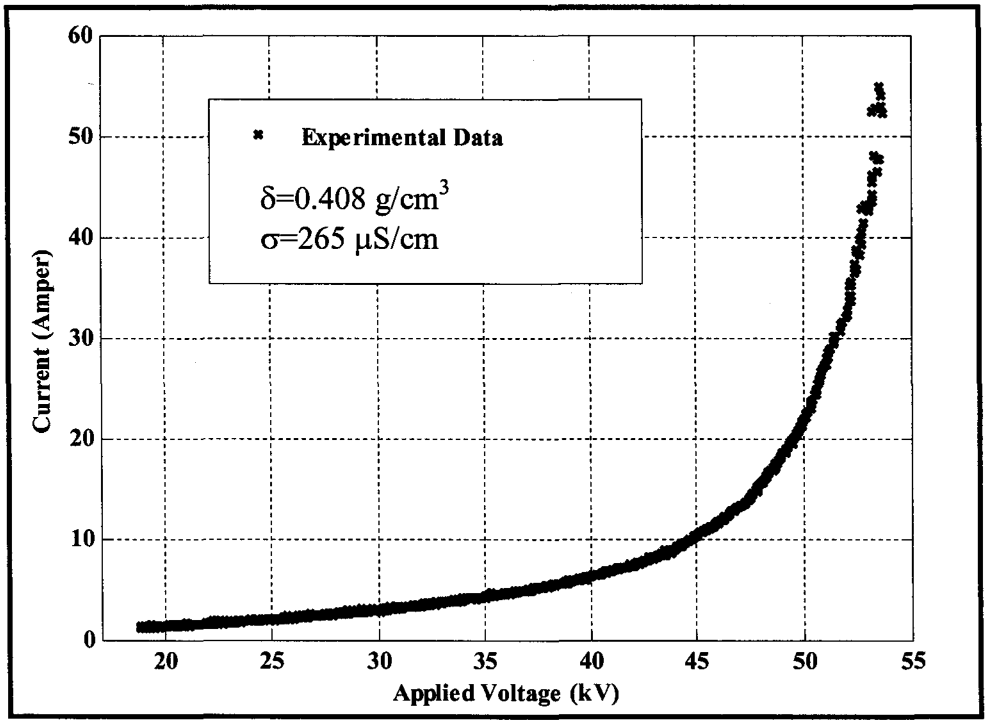



**Figure 4.8:** A typical example of voltage-current characteristic of snow covered insulator

In this Figure, it is shown that when the voltage across snow increases linearly, the current flowing through it increases exponentially. This means that when the voltage across snow increases, its resistance decreases rapidly. This behavior is depicted in Figure 4.9 for a snow density of $0.41 g/cm^3$ and a conductivity of water melted from snow equal to 265 µS/cm. It may be observed that the relationship between snow resistance per unit length and the applied voltage is linear and may be approximated by the following relation:

$$R = \alpha(\delta,\sigma).V + \beta(\delta,\sigma)\Big|_{\substack{\delta=0.41 \\ \sigma=265}} \Rightarrow R = -0.04V + 2.2 \qquad (4.25)$$

where R is the resistance of snow in MΩ/cm, V is the applied voltage in kV, α and β are constants depending on the snow density and conductivity of water melted from snow.

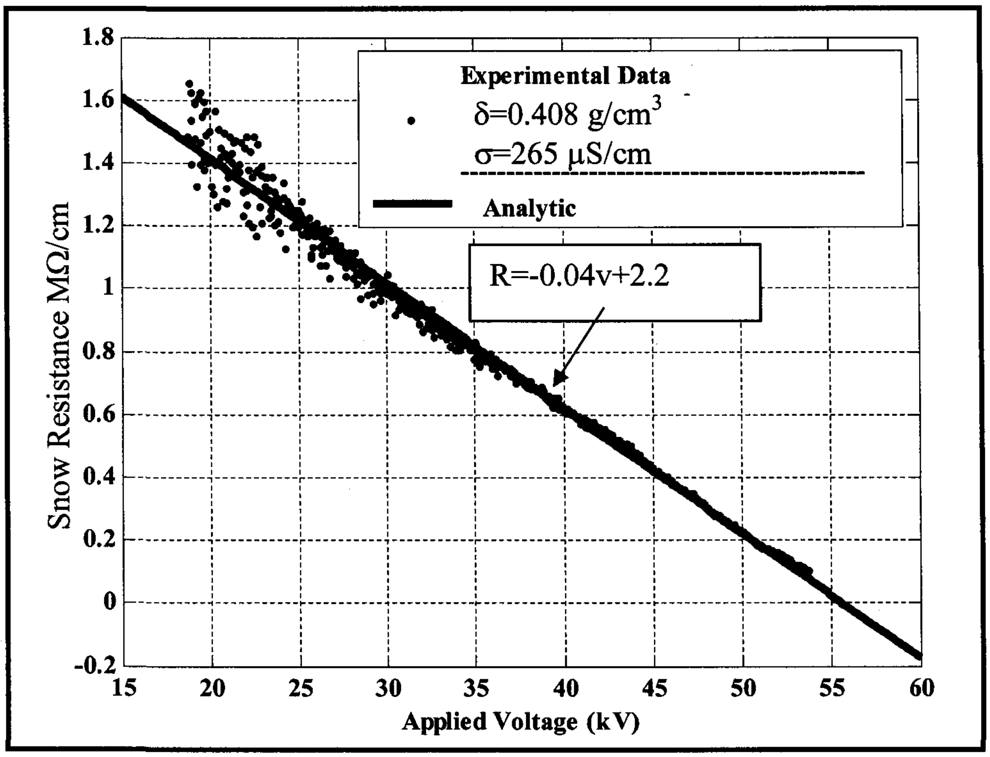
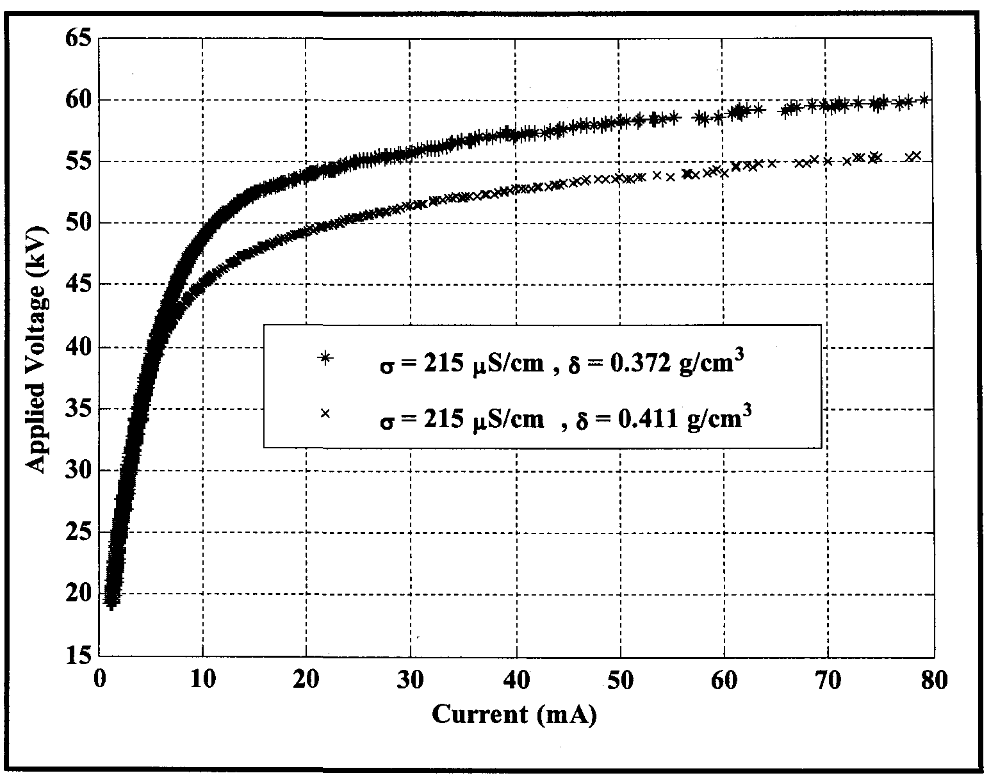



**Figure 4.9:** Evolution of the snow resistance as a function of the applied voltage

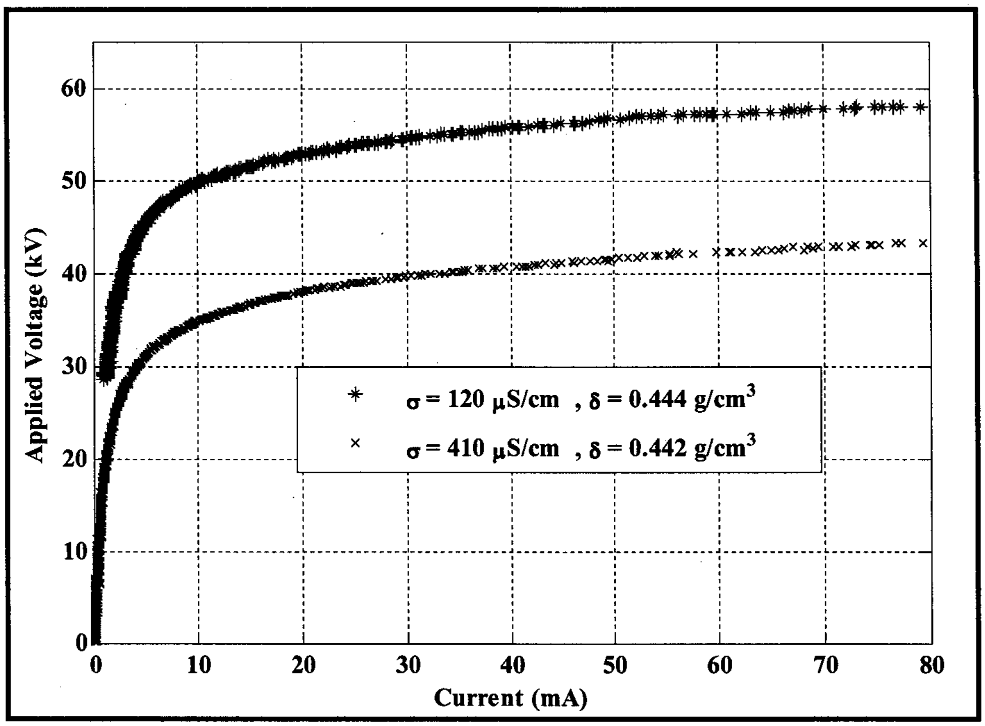
It should be pointed out that the control and adjustment of snow density and melted water conductivity for each test was not an easy matter. Moreover, the estimation of snow resistance as a function of applied voltage was very sensitive to these parameters.

### 4-5-2 Analytic model of the V-I characteristics of snow

The voltage-current characteristics of snow were highly affected by the density and conductivity of snow. As mentioned above, it was difficult to control and adjust these parameters to the desired test values. Experiments were therefore performed for various values of density and conductivity. Figure 4.10 shows the voltage-current characteristics of snow for two values of density as well as for two different values of conductivity of water melted from snow. It can be observed that the variation of density and conductivity has a considerable effect on the resistance characteristics of snow. Even though it was not possible to adjust the density/conductivity as a constant parameter in tests, the experimental results show that an increase in either the density of snow or the conductivity of water melted from snow decreases its electric resistance. For a given applied voltage, a high current is therefore allowed to flow through snow.




(a)




(b)

**Figure 4.10:** Voltage as the function of current measured experimentally for snow samples having different density and conductivity.
a) Sample with similar conductivity b) Sample with similar density

A mathematical processing of the data allowed the establishment of a relationship between the voltage across snow and the current flowing through it within the framework of this experiment. Indeed, as shown in Figure 4.8, leakage current through snow may be expressed as an exponential function of voltage.

$$I = K_1 \exp(K_2 V) \qquad (4.26)$$

where V is the voltage in kV, I is the current in mA, and $K_1$ and $K_2$ are the constant coefficients depending on the snow characteristics and test object dimensions.

The evolution of voltage and current through snow can be predicted by relations 4.27 and 4.28.

$$V(t) = A.t.\sin(\omega t + \theta_0) \quad (4.27)$$

$$I(t) = B(e^{C.t} - 1).\sin(\omega t + \theta_0) \approx B.e^{C.t}.\sin(\omega t + \theta_0) \quad (4.28)$$

The peak values V and I of applied voltage and leakage current are expressed in kV and mA respectively, and are time-dependant and may be represented by the following relations:

$$V = A.t \quad \text{and} \quad I = B.e^{C.t} \quad (4.29)$$

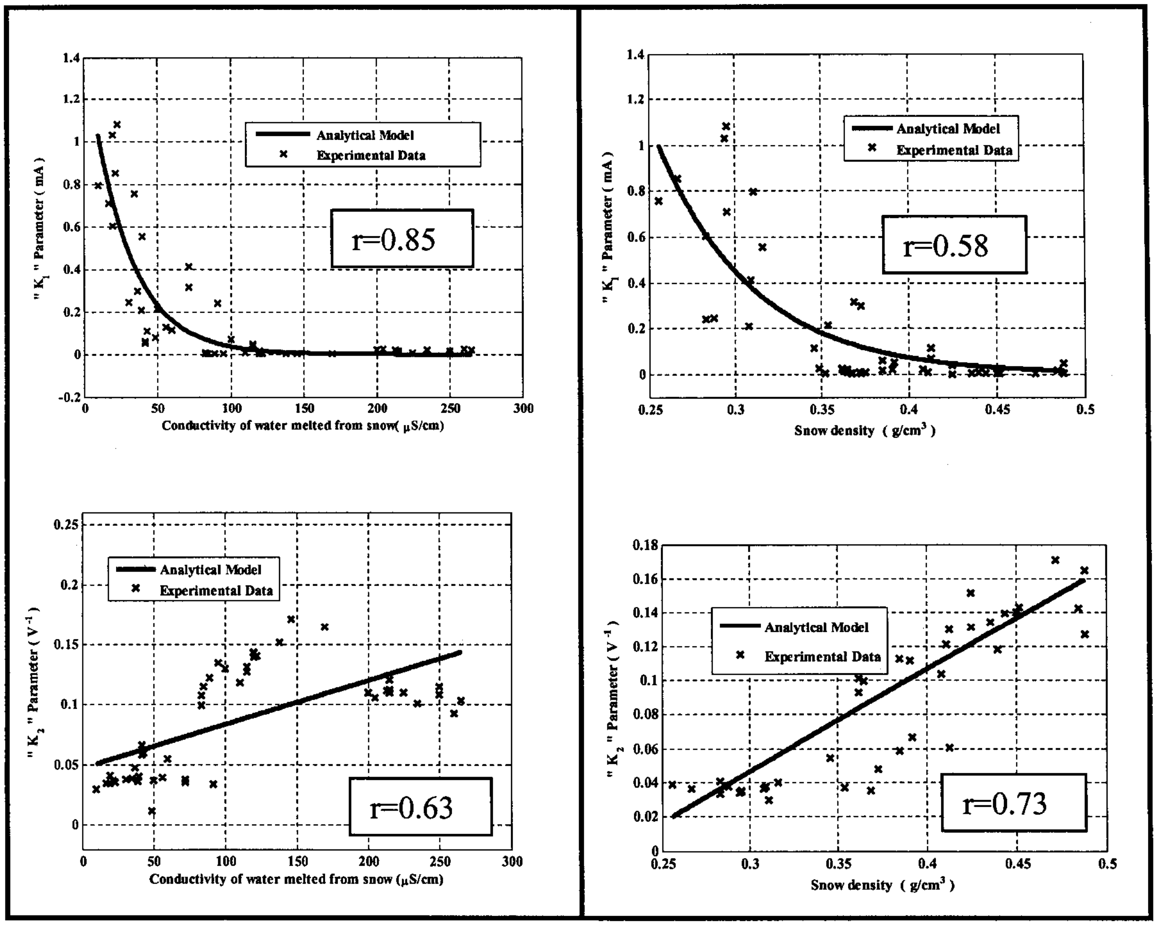
where A, B, and C are constants and depend on the density and the conductivity of water melted from snow. These constants, A, B, and C, are expressed in kV/s, mA, and $s^{-1}$ respectively.

Combining the two relations by eliminating the parameter t between V and I, it yielded $I = Be^{C\frac{V}{A}}$. The identification of this relation with Equation 4.26 allows the determination of the coefficients $K_1$ and $K_2$, that is:

$$K_1 = B \quad (4.30)$$

$$K_2 = \frac{C}{A} \quad (4.31)$$

In order to elaborate a precise model enabling the simulation of the leakage current inside snow, more than one hundred tests were performed. From the obtained results, all the voltage-current characteristics of snow were analyzed. For each voltage-current characteristic, the dates were fitted with Equation 4.26, and the coefficients $K_1$ and $K_2$ were determined. Figure 4.11 shows the dependence of these coefficients with the snow density and the conductivity of water melted from snow.




**a)** $K_1$ and $K_2$ as a function of conductivity **b)** $K_1$ and $K_2$ as a function of density

**Figure 4.11**: Evolution of the coefficients $K_1$ and $K_2$ as the function of the density and the conductivity of snow

From these Figures, it can be seen that coefficient $K_1$ can be fitted by an exponential function of snow density and conductivity of snow, but coefficient $K_2$ is very close to a linear function of these parameters. Thus, these coefficients can be modeled using relations 4.32 and 4.33.

$$K_1 = a_1.\exp(a_2\sigma) \equiv a_3.\exp(a_4 D) \tag{4.32}$$

$$K_2 = b_1 + b_2\sigma \equiv b_3 + b_4 D \tag{4.33}$$

Equations 4.32 and 4.33 can be rewritten as follows:

$$K_1 = \sqrt{a_1.a_3}.\exp(\frac{a_2}{2}\sigma + \frac{a_4}{2}D) \tag{4.34}$$

$$K_2 = \frac{b_1 + b_3}{2} + \frac{b_2}{2}\sigma + \frac{b_4}{2}D \qquad (4.35)$$

where $\sigma$ is the conductivity in $\mu S/cm$, D is the density in gr/cm$^3$, and the coefficients $a_{i=1-4}$ and $b_{i=1-4}$ are constants that are determined using the experimental data. The average values of these coefficients can be found in Table 4.3 and Table 4.4.

**Table 4.3:** Average values of the parameters, $a_1$, $a_2$, $a_3$ and $a_4$

| coefficient | $a_1$ [mA] | $a_2$ [cm /μS] | $a_3$ [mA] | $a_4$ [cm$^3$/g] |
|---|---|---|---|---|
| value | 1.504 | -0.03707 | 103.5 | -18.13 |

**Table 4.4**: Average values of the parameters, $b_1$, $b_2$, $b_3$ and $b_4$

| coefficient | $b_1$ [kV$^{-1}$] | $b_2$ [cm /μS] | $b_3$ [kV$^{-1}$] | $b_4$ [cm$^3$/g] |
|---|---|---|---|---|
| value | 0.04712 | 0.000363 | -0.1337 | 0.6 |

Introducing the values of coefficients $a_{i=1-4}$ and $b_{i=1-4}$, from tables 4.3 and 4.4 into relations 4.36 and 4.37, the coefficient $K_1$ and $K_2$ will finally be obtained as function of snow density and conductivity of water melted from snow.

$$K_1 = 12.477e^{-(0.0185\sigma + 9.065D)} \qquad (4.36)$$

$$K_2 = 0.0001815\sigma + 0.3D - 0.0433 \qquad (4.37)$$

Substituting coefficients $K_1$ and $K_2$ from equations 4.36 and 4.37 into Equation 4.26 gives Equation 4.38, which shows the general relation needed to simulate the leakage current through snow accumulated on insulator.

$$I = 12.477e^{(-(0.0185\sigma + 9.065D) + (0.0001815\sigma + 0.3D - 0.0433)V)} \qquad (4.38)$$

Figure 4.12 shows the comparison of voltage-current characteristics of snow obtained from relation 4.38 and the measured values deduced from Table 4.5 for snow having a density and conductivity of water melted from snow respectively equal to 0.367 g/cm$^3$ and 85 μS/cm. A good correlation is to be noticed between the predicted values and the experimental ones.

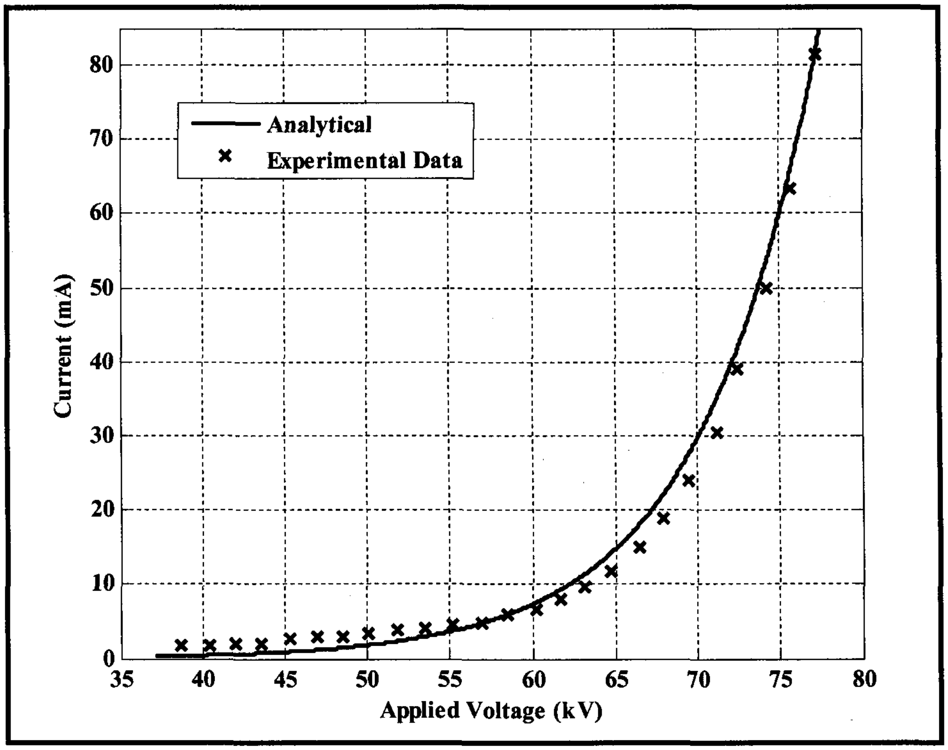
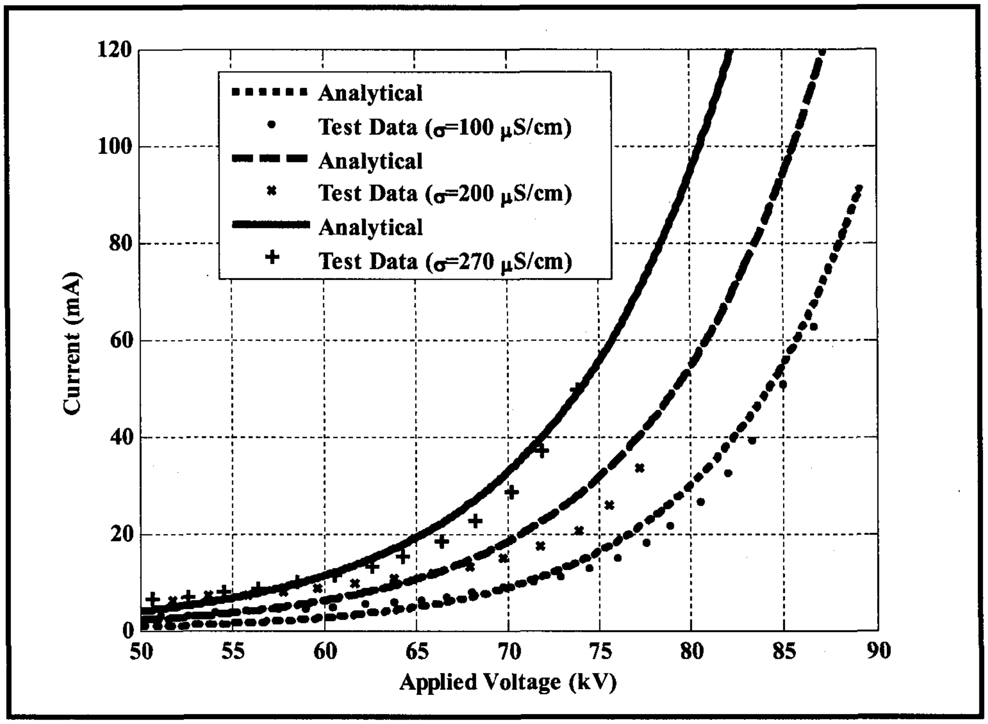
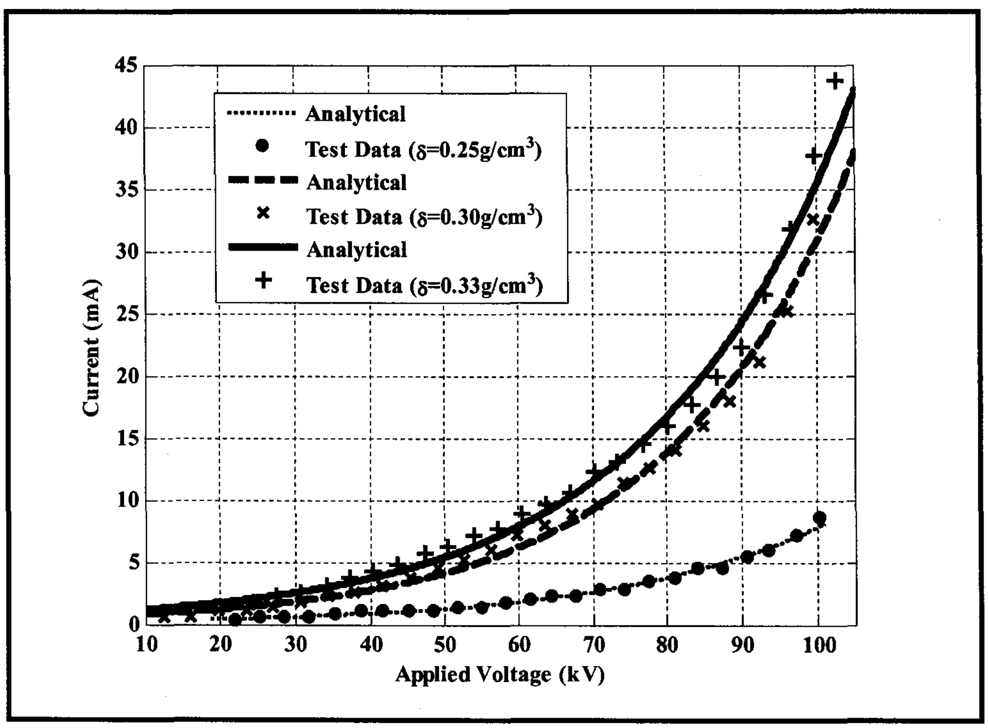



**Figure 4.12**: Comparison of voltage-current characteristic of snow covered insulator predicted by equation 4.38 with the experimental data (for a density equal to 0.367 g/cm$^3$ and conductivity of water melted from snow equal to 85 μS/cm)

Figures 4.13-a and 4.13-b depict the comparison of voltage-current characteristics of snow predicted by relation 4.38 and the experimental values for different snow densities and water melted conductivities.




a)




b)

**Figure 4.13**: Comparison of voltage-current characteristic of snow covered insulator predicted by equation 4.38 with the experimental data for different snow parameters

a) Effect of water melted from snow conductivity ($\delta$=0.25 g/cm$^3$)

b) Effect of snow density ($\sigma$=100 $\mu$S/cm)

**Table 4.5**: Peak values of applied voltage across snow and the current flowing through, for a density equal to 0.367 g/cm$^3$ and conductivity of water melted from snow equal to 85 μS/cm

| I [mA] | V [kV] | I [mA] | V [kV] | I [mA] | V [kV] |
|---|---|---|---|---|---|
| 1.7142 | 38.7055 | 4.5712 | 55.1230 | 14.8564 | 66.4660 |
| 1.9999 | 41.9890 | 4.8569 | 56.9140 | 18.8562 | 67.9585 |
| 2.5713 | 45.2725 | 5.9997 | 58.5060 | 23.9988 | 69.4510 |
| 2.8570 | 46.9640 | 6.5711 | 60.1975 | 30.5699 | 71.2420 |
| 3.4284 | 50.0485 | 7.9996 | 61.6900 | 39.1409 | 72.4360 |
| 3.7141 | 51.8395 | 9.7138 | 63.1825 | 49.9975 | 74.2270 |
| 3.9998 | 53.5310 | 11.7137 | 64.6750 | 63.4254 | 75.7195 |

From the results obtained, it can be seen that both the density and the conductivity of water melted from snow influence the leakage current. The results in their actual forms neither allow their direct influence to be quantified nor permit the parameter that has the highest influence on the leakage current to be identified. In this connection, it is important to know the increasing rate of those parameters on the leakage current by defining the three increasing rates as follow:

$$\text{Av.}(\Delta I)=\text{average}\ \{\frac{\Delta I}{I_0+\Delta I}\times 100\}\ (\%) \qquad (4.39)$$

$$\text{Av.}(\Delta \sigma)=\text{average}\ \{\frac{\Delta \sigma}{\sigma_0+\Delta \sigma}\times 100\}\ (\%) \qquad (4.40)$$

$$\text{Av.}(\Delta \delta)=\text{average}\ \{\frac{\Delta \delta}{\delta_0+\Delta \delta}\times 100\}\ (\%) \qquad (4.41)$$

The combination of these equations with Equation 4.38, allows the leakage current increasing rate as a function of the density and the conductivity of water melted from snow to be quantified. The results are presented in Figure 4.14. From this Figure, it can be seen that an increase in the conductivity of water melted from snow has more effect on leakage current when compared to snow density.

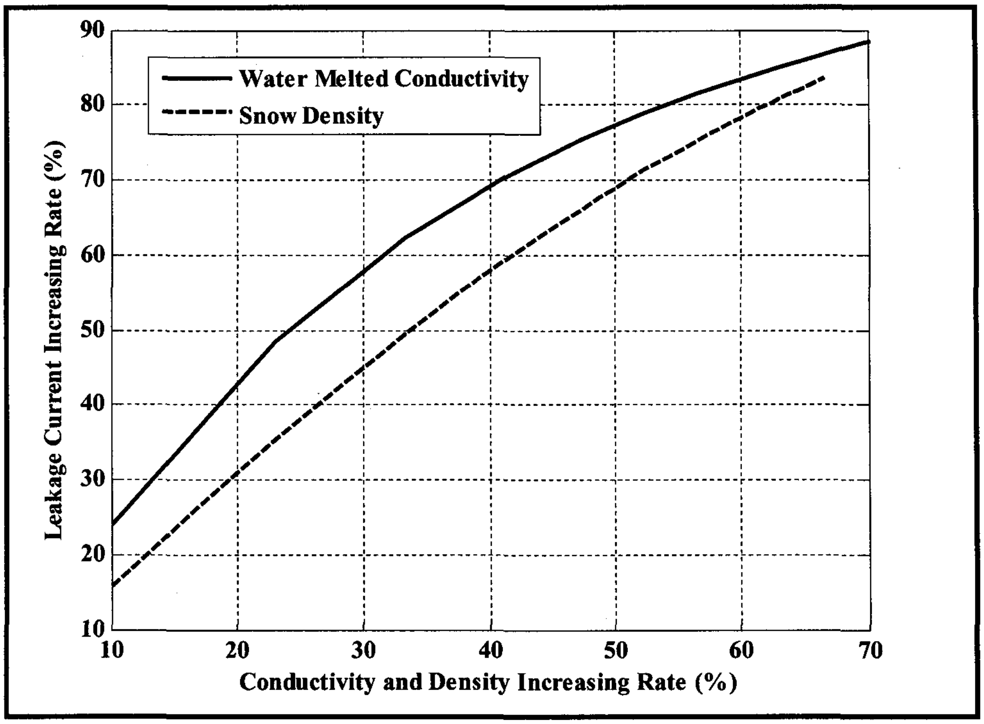



**Figure 4.14**: Comparison of the effect of snow parameters increasing rate on the leakage current.

## 4-6 Summary

The main objective of this chapter was to quantify the snow residual resistance and also to study the electrical behavior of snow. In this regard, a series of tests were carried out and the results obtained analyzed. The applied voltage and leakage current flowing through it were recorded and analyzed. From the results obtained, the following conclusions may be drawn:

- Some analytical relationships between the equivalent volume conductivity $\gamma_e$ and $\delta$ and $\sigma$ were established, considering different current distribution profiles.
- Some equations expressing the residual snow resistance were derived.

- The voltage across snow and the leakage current flowing through the snow-covered insulator are almost in the same phase, within 2 degrees. This means that an insulator covered with snow acts as a pure resistance.

- The resistance of snow is not linear, as it decreases when the voltage across snow increases.

- Experimental results allowed the establishment of an analytical model to simulate the leakage current of snow-covered insulators. This model shows that the current flowing through the snow 'I' depicts an exponential relation with the applied voltage 'V'.

- It is shown that an increase in the density of snow and/or the conductivity of water melted from snow increases the current flowing through the snow. It is due to the increase of electric conductivity of snow which is extremely affected by the applied voltage.

- The increasing rate of leakage current through snow is more sensitive to the conductivity of the water melted from snow in comparison to the snow density. It was also found to be extremely dependent on the electric field over the snow sample.

- The voltage-current characteristics of snow predicted by the proposed analytical model were found to be in good agreement with those obtained experimentally. The proposed model also allowed the prediction of the leakage current of snow for the various densities, as well as for various conductivities of water melted from snow. The proposed models give little insight into the design parameters and characteristics which are necessary to assure reliable operation.

# CHAPTER 5:

# CHARACTERISTICS OF FLASHOVER ARC ON SNOW-COVERED INSULATORS

## 5-1 Introduction

Many researchers have measured the arc characteristics on polluted/ice surfaces as described in Chapter 2. Various values for A and n have been summarised. From these studies, local arc voltage was found to be influenced not only by the arc current, but also by other environmental conditions, such as the surrounding air humidity, air pressure, and type of voltage [3, 21, 23, 38, 40, 41, 50, 51, 52, 53].

As described in Chapter 2, flashover on snow-covered insulator surfaces is the process of local arc propagation in air gaps and inside snow. The determination of local arc characteristics in both media is of great importance for the modelling of electrical arcs on snow-covered insulator surfaces. Arc constants for ice surfaces were not known until research at UQAC demonstrated therein. The characteristics of local arc on ice surfaces were measured at the UQAC high-voltage laboratory [25, 37, 72, 73], taking into consideration the influences of environmental conditions, such as ice surface conditions and type of voltage, on local arc characteristics. To the best of our knowledge, arc constants inside wet snow have never been determined. In the present study, arc constants were measured directly on a snow tubing physical model under ac voltages. Such investigations will be of great importance in increasing the reliability of insulators, and finally closing some major gaps in the existing knowledge of snow-covered insulator surface flashover.

## 5-2 Arc constant measuring method

A snow-covered actual insulator presents a complex geometry, which makes it difficult to determine arc characteristics. Therefore, a simplified physical model was considered for the present study. For the purposes of arc modeling, similar studies, performed on polluted or ice surfaces, used triangular samples [3, 25, 74, 75]. Since, for an insulator covered with snow, the arc propagates inside the snow, a different physical model, shown in Figure 5.1, has been used for the present study.

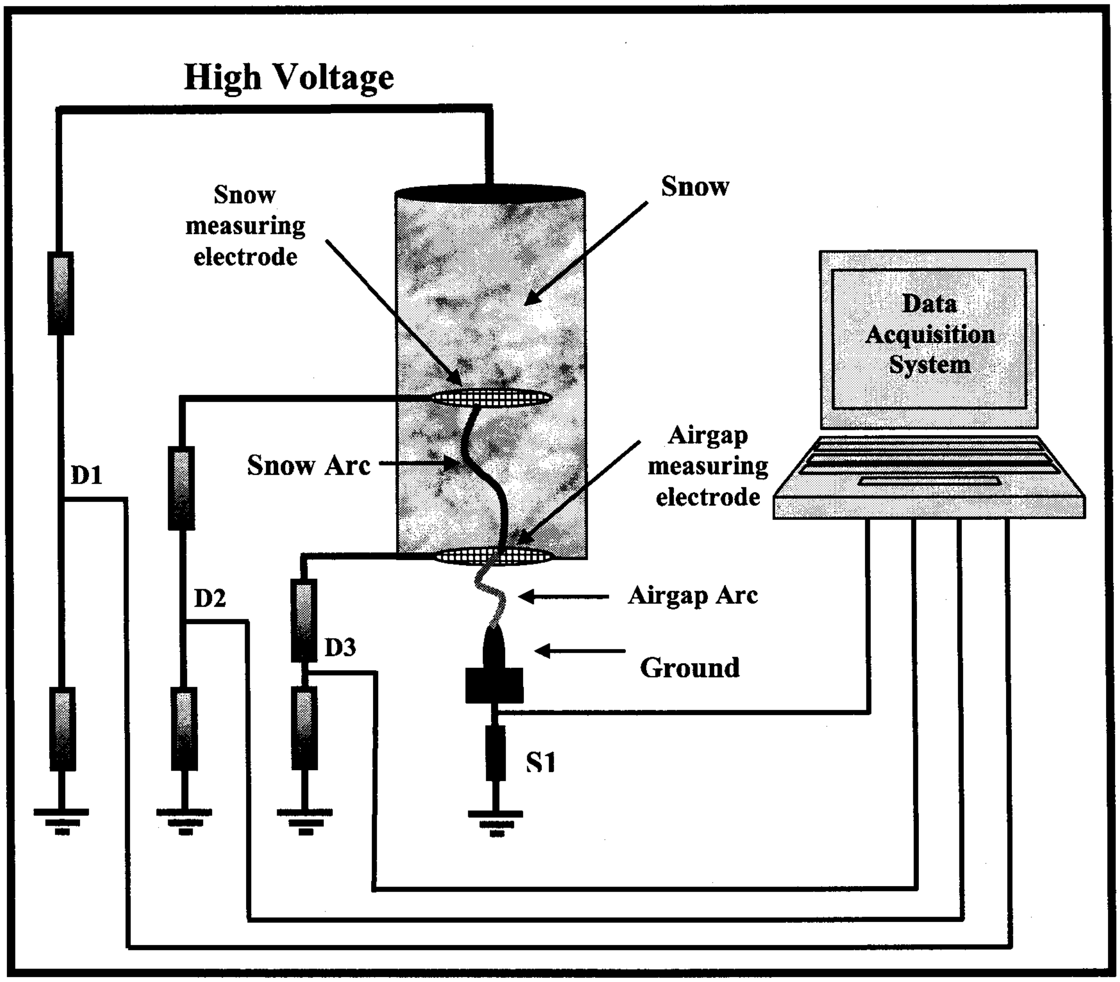



**Figure 5.1:** Sample and test circuit to determine of static arc constants. D1, D2, D3—Voltage divider; S1—Current shunt.

The height and diameter of the glass tubing are 30 cm and 11.4 cm respectively. Snow samples were formed by filling glass tubing with snow in a cold chamber at –12°C. The geometry of the snow sample and the electrode size ensure the formation of a single local arc in the central region of the model, facilitating the measure of the voltage drop across the arc. To determine the arc constants, a series of tests were carried out on the physical model. After the formation of the snow sample, the airgap-measuring electrode and snow-measuring electrode were adjusted to certain positions corresponding to the desired arc length in airgap or snow sample. The snow sample was changed for further measurement with a different position of the measuring electrodes. The length of the arc was adjusted to vary between 0.5 and 4 cm for airgap and 1 to 7 cm for snow.

A single-phase test voltage transformer of 120 kV (maximum), 240 kVA and 60 Hz was used, as well as a regulator to vary the output voltage from 0-120 kV. The voltage was increased either manually or automatically at an approximately constant rate of 3.9 kV/s. The overall short-circuit current of the HV system was about 28 A at the maximum operating voltage of 120 kV rms.

For each arc length chosen, x, the applied voltage, $V_1$, the voltages on the measuring electrodes, $V_2$ and $V_3$, and the leakage current, I, were recorded simultaneously using a Data Acquisition System (DAS). A LabVIEW graphical software program was used to acquire high quality data. The voltage signal was attenuated by using a capacitive voltage divider. The current signal was transferred to a voltage signal using a low-resistance shunt of 10 Ω. The test signals were connected to a measuring set through a conditioning box providing protection and insulation. A NI-DAQ device, model PCI-6035E, was used for this purpose. This data acquisition system (DAS) sampling rate was between 2400 - 7200 samples/min.

## 5-3 Analysis of the Results

The typical waveforms are shown in Figures 5.2 and 5.3.

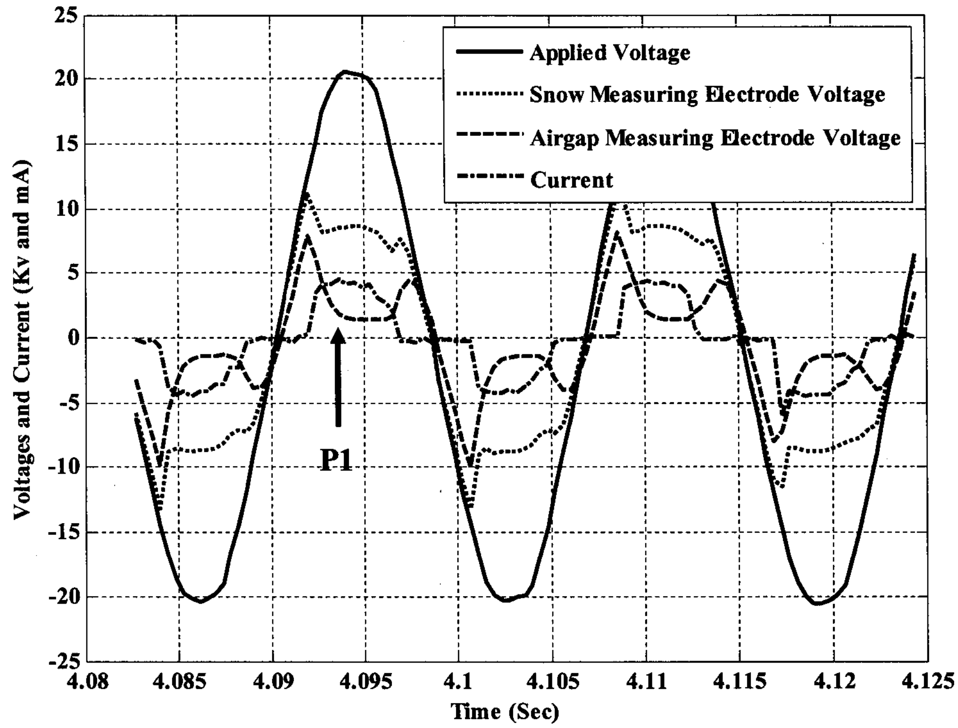



**Figure 5.2:** Typical waveforms on time the arc occurs in air gap.

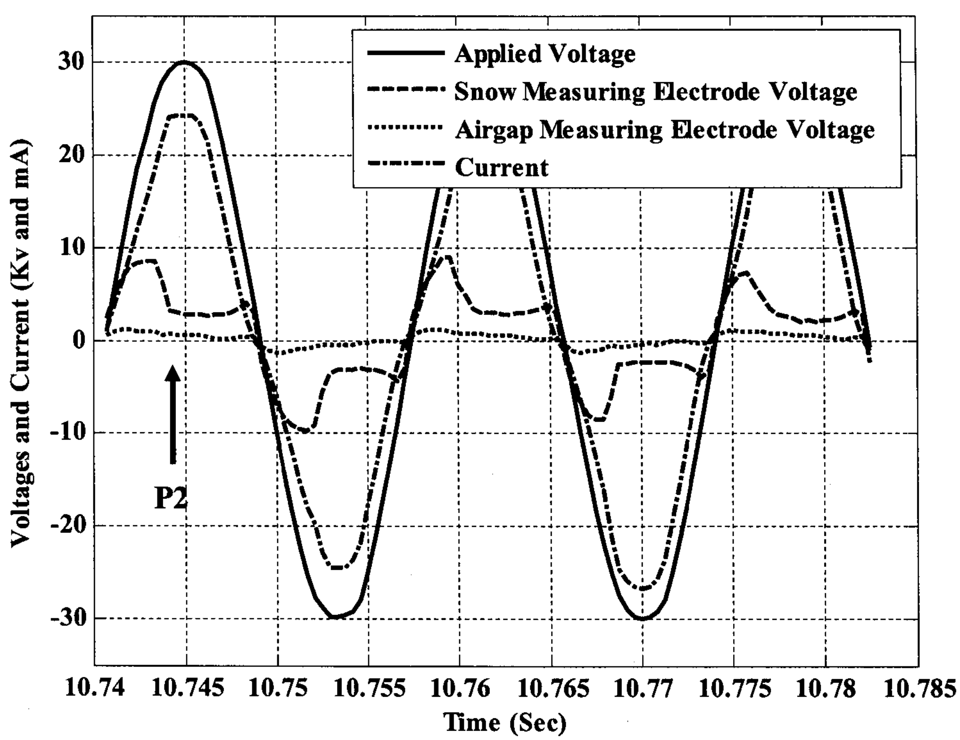



**Figure 5.3:** Typical waveforms on time the arc reaches to measuring electrode inside snow.

From Figure 5.2, it can be observed that, when the leakage current is very low, the measuring electrode voltage increases as the applied voltage increases. This behavior is observable up to the inception of an arc in the air gap.

When the applied voltage reaches a certain value, an arc occurs in the air gap. Because of the ensuing short circuit, the measuring electrode voltage drops suddenly. From point $P_1$ (Figure 5.2), the leakage current starts to increase following the applied voltage curve shape. If the applied voltage is increased at a constant rate, the arc reaches the airgap measuring electrode after several periods. When the arc reaches the airgap measuring electrode, its voltage drops suddenly (point $P_1$ in Figure 5.2), and the airgap measuring voltage is equal to the arc voltage of the airgap. Due to the descending V-I arc characteristics [76], the lowest value of the measuring electrode voltage is near the current peak value. It can be clearly seen that the same phenomena occur in Figure 5.3 for an arc voltage inside snow from point $P_2$ (Figure 5.3). When the applied voltage increases again, an arc propagates up to the snow-measuring electrode. At the time the arc reaches this electrode, its voltage drops suddenly and the snow-measuring electrode voltage equals the arc voltage of airgap and snow. At this time, the airgap-measuring electrode is measurable and has low value. Determining arc drop voltage inside snow is possible by deducing arc voltage the airgap measuring electrode from arc voltage at the snow-measuring electrode.

### 5-3-1 A and n parameters in airgap

In order to determine the arc constants in the airgap, several tests were carried out under various conditions and various airgap snow ratios. The conductivity of water melted from snow was modified by spraying the snow with salted water. Snow density was adjusted by compressing the snow. To reduce inhomogeneity due to uni-axial compression, the snow sample was subjected to a multi-axial compression on the glass tubing structure so as to obtain a uniform snow density between the electrodes as well as the desired snow density. Considering these procedures, it is understandable that it was difficult to precisely achieve predetermined values for σ and δ. From Equation 4.1, voltage drop across the arc in airgap is given by:

$$V_{arc} = A_a x_1 I_m^{-n_a} \tag{5.1}$$

The average voltage gradient ($E_{arc}$) of the arc is:

$$E_{arc} = \frac{V_{arc}}{x_1} \tag{5.2}$$

After combining the above equations, the E-I characteristics of the arc can be expressed as:

$$E_{arc} = A_a I_m^{-n_a} \tag{5.3}$$

The results corresponding to airgap arc characteristics are presented in Figure 5.2. The arc constants, $A_a$ and $n_a$, can be determined by using regression analysis on the test results [3, 21, 24, 25] as shown in Figures 5.4, 5.5.

The voltage gradient of the arc ($E_{arc}$) as a function of the current peak value ($I_m$) can therefore be approximated by the following equation:

$$E_{arc} = 100.25 I_m^{-0.6577} \tag{5.4}$$

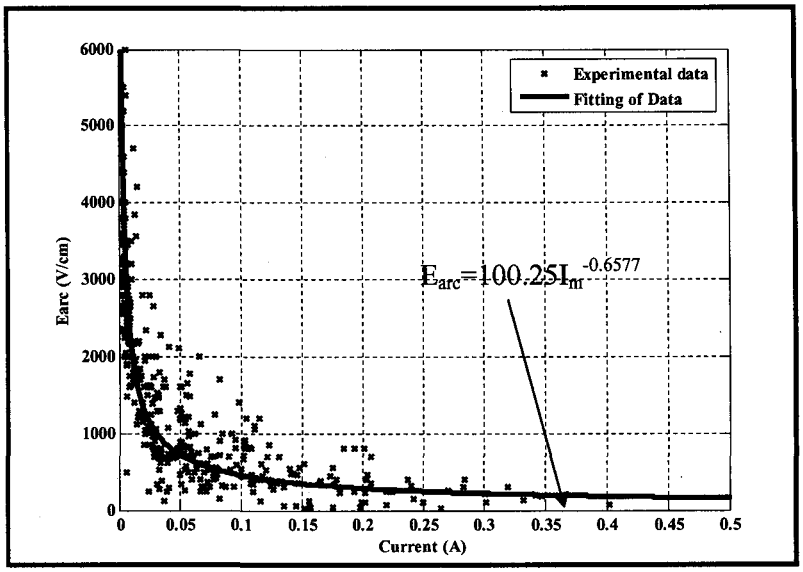



**Figure 5.4:** E-I characteristics of arc in airgap for all airgap distances

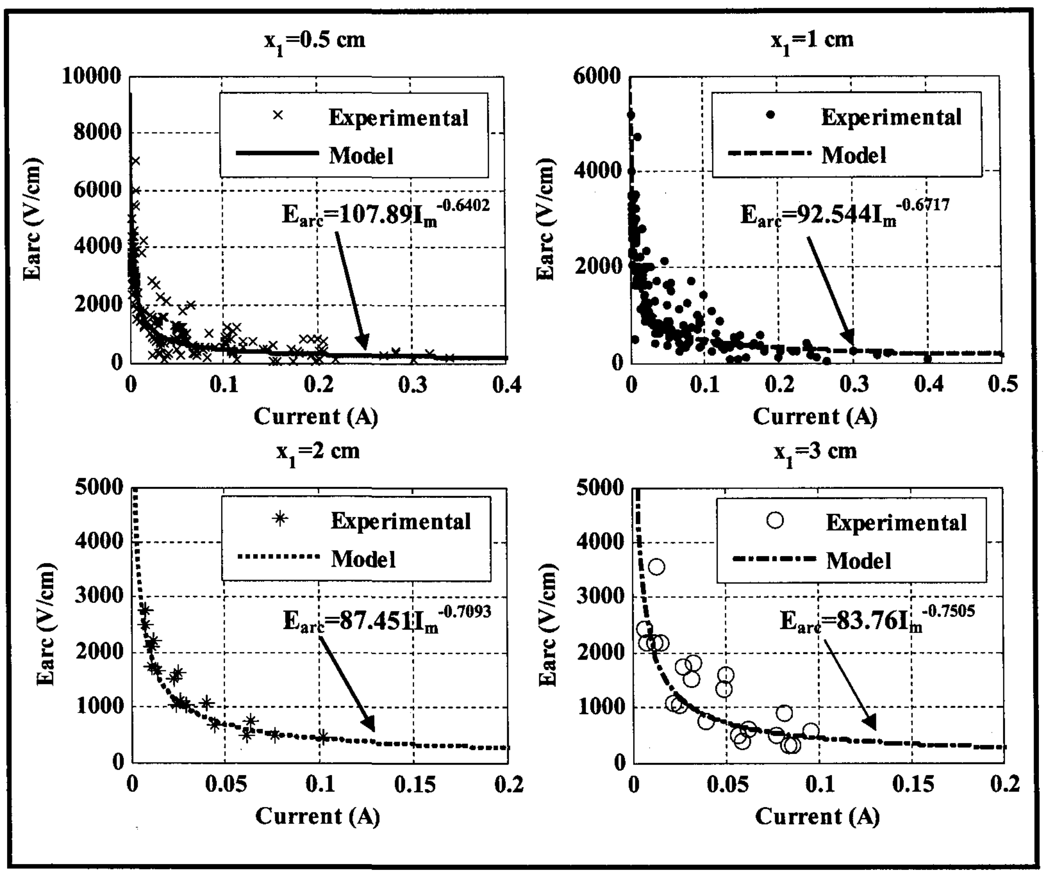



**Figure 5.5:** E-I characteristics of arc in air for different airgap distances

The values of parameters $A_a$ and $n_a$ are different from those determined for flashover on ice surfaces, which is A = 204.7 and n =0.5607 [3, 25]. The divergence obviously arises from the difference in the propagation medium. Indeed, a survey of the literature shows that the values of $A_a$ and $n_a$, as measured or utilized by different investigators, vary over a wide range for different types of arc as shown in Table 2.3. These values depend on various parameters, including the arc propagation medium [35, 42].

Figure 5.4 shows the arc constants $A_a$ and $n_a$ for airgap length in the presence of snow that can be obtained by using regression of experimental results ($A_a$=100.25 and $n_a$=0.6577). Figure 5.5 shows the effect of arc length on the $A_a$ and $n_a$ parameter in the airgap. The results obtained from the regression are summarized in Table 5.1.

**Table 5.1:** Effect of arc length on the arc constants in airgap

| Airgap Arc Length $X_l$ (cm) | $A_a$ | $n_a$ |
|---|---|---|
| 0.5 | 107.89 | 0.6402 |
| 1 | 92.544 | 0.6717 |
| 2 | 87.451 | 0.7093 |
| 3 | 83.76 | 0.7505 |

As shown in Table 5.1, arc constants $A_a$ and $n_a$ vary with arc length. When the arc length increases, $A_a$ decreases, while $n_a$ increases. This may be due to the fact that the voltage drop on the electrodes is neglected [25].

### 5-3-2 A and n parameters inside snow

In order to determine the arc constants inside snow, the voltage drop on the arc inside snow was determined by deducing the airgap-measuring electrode voltage from snow-measuring electrode voltage (Figure 5.3). The voltage drop across the arc inside snow is then deduced from Equation 4.1:

$$V_{arc} = A_s x_2 I_m^{-n_s} \tag{5.5}$$

The average voltage gradient ($E_{arc}$) of the arc is:

$$E_{arc} = \frac{V_{arc}}{x_2} \tag{5.6}$$

After combining the above equations, the E-I characteristics of the arc can be expressed as:

$$E_{arc} = A_s I_m^{-n_s} \tag{5.7}$$

The results corresponding to snow arc characteristics are presented in Figure 5.2. The arc constants, $A_s$ and $n_s$, can be determined by using regression analysis on the test results [3, 21, 24, 25] as shown in Figures 5.6 and 5.7.

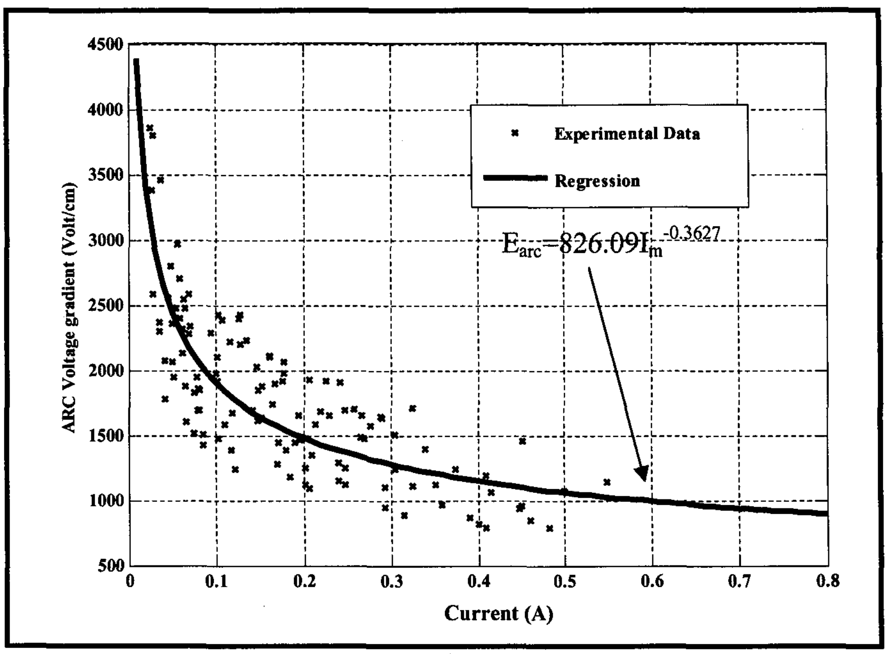



**Figure 5.6:** E-I characteristics of arc inside snow airgap for all snow measuring electrode distances

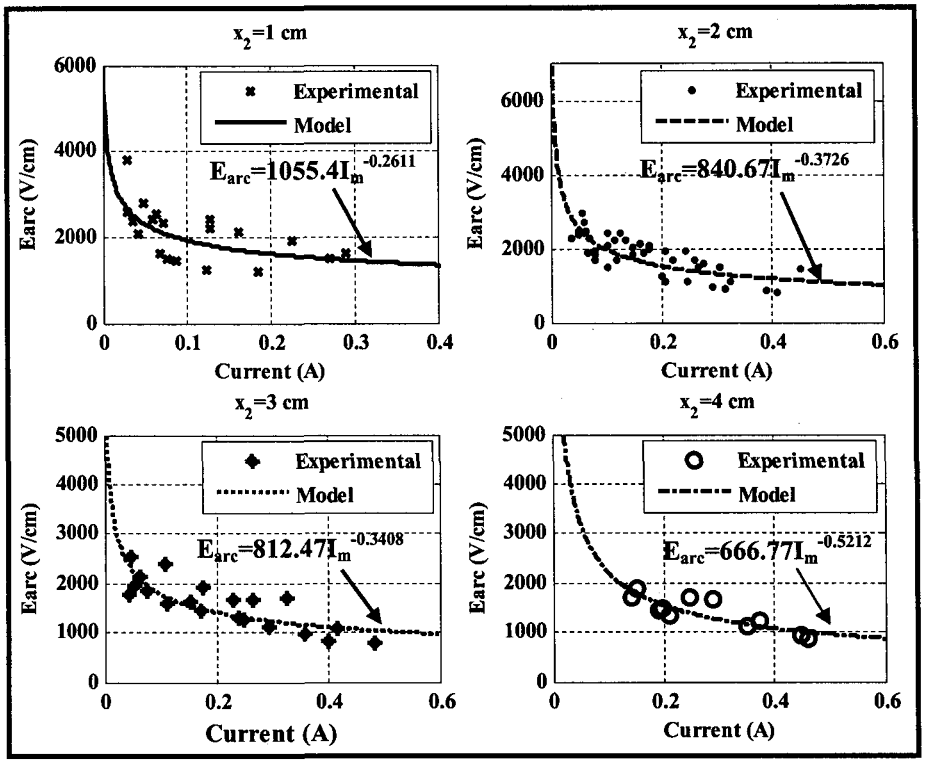



**Figure 5.7:** E-I characteristics of arc inside snow for different arc length.

The voltage gradient of the arc ($E_{arc}$) as a function of the current peak value ($I_m$) can be approximated by the following equation:

$$E_{arc} = 826.09 I_m^{-0.3627} \qquad (5.8)$$

Figure 5.6 shows the arc characteristic for an arc propagating inside snow sample. The constants, $A_s$ and $n_s$, are obtained by using regression of experimental results ($A_s$=826.09 and $n_s$=0.3627). Figure 5.7 shows the effect of arc length on the $A_s$ and $n_s$ parameter inside snow. The results obtained from the regression are summarized in Table 5.2.

**Table 5.2:** Effect of arc length on the arc constants inside snow

| Snow Arc Length $X_2$ (cm) | $A_s$ | $n_s$ |
|---|---|---|
| 1 | 1055.4 | 0.2611 |
| 2 | 840.67 | 0.3726 |
| 3 | 812.47 | 0.3408 |
| 4 | 666.77 | 0.5212 |

As seen in Table 5.2, the arc constants, $A_s$ and $n_s$, vary with arc length. When the arc length increases, $A_s$ decreases, while $n_s$ increases .

### 5-3-3 K and b parameters

The arc re-ignition condition is expressed by Equation 4.3. This equation shows that, under critical conditions, for a certain peak value of both applied voltage and current, the length of arc can reach x cm. In order to obtain the re-ignition constants $k_{as}$ and $b_{as}$, some tests were carried out, and the peak values of applied voltage ($V_m$) and current ($I_m$) were recorded. The point $P_2$ (Figure 5.3) depicts this situation. The results are shown in Figure 5.8. From these results, the re-ignition constants are determined: $k_{as}$ = 6.3663 and $b_{as}$ = 0.4855. Index "*as*" is used to specify the relevancy of these parameters with regards to airgap and snow at the same time. The re-ignition condition (Equation 4.3) can therefore be expressed as following equation:

$$V_m \geq \frac{6.3663\,x}{I_m^{0.4855}} \tag{5.9}$$

where $V_m$ is peak value of applied voltage in kV, $I_m$ is current in A and x is arc length in cm.

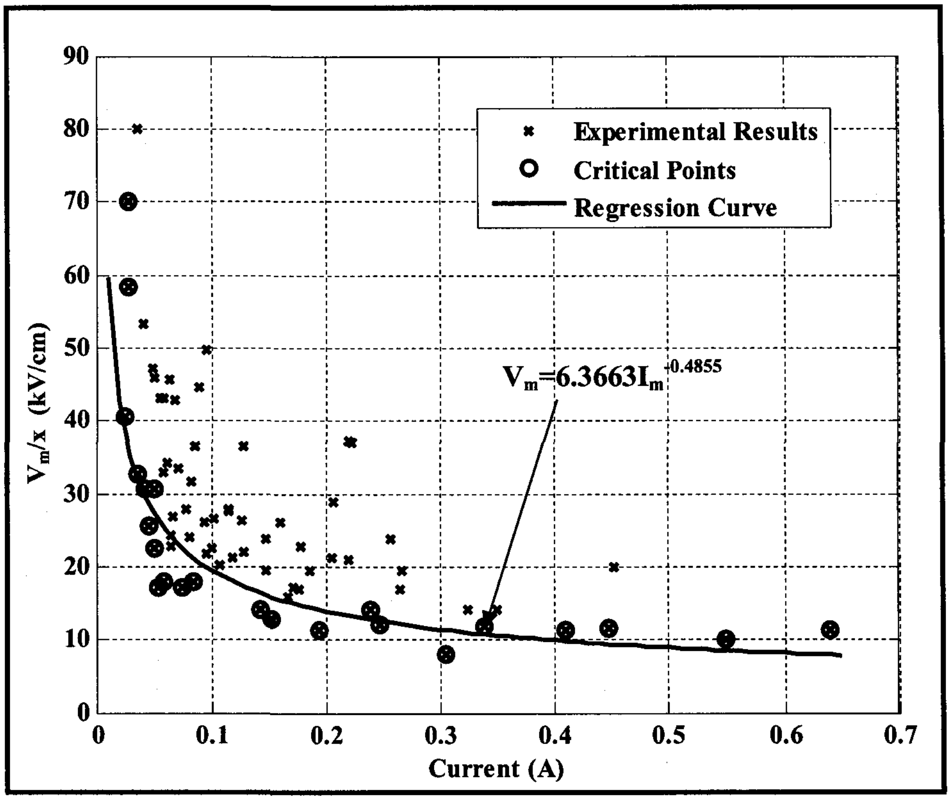



**Figure 5.8:** Measured results for re-ignition condition.

## 5-4 Summary

Experiments have been carried out to study the behavior of an electric arc inside wet snow. Also, the electrical behavior of arc has been studied for airgap in series with snow and inside of snow. From the results obtained, the following conclusions may be drawn:

- The voltage gradient of the arc in airgap as a function of leakage current can be modeled using the following equation:

$$E_{arc} = 100.25 I_m^{-0.6577}$$

- In the case of an arc propagating inside snow, the voltage gradient of the arc ($E_{arc}$, in V/m) as a function of the current peak value ($I_m$, in A) can be expressed by the following equation:

$$E_{arc} = 826.09 I_m^{-0.3627}$$

It can be seen that the constants of an arc propagating inside wet snow are different from those obtained for an arc propagating on an ice surface [25], indicating the role and importance played by the propagation medium.

- The re-ignition condition of the arc under ac voltage was determined experimentally. The re-ignition condition can be expressed by an equation of the arc peak value of applied voltage ($V_m$, in V) and the arc length (x, in cm) and the peak value of leakage current ($I_m$, in A):

$$V_m \geq \frac{6.3663\,x}{I_m^{0.4855}}$$

# CHAPTER 6:

# ANALYSIS OF THE EXPERIMENTAL DATA AND VALIDATION OF THE PROPOSED MODEL

## 6-1 Introduction

Various experimental tests were carried out in the CIGELE cold chamber in order to validate the static model developed and discussed in the preceding chapters.

First of all, this chapter will provide an overview of the experimental set-up and the instruments involved in the tests carried out to validate the static model. Then, the flashover of an EPDM suspension insulator covered with snow will be analyzed using the mathematical model established in the last chapter.

Natural conditions were simulated as closely as possible by depositing artificially the natural snow on the real insulators.

The density of snow was adjusted to between 0.25 and 0.488 $g/cm^3$ and the water melted from snow conductivity was adjusted to between 260 and 515 μS/cm.

Because of the limitation of the applied voltage, airgap was considered to be zero, and so to speak, complete snow accumulation condition was considered.

## 6-2 Assessment of flashover voltage inside snow

The model was applied to an EPDM suspension insulator covered with snow as shown Figure 6.1 and then the flashover voltages calculated from this model were validated by the experimental results.

Figure 6.2 shows the schematic diagram of the experimental setup, which consists of a 350 kV AC high voltage system and a vertical circulation climate room with sliding roof, which makes possible not only very realistic simulations of different types of atmospheric ice, but also the collection of natural cold precipitation, snow in particular.

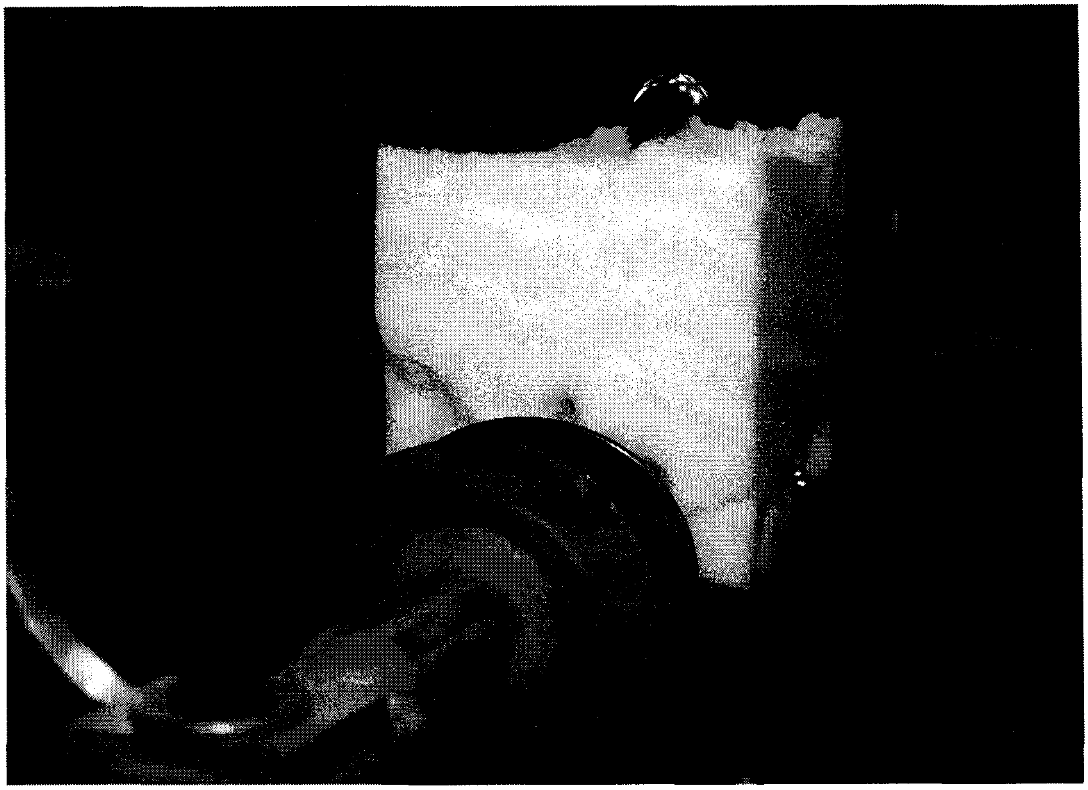


**Figure 6.1:** An example of EPDM insulator artificially covered with snow

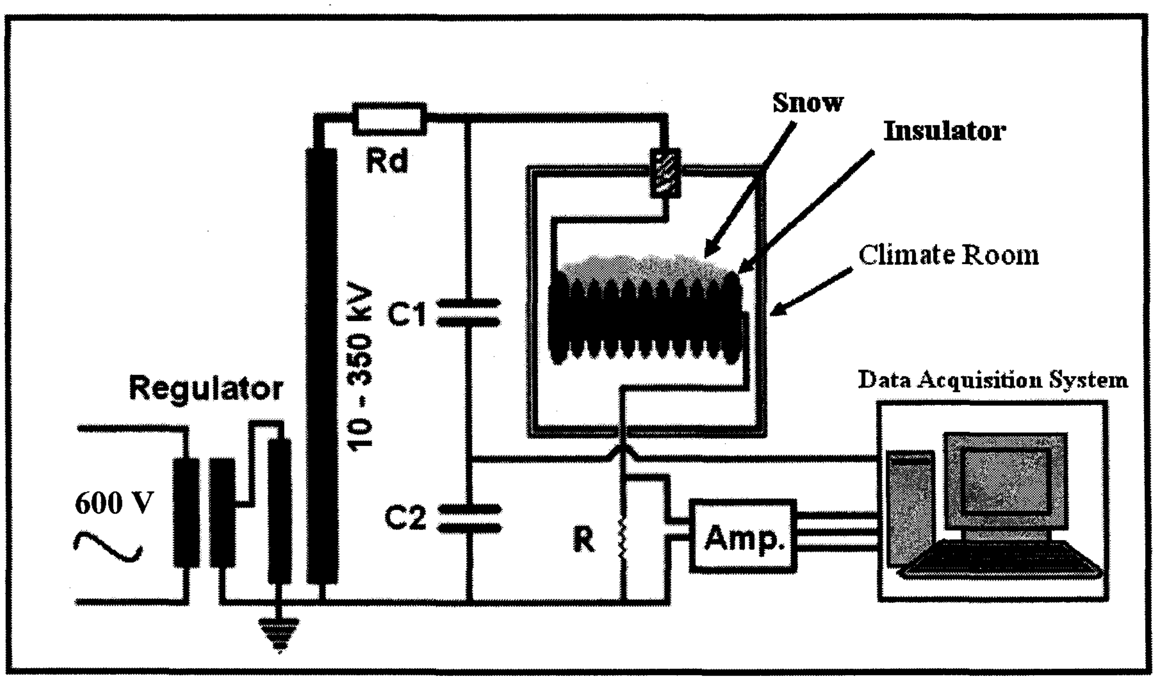



**Figure 6.2**: Overview of experimental setup (Evaluation of the model)

Natural snow was collected from the area surrounding the laboratory and deposited manually on the horizontal insulator, where its density and impurity were controlled and measured.

To cover the insulator with snow, the natural salt-contaminated snow is compressed using a custom-made frame, removed before voltage is applied. The conductivity of water melted from snow was modified by spraying the snow with salted water and the snow density was adjusted by compressing the snow.

In order to have, a general model, a combined relation between $\gamma$, $\sigma$ and $\delta$ has to be derived. The relations to be combined are described in equations 4.15 and 4.23 depicted in Chapter 4; the derived relationship of the equivalent conductivity as a function of snow density and conductivity of water melted from snow is presented in Equation 4.24.

Figure 6.3 shows the schematic sketch of residual resistance calculation for modeling; the leakage current is considered to be distributed in pyramidal shape.

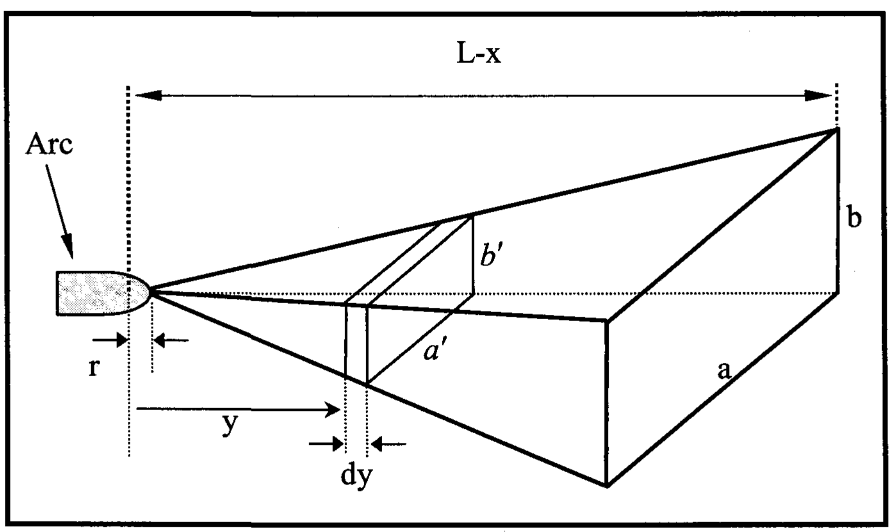



**Figure 6.3**: Snow residual resistance calculation diagram

From this figure, the residual resistance can be expressed as follow:

$$R_S(X) = \int_r^{L-x} \frac{1}{\gamma_e} \cdot \frac{dy}{a' \cdot b'} \qquad (6.1)$$

From Thales geometric relationship, we derived:

$$\frac{a' \cdot b'}{a \cdot b} = \left( \frac{y}{L-x} \right)^2 \qquad (6.2)$$

By substituting the relation 6.2 into the equation (6.1), it yields:

$$R_S(X) = \frac{(L-X)^2}{\gamma_e \cdot a \cdot b} \left( \frac{1}{r} - \frac{1}{L-X} \right) \qquad (6.3)$$

where X, is the arc length in cm, $\gamma_e$ is snow equivalent conductivity in µS/cm, a, b and L are deposited snow dimensions on the insulator in cm and r is arc radius in cm which, can be determined from relation as bellow [24, 26]:

$$r = \sqrt{\frac{I_m}{2.439\pi}} \qquad (6.4)$$

where $I_m$ is the peak value of leakage current in mA.

### 6-2-1 Validation of the proposed model at -12 °C

A large number of flashover experiments were carried out under several snow conditions at -12 °C. The snow was collected from surrounding of laboratory and was stored in a refrigerator at -12 °C. The snow equivalent conductivity was therefore determined at -12 °C. This relation has been presented in the chapter 4 and has been used to determine the snow residual resistance by means of the relations 6.3.

The experimental results were obtained for snow density varying between "0.25 – 0.488" g/cm$^3$ and water-melted conductivity between "260 – 515" µS/cm. The test results as well as the results calculated from the mathematical model are shown in Figures 6.4 and 6.5. In order to have flashover, the applied voltage was increased linearly till a flashover occurred; accordingly these figures show the critical value of flashover voltages.

As already mentioned in chapter 4, it was very difficult to adjust the snow parameters. Figures 6.4 and 6.5 were obtained for the mean value of the snow parameters used in the experimental.

From Figures 6.4 and 6.5, it can be seen that there is a good agreement between the flashover voltages calculated from the model and those obtained from experiments in the laboratory.

Tables 6.1 to 6.6 summarize the results obtained experimentally as well as those computed from the mathematical model. It should be pointed out that, the flashover voltages have been computed by the model considering mean values of snow parameters used in the experiments.

Tables 6.1 to 6.3 show the results for three different values of water melted from snow conductivities. Since it was very difficult to adjust the snow conductivities to a certain value, the values considered in these investigations have been categorized in three groups; that is:

- Low conductivity, for values of conductivities varying between "260 – 345" μS/cm, with a mean value of about 296 μS/cm.
- Medium conductivity, for values of conductivities varying between "350 – 420" μS/cm, with a mean value of about 375 μS/cm.
- High conductivity, for values of conductivities varying between "450 – 515" μS/cm, with a mean value of about 481 μS/cm.

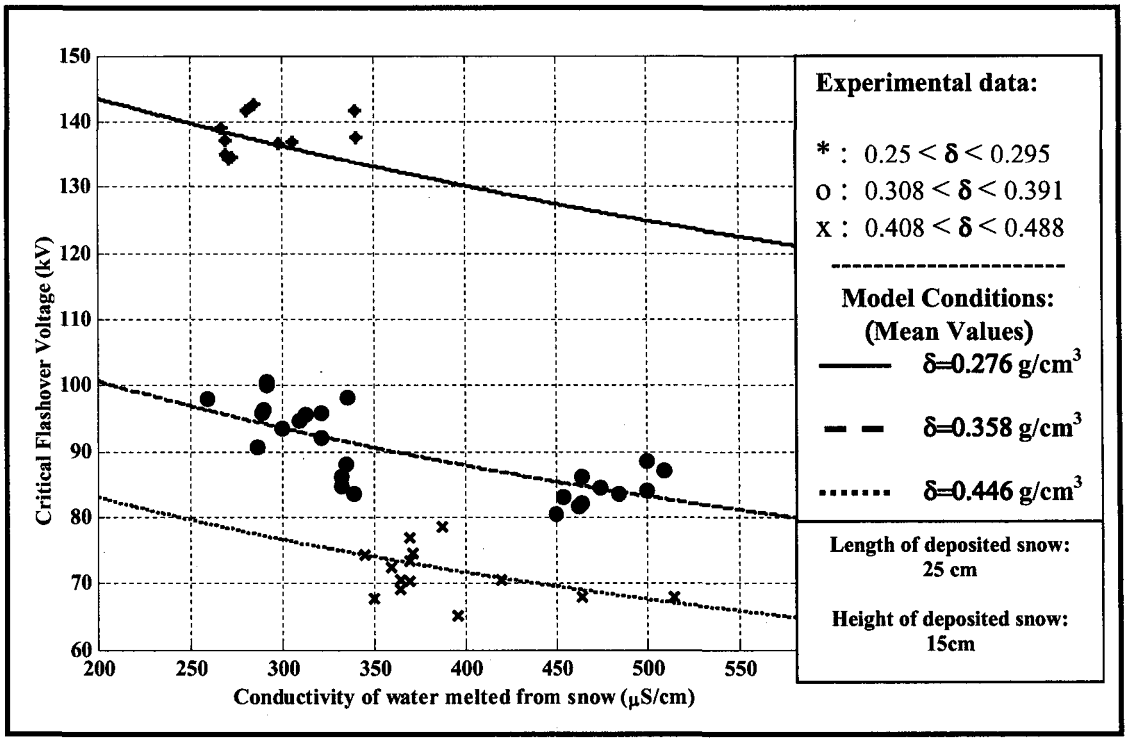



**Figure 6.4**: Critical flashover voltage as a function of water melted from snow conductivity, comparison of the calculated results of flashover voltage with those obtained experimentally at -12 °C

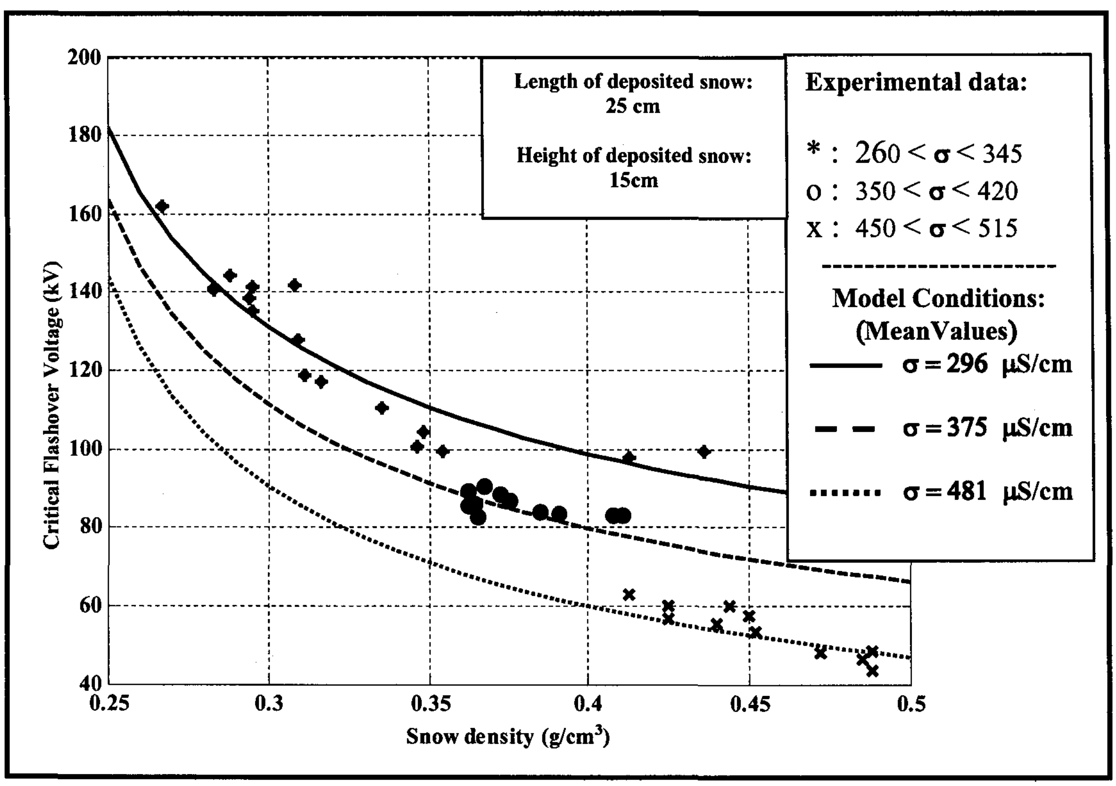



**Figure 6.5**: Critical flashover voltage as a function of snow density - comparison of the calculated results of flashover voltage with those obtained experimentally at -2 °C

**Table 6.1:** Critical flashover voltages obtained from experimental investigations and those calculated from the model using «low water melted from snow conductivity» (mean value = 296 μS/cm)

* : values obtained and errors calculated using the mean value of water melted from snow conductivities (Figure 6.3)
** : values obtained and errors calculated considering the real values of water melted from snow conductivities

| Test Number | Snow Density ($g/cm^3$) | Water melted from snow conductivity (μS/cm) | Flashover voltage (Experiment) (kV) | Flashover voltage (Model) (kV) * | Flashover voltage (Model) (kV) ** | Error * (%) | Error ** (%) |
|---|---|---|---|---|---|---|---|
| 1 | 0.311 | 260 | 118.9 | 125.2 | 127 | 5.2986 | 6.8124 |
| 2 | 0.295 | 267 | 141.4 | 133.9 | 138.8 | 5.3041 | 1.8388 |
| 3 | 0.283 | 270 | 140.5 | 142.2 | 144 | 1.21 | 2.4911 |
| 4 | 0.294 | 270 | 138.7 | 134.5 | 137.5 | 3.0281 | 0.8652 |
| 5 | 0.267 | 271.6 | 161.8 | 157.1 | 163.4 | 2.9048 | 0.9889 |
| 6 | 0.295 | 273 | 135.1 | 133.9 | 136.8 | 0.8882 | 1.2583 |
| 7 | 0.288 | 281 | 144.1 | 138.5 | 145 | 3.8862 | 0.6246 |
| 8 | 0.308 | 289 | 141.9 | 126.7 | 135.5 | 10.7118 | 4.5102 |
| 9 | 0.316 | 290 | 117.3 | 122.9 | 127.1 | 4.7741 | 8.3546 |
| 10 | 0.413 | 293 | 97.7 | 96.3 | 95.1 | 1.433 | 2.6612 |
| 11 | 0.354 | 300 | 99.4 | 109.4 | 103.2 | 10.0604 | 3.8229 |
| 12 | 0.346 | 310 | 100.6 | 111.7 | 103.1 | 11.0338 | 2.4851 |
| 13 | 0.335 | 313 | 110.5 | 115.4 | 103 | 4.4344 | 6.7873 |
| 14 | 0.309 | 322 | 127.9 | 126.2 | 110 | 1.3292 | 13.9953 |
| 15 | 0.348 | 336 | 104.2 | 111.1 | 101.2 | 6.6219 | 2.8791 |
| 16 | 0.283 | 341.5 | 141.1 | 142.2 | 139.4 | 0.7796 | 1.2048 |
| 17 | 0.436 | 345 | 99.3 | 92.6 | 95.9 | 6.7472 | 3.424 |
| Mean value of water melted from snow conductivity (μS/cm) | | 296 | | | | | |

**Table 6.2:** Flashover voltages obtained from experimental investigations and those calculated from the model using «medium water melted from snow conductivity» (mean value = 375 μS/cm)

* : values obtained and errors calculated using the mean value of water melted from snow conductivities (Figure 6.3)
** : values obtained and errors calculated considering the real values of water melted from snow conductivities.

| Test Number | Snow Density (g/cm3) | Water melted from snow conductivity (μS/cm) | Flashover voltage (Experiment) (kV) | Flashover voltage (Model) (kV) * | Flashover voltage (Model) (kV) ** | Error * (%) | Error ** (%) |
|---|---|---|---|---|---|---|---|
| 1 | 0.362 | 350 | 89.1 | 88.0 | 91 | 1.2346 | 2.1324 |
| 2 | 0.365 | 360 | 82.5 | 87.2 | 90.2 | 5.697 | 9.3333 |
| 3 | 0.362 | 365 | 85.4 | 88.0 | 90 | 3.0445 | 5.3864 |
| 4 | 0.411 | 365 | 83.0 | 77.8 | 81.1 | 6.2651 | 2.2892 |
| 5 | 0.367 | 370 | 90.5 | 86.7 | 90.5 | 4.1989 | 0 |
| 6 | 0.375 | 370 | 86.5 | 84.8 | 89.4 | 1.9653 | 3.3526 |
| 7 | 0.391 | 370 | 83.5 | 81.4 | 86.8 | 2.515 | 3.9521 |
| 8 | 0.372 | 372 | 88.2 | 85.5 | 88.1 | 3.0612 | 0.1134 |
| 9 | 0.364 | 388 | 86.0 | 87.5 | 88.5 | 1.7442 | 2.907 |
| 10 | 0.385 | 396 | 84.0 | 82.7 | 84 | 1.5476 | 0 |
| 11 | 0.408 | 420 | 83.0 | 78.3 | 81.5 | 5.6627 | 1.8072 |
| Mean value of water melted from snow conductivity (μS/cm) | | 375 | | | | | |

**Table 6.3:** Critical flashover voltages obtained from experimental investigations and those calculated from the model using «high water melted from snow conductivity» (mean value = 481 μS/cm)

* : values obtained and errors calculated using the mean value of water melted from snow conductivities (Figure 6.3)
** : values obtained and errors calculated considering the real values of water melted from snow conductivities.

| Test Number | Snow Density (g/cm³) | Water melted from snow conductivity (μS/cm) | Flashover voltage (Experiment) (kV) | Flashover voltage (Model) (kV) * | Flashover voltage (Model) (kV) ** | Error * (%) | Error ** (%) |
|---|---|---|---|---|---|---|---|
| 1 | 0.440 | 450 | 55.3 | 53.7 | 57.1 | 2.8933 | 3.255 |
| 2 | 0.485 | 463 | 46.3 | 48.4 | 50.2 | 4.5356 | 8.4233 |
| 3 | 0.450 | 465 | 57.6 | 52.4 | 56.3 | 9.0278 | 2.2569 |
| 4 | 0.472 | 465 | 48.0 | 49.8 | 52.2 | 3.75 | 8.75 |
| 5 | 0.488 | 465 | 43.5 | 48.1 | 50.1 | 10.5747 | 15.1724 |
| 6 | 0.452 | 475 | 53.2 | 52.1 | 53.5 | 2.0677 | 0.5639 |
| 7 | 0.425 | 485 | 60.0 | 55.8 | 54.5 | 7.0 | 9.1667 |
| 8 | 0.425 | 500 | 56.6 | 55.8 | 54.1 | 1.4134 | 4.417 |
| 9 | 0.444 | 500 | 59.9 | 53.2 | 53.9 | 11.1853 | 10.0167 |
| 10 | 0.413 | 510 | 62.7 | 57.6 | 55.8 | 8.134 | 11.0048 |
| 11 | 0.488 | 515 | 48.5 | 48.1 | 46.5 | 0.8247 | 4.1237 |
| Mean value of water melted from snow conductivity (μS/cm) | | 481 | | | | | |

**Table 6.4:** Flashover voltages obtained from experimental investigations and those calculated from the model using «low snow density» (mean value= 0.276 g/cm³)

* : values obtained and errors calculated using the mean value of snow densities (Figure 6.4)
** : values obtained and errors calculated considering the real values of snow densities

| Test Number | Water melted from snow conductivity (μS/cm) | Snow Density (g/cm³) | Flashover voltage (Experiment) (kV) | Flashover voltage (Model) (kV) * | Flashover voltage (Model) (kV) ** | Error * (%) | Error ** (%) |
|---|---|---|---|---|---|---|---|
| 1 | 306 | 0.25 | 129.5 | 135.9 | 138.1 | 4.9421 | 6.6409 |
| 2 | 299 | 0.256 | 129.1 | 136.4 | 137.2 | 5.6545 | 6.2742 |
| 3 | 285 | 0.256 | 135 | 137.3 | 137 | 1.7037 | 1.4815 |
| 4 | 272 | 0.267 | 126.8 | 138.2 | 137.5 | 8.9905 | 8.4385 |
| 5 | 340 | 0.27 | 134.1 | 133.8 | 135 | 0.2237 | 0.6711 |
| 6 | 342 | 0.283 | 130.1 | 133.6 | 128.9 | 2.6902 | 0.9224 |
| 7 | 270 | 0.283 | 127.5 | 138.4 | 130.7 | 8.549 | 2.5098 |
| 8 | 281 | 0.288 | 134.1 | 137.6 | 131.1 | 2.61 | 2.2371 |
| 9 | 270 | 0.294 | 129.7 | 138.4 | 130.6 | 6.7078 | 0.6939 |
| 10 | 273 | 0.295 | 127.1 | 138.1 | 130.5 | 8.6546 | 2.6751 |
| 11 | 267 | 0.295 | 131.4 | 138.5 | 131.5 | 5.4033 | 0.0761 |
| Mean value of snow density (g/cm³) | | 0.276 | | | | | |

**Table 6.5:** Critical flashover voltages obtained from experimental investigations and those calculated from the model using «medium snow density» (mean value= 0.3576 g/cm$^3$)

* : values obtained and errors calculated using the mean value of snow densities (Figure 6.4)
** : values obtained and errors calculated considering the real values of snow densities.

| Test Number | Water melted from snow conductivity (µS/cm) | Snow Density (g/cm$^3$) | Flashover voltage (Experiment) (kV) | Flashover voltage (Model) (kV) * | Flashover voltage (Model) (kV) ** | Error * (%) | Error ** (%) |
|---|---|---|---|---|---|---|---|
| 1 | 289 | 0.308 | 95.9 | 94.3 | 96.4 | 1.6684 | 0.5214 |
| 2 | 322 | 0.309 | 91.9 | 92.2 | 93.8 | 0.3264 | 2.0675 |
| 3 | 260 | 0.311 | 97.9 | 96.2 | 98.4 | 1.7365 | 0.5107 |
| 4 | 290 | 0.316 | 96.3 | 94.2 | 97.1 | 2.1807 | 0.8307 |
| 5 | 313 | 0.335 | 95.5 | 92.7 | 96.7 | 2.9319 | 1.2565 |
| 6 | 310 | 0.346 | 94.6 | 92.9 | 95 | 1.797 | 0.4228 |
| 7 | 336 | 0.348 | 98.2 | 91.4 | 94.5 | 6.9246 | 3.7678 |
| 8 | 455 | 0.349 | 83.0 | 85.2 | 87.8 | 2.6506 | 5.7831 |
| 9 | 333 | 0.352 | 84.7 | 91.5 | 92.2 | 8.0283 | 8.8548 |
| 10 | 300 | 0.354 | 93.4 | 93.6 | 94.3 | 0.2141 | 0.9636 |
| 11 | 510 | 0.362 | 87.1 | 82.7 | 81.5 | 5.0517 | 6.4294 |
| 12 | 485 | 0.362 | 83.4 | 83.8 | 82.5 | 0.4796 | 1.0791 |
| 13 | 500 | 0.364 | 84.0 | 83.2 | 82 | 0.9524 | 2.381 |
| 14 | 333 | 0.365 | 86.2 | 91.5 | 88.8 | 6.1485 | 3.0162 |
| 15 | 450 | 0.365 | 80.5 | 85.4 | 81.7 | 6.087 | 1.4907 |
| 16 | 500 | 0.367 | 88.5 | 83.2 | 83.1 | 5.9887 | 6.1017 |
| 17 | 339 | 0.368 | 83.6 | 91.2 | 85.9 | 9.0909 | 2.7512 |
| 18 | 322 | 0.369 | 95.7 | 92.2 | 91.1 | 3.6573 | 4.8067 |
| 19 | 465 | 0.372 | 86.2 | 84.7 | 83.5 | 1.7401 | 3.1323 |
| 20 | 287 | 0.373 | 90.6 | 94.4 | 90.1 | 4.1943 | 0.5519 |
| 21 | 335 | 0.373 | 88.0 | 91.4 | 88.9 | 3.8636 | 1.0227 |
| 22 | 475 | 0.375 | 84.5 | 84.3 | 82.5 | 0.2367 | 2.3669 |
| 23 | 292 | 0.385 | 100.4 | 94.1 | 93.2 | 6.2749 | 7.1713 |
| 24 | 465 | 0.385 | 82.0 | 84.7 | 80.9 | 3.2927 | 1.3415 |
| 25 | 463 | 0.391 | 81.5 | 84.8 | 80.8 | 4.0491 | 0.8589 |
| 26 | 292 | 0.392 | 100.1 | 94.1 | 92.8 | 5.994 | 7.2927 |
| Mean value of snow density (g/cm$^3$) | | 0.3576 | | | | | |

**Table 6.6:** Critical flashover voltages obtained from experimental investigations and those calculated from the model using «high snow density» (mean value= 0.4455 g/cm$^3$)

* : values obtained and errors calculated using the mean value of snow densities (Figure 6.4)
** : values obtained and errors calculated considering the real values of snow densities.

| Test number | Water melted from snow conductivity (μS/cm) | Snow Density (g/cm$^3$) | Flashover voltage (Experiment) (kV) | Flashover voltage (Model) (kV) * | Flashover voltage (Model) (kV) ** | Error * (%) | Error ** (%) |
|---|---|---|---|---|---|---|---|
| 1 | 515 | 0.408 | 68.0 | 67.1 | 70.7 | 1.3235 | 3.9706 |
| 2 | 465 | 0.411 | 68.0 | 68.9 | 71.5 | 1.3235 | 5.1471 |
| 3 | 350 | 0.413 | 67.7 | 74 | 77.3 | 9.3058 | 14.1802 |
| 4 | 365 | 0.425 | 69.0 | 73.3 | 75.2 | 6.2319 | 8.9855 |
| 5 | 388 | 0.425 | 78.6 | 72.2 | 75 | 8.1425 | 4.5802 |
| 6 | 345 | 0.436 | 74.3 | 74.3 | 73.5 | 0 | 1.0767 |
| 7 | 360 | 0.44 | 72.3 | 73.5 | 73.4 | 1.6598 | 1.5214 |
| 8 | 370 | 0.444 | 76.9 | 73 | 72 | 5.0715 | 6.3719 |
| 9 | 372 | 0.45 | 74.6 | 73 | 72.1 | 2.1448 | 3.3512 |
| 10 | 370 | 0.452 | 70.2 | 73 | 70.5 | 3.9886 | 0.4274 |
| 11 | 396 | 0.472 | 65.0 | 71.8 | 66.6 | 10.4615 | 2.4615 |
| 12 | 370 | 0.485 | 73.3 | 73 | 71.6 | 0.4093 | 2.3192 |
| 13 | 420 | 0.488 | 70.5 | 70.8 | 68.9 | 0.4255 | 2.2695 |
| 14 | 365 | 0.488 | 70.5 | 73.3 | 71.2 | 3.9716 | 0.9929 |
| Mean value of snow density (g/cm$^3$) | | 0.4455 | | | | | |

Tables 6.4 to 6.6 show the results for three different values of snow densities. Since it was very difficult to adjust the snow conductivities to a certain value, the values considered in these investigations have been categorized in three groups; that is:

- Low density, for values of densities varying between "0.25 – 0.295" g/cm$^3$, with a mean value of about 0.276 g/cm$^3$.
- Medium density, for values of densities varying between "0.308 – 0.392" g/cm$^3$, with a mean value of about 0.3576 g/cm$^3$.
- High density, for values of densities varying between "0.408 – 0.488" g/cm$^3$, with a mean value of about 0.4455 g/cm$^3$.

From Tables 6.1 to 6.3, it can be seen that the maximum error between the calculated results and the test results is about 11.19% when using the average values of water melted from snow conductivities in the model to compute the flashover voltage (see Tables 6.1 to 6.3).

The same observation can be made from Tables 6.4 to 6.6 where the maximum error is found to be about 10% when using the average values of snow densities in the model to compute the flashover voltage (see Tables 6.4 to 6.6).

From Tables 6.1 to 6.6, it can be seen that the average errors between test results and those calculated from model using average and real values of snow parameters are 4.04 % and 3.28 % respectively. For snow density, those errors are 4.58 % and 4.05 % respectively for average and real snow density values. These results show that the errors are minimized when considering real values of snow parameters in the model to predict the flashover voltage (FOV).

### 6-2-2 Validation of the proposed model at -2 °C

As mentioned in previous section the snow equivalent conductivity was determined at -12 °C. Snow characteristics change with temperature, especially, near melting temperature, it is impossible to keep its characteristics in certain values. To validate the proposed model at -2 °C, it was necessary to determine snow residual resistance or snow equivalent conductivity at this temperature. To convert the relation 4.24 from -12 °C to -2 °C, the following empirical relations was used [77]:

$$\sigma_{20} = \sigma_\theta[1 - b(\theta - 20)] \qquad (6.5)$$

where $\sigma_{20}$ is the conductivity at 20°C, $\sigma_\theta$ is the conductivity at $\theta$ °C and $\theta$ is the desired temperature; b can be expressed as follow [77]:

$$b = -0.000499\,\theta + 0.0335 \qquad (6.6)$$

By using the relations as mentioned above, the snow equivalent conductivity can be shown for -12 °C and -2 °C as:

For $\theta = -12$ °C: $\gamma_{e,20} = \gamma_{e,-12}[1 - b_{-12}(-12 - 20)]$ (6.7)

And b at -12 °C by using relation 6.6 will be as follow:

$b_{-12} = -0.000499(-12) + 0.0335 = 0.039488$ (6.8)

For $\theta = -2$ °C: $\gamma_{e,20} = \gamma_{e,-2}[1 - b_{-2}(-2 - 20)]$ (6.9)

And b at -2 °C will be:

$b_{-2} = -0.000499(-2) + 0.0335 = 0.034498$ (6.10)

By substituting b values in the relations 6.7 and 6.8:

$\gamma_{e,20} = 2.2636\,\gamma_{e,-12}$ (6.11)

$\gamma_{e,20} = 1.759\gamma_{e,-2}$ (6.12)

Finally, by weighting these two relations the relation between snow equivalent conductivity at -12 and -2 °C can be expressed as follow:

$\gamma_{e,-2} = 1.2871\,\gamma_{e,-12}$ (6.13)

When combining relation 6.13 and 4.24, the snow equivalent conductivity at -2 °C becomes:

$$\gamma_e = 1.2871(0.0057\sigma\delta + 1.2893\delta - 0.00135\sigma - 0.2346) \quad (6.14)$$

The test results as well as the results calculated from the mathematical model at -2 °C are shown in Figures 6.6 and 6.7. As already mentioned, it was very difficult to adjust the snow parameters. Figures 6.6 and 6.7 were plotted for the mean value of the snow parameters used in the experimental.

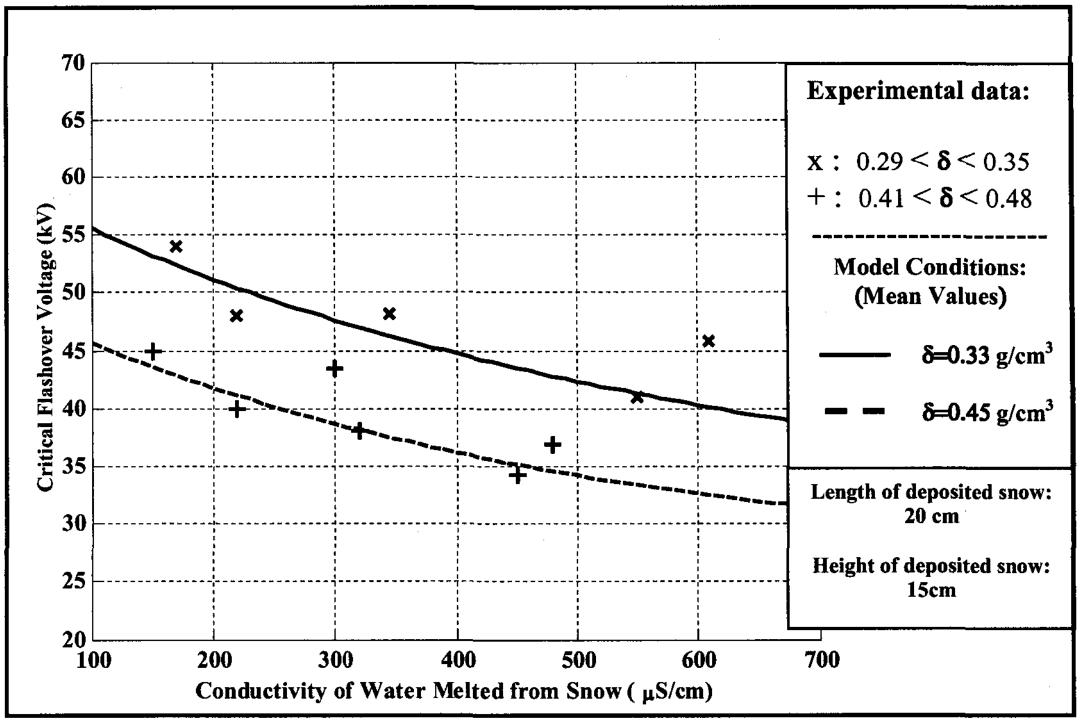



**Figure 6.6**: Critical flashover voltage as a function of water melted from snow conductivity - comparison of the calculated results of flashover voltage with those obtained experimentally at -2°C
(Related Liquid water content trough the snow determined by means of equation 3.3 is LWC = 6%)

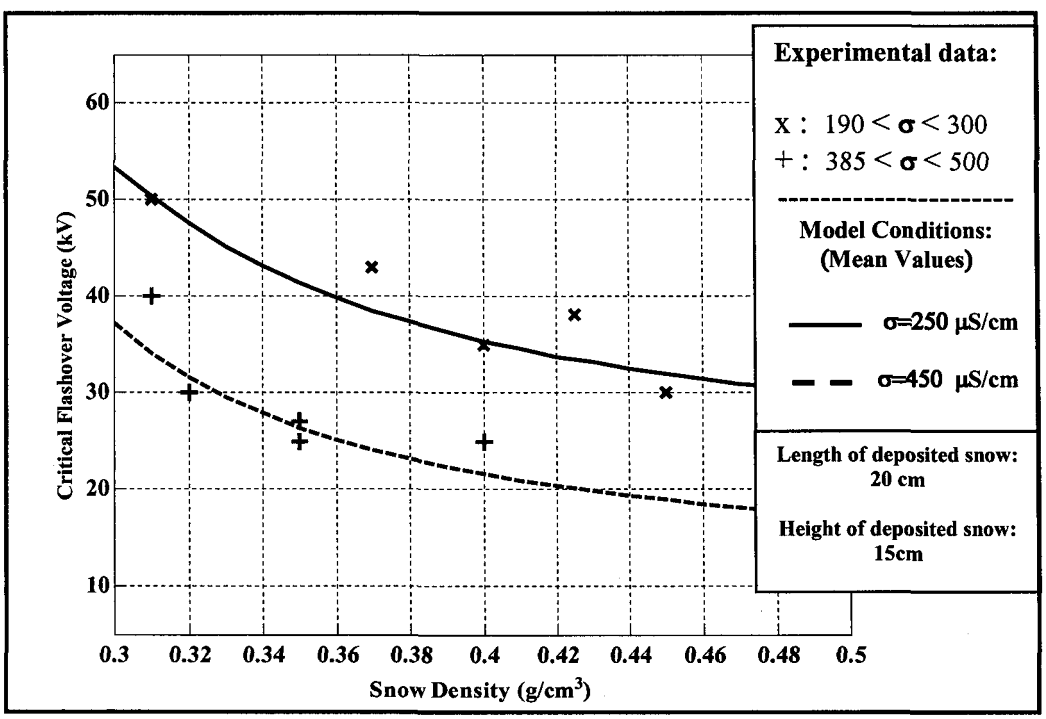



**Figure 6.7**: Flashover voltage as a function of snow density - comparison of the calculated results of flashover voltage with those obtained experimentally at -2 °C
(Related Liquid water content trough the snow determined by means of equation 3.3 is LWC = 6%)

From these Figures it can be observed that, there is a good concordance between the results obtained from experimental and the data calculated from the proposed model. In Figure 6.6, the maximum error is 12.5% while for Figure 6.7, it is about 14.8 %.

As it can be observed from the figures 6.4 to 6.7, the critical flashover voltages are more than the service voltage of this type of insulator, one of the main reasons is the fact that the experiments have been carried out on the clean insulators, so that, there was no artificial contamination on the insulators.

## 6-3 Influence of snow conductivity and density on the flashover voltage (FOV)

### 6-3-1 Influence of water melted from snow conductivity

It is well-known that the condition of snow varies from site to site along power transmission lines [78, 79]. In the present section, the influence of the water melted from snow conductivity on the flashover voltage (of an EPDM insulator) will be studied using the mathematical model.

From field data records, it has been found that snow density varies between 0.2 to 0.5 g/cm$^3$ while its water-melted conductivities may not exceed 1500 μS/cm [77, 78]. These values will be used for modeling in the present section.

Water melted from snow conductivities varying from 10 to 1500 μS/cm were chosen for this study. Considering three different densities, that is 0.3, 0.4 and 0.5 g/cm$^3$, the FOV was computed from the model for water melted from snow conductivities varying from 10 to 1500 μS/cm. It can be seen from Figures 6.8 and 6.9 that, the FOV decreases with an increase in the water melted from snow conductivity. Also, for the given water melted from snow conductivity, the lower the FOV, the higher snow density is. The rate of snow density increase is not proportional to the decreasing rate in the FOV.

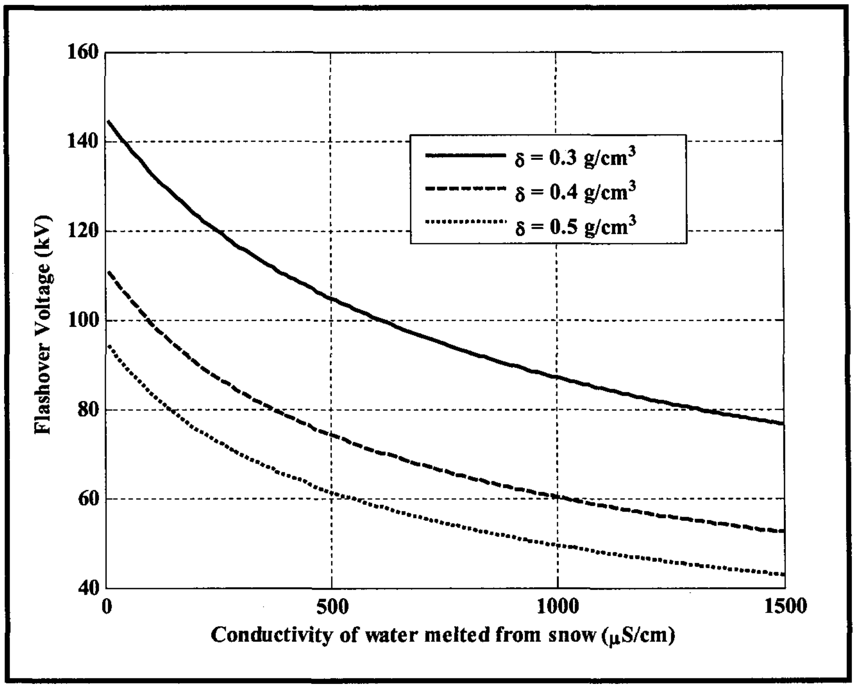



**Figure 6.8**: FOV computed results as a function of water melted from snow conductivities for different snow densities at -12 °C (Length of deposited snow: 25 cm and height of deposited snow: 15 cm)

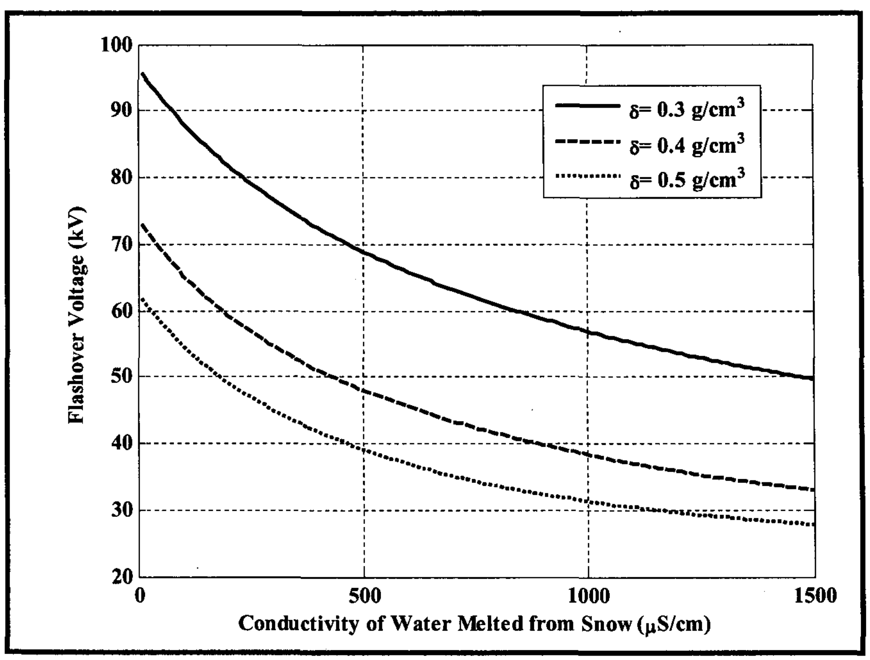



**Figure 6.9**: FOV computed results as a function of water melted from snow conductivities for different snow densities at -2 °C (Length of deposited snow: 20 cm and height of deposited snow: 15 cm)

### 6-3-2 Influence of snow density

In this section, the influence of snow density on the FOV (EPDM insulator) is studied using the proposed mathematical model.

Considering three different conductivities of water melted from snow; that is 200, 500 and 800 μS/cm, the FOV was computed from the model for snow density varying from 0.25 to 0.5 $g/cm^3$.

It can be seen from Figure 6.7 that, the FOV decreases with an increase in the snow density. Also for the given snow density, the lower the FOV, the higher the conductivity of water melted from snow. The rate of snow density increase is not proportional to the decreasing rate in the FOV.

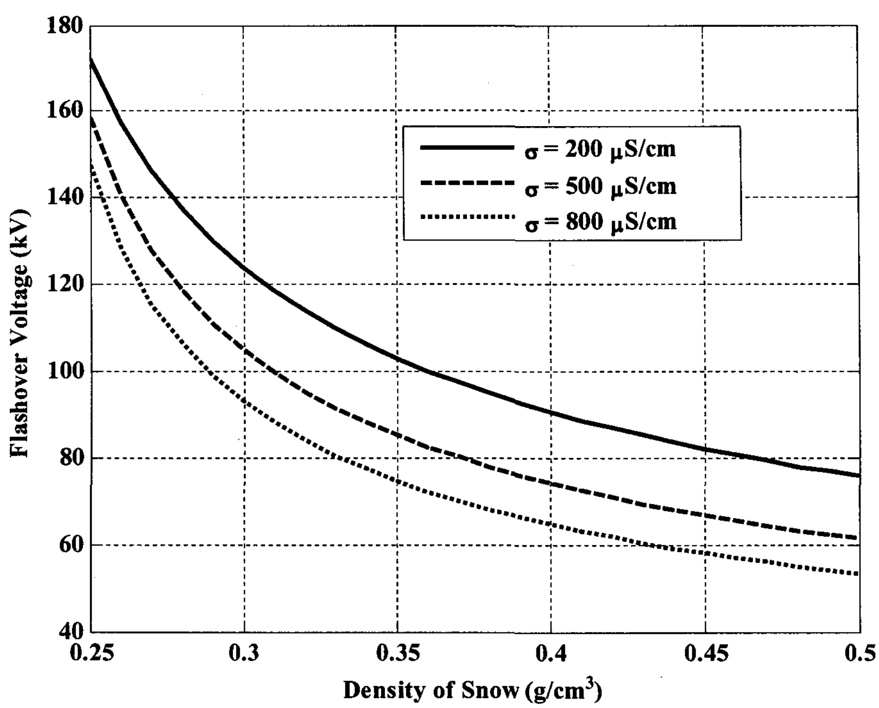



**Figure 6.10**: FOV computed results as a function of snow densities for different water melted from snow conductivities at -12 °C (Length of deposited snow: 25 cm and height of deposited snow: 15 cm)

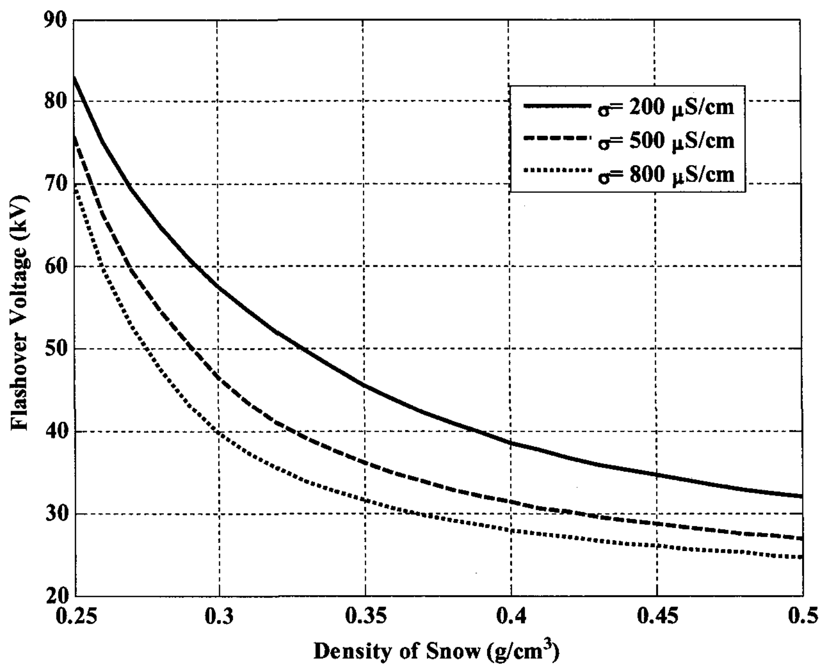



**Figure 6.11**: FOV computed results as a function of snow densities for different water melted from snow conductivities at -2 °C (Length of deposited snow: 20 cm and height of deposited snow: 15 cm)

## 6-4 Summary

On the basis of the experimental investigations on snow-covered insulators and the Obenaus concept, the electrical arc inside snow samples was analyzed and a mathematical model was established for flashover inside snow under ac voltage. From the results obtained, the following conclusions may be drawn:

- A good agreement between the results obtained by mathematical model and those determined experimentally was found at -12 °C and -2 °C.
- The error between the test results and those computed by the model are about 10 % and 11.19 % at -12 °C, respectively for a given snow density and conductivities of water melted from snow and 12.5 % and 14.8 % at -2 °C, respectively for a given snow density and conductivities of water melted from snow.

- These errors are minimized when considering real values of snow parameters in the model to predict the flashover voltage (FOV) at -12 $^{o}$C.
- It was found that the computed FOV decreases with an increase in the snow density.
- It was found that the computed FOV decreases with an increase in the conductivity of water melted from snow.

# CHAPTER 7:

# CONCLUSIONS AND RECOMMENDATIONS

## 7-1 Concluding remarks

One of the consequences of ice and snow accretion on power network equipment is a reduction in the electrical performance of high voltage insulators with the resulting power outage. The present study carried out within the framework of CIGELE/INGIVRE at UQAC, aims at developing an AC static model to predict of flashover voltage under various snow parameters, in this regard several tests have been carried out under various conditions during winters of 2003 to 2006.

The originality of this work required to carry out plenty of experiment in order to have characteristics of natural snow.

For this purpose concluding remarks divides to two parts as follows:

### 7-1-1 Snow Characteristics

Very few investigations have been focused on arc modeling inside or in presence of snow. Concerning the parameters that influence the dielectric performance of snow-covered insulators, it was found that two parameters of snow are important; that is, its density and impurity of snow or its conductivity. Based on experiments carried out for the dielectric performance of snow the following conclusions may be drawn:

- ✓ DC conductivity of snow was found to be a function of snow temperature and density, as well as of the conductivity of water melted from snow.
- ✓ The apparently curious behavior of the dc conductivity of snow near the melting temperature, where peak conductivity is reached, seems to be directly related to the sensitivity of snow crystal growth to temperature and humidity. The existence of the peak may be related to the dynamics of disappearance and

reconstruction of weak bonds and contacts in the snow. Indeed, this phenomenon would indicate that peak temperatures constitute a limiting factor for snow-covered insulator flashover performance, because the highest conductivity is observed at that peak temperature (near -2°C).

✓ Empirical relationship between the density and conductivity of water melted from snow, on one hand, and snow dc conductivity, on the other hand, was proposed. Even though the obtained relationships cannot yet be considered universally well established for natural snow, because of the limited number of samples tested, this result, however, is of primary importance since it allows predicting $\sigma_{dc}$ under the selected conditions under consideration.

✓ Some analytical relationships between the equivalent volume conductivity $\gamma_e$ and $\delta$ and $\sigma$ were established, considering different current distribution profiles.

✓ Some equations expressing the residual snow resistance were derived.

✓ The voltage across snow and the leakage current flowing through the snow-covered insulator are almost in the same phase, within 2 degrees. This means that an insulator covered with snow acts as a pure resistance.

✓ The resistance of snow is not linear, as it decreases when the voltage across snow increases.

✓ Experimental results allowed establishing an analytical model to simulate the leakage current of snow covered insulator. This model shows that the current flowing through the snow 'I' depicts an exponential relation with the applied voltage 'V'.

✓ It is shown that an increasing in the density of snow and/or the conductivity of water melted from snow increases the current flowing through the snow. It is due to the increasing of electric conductivity of snow which is extremely affected by the applied voltage.

✓ The increasing rate of leakage current through snow is more sensitive to the conductivity of the water melted from snow compared to the snow density. It was also found to be extremely dependent on the electric field over the snow sample.

✓ The voltage-current characteristics of snow predicted by the proposed analytical model were found to be in good agreement with those obtained experimentally. The proposed model also allowed predicting the leakage current of snow for the various densities, as well as for various conductivity of water melted from snow. The proposed models give little insight into the design parameters and characteristics which are necessary to assure reliable operation.

### 7-1-2 Static Modeling

On the basis of the experimental investigations on snow-covered insulators and the Obenaus concept, the electrical arc inside snow samples was analyzed and a mathematical model was established for flashover inside snow under ac voltage. From the results obtained, the following conclusions may be drawn:

✓ The voltage gradient of the arc in airgap as a function of leakage current can be shown by the following equation:

$$E_{arc} = 100.25 I_m^{-0.6577}$$

✓ There are differences between the constants of an arc propagating on an ice surface and those of one propagating inside wet snow. In the case of snow, the voltage gradient of the arc ($E_{arc}$, in V/m) as a function of the current peak value ($I_m$, in A) can be expressed by the following equation:

$$E_{arc} = 826.09 I_m^{-0.3627}$$

✓ The re-ignition condition of the arc under ac voltage, was determined experimentally. The re-ignition condition can be expressed by an equation of the arc peak value of applied voltage ($V_m$, in V) and the arc length (x, in cm) and the peak value of leakage current ($I_m$, in A):

$$V_m \geq \frac{6.3663x}{I_m^{0.4855}}$$

✓ It can be seen there is a good concordance between the results obtained by mathematical model and experiment results when evaluating the proposed model.

✓ Error between the test results and calculated results are about 10 and 11.19 % for a given snow densities and water melted from snow conductivities respectively at -12 °C.

✓ Error between the test results and calculated results are about 12.5 and 14.8 % for a given snow densities and water melted from snow conductivities respectively at -2°C.

✓ Model shows the average errors when using real values of snow parameters as comparing the errors of average snow parameters that means it was not perfectly adjusted the snow parameters.

✓ It can be seen that the flashover voltage calculated decreases with an increase in the snow density.

✓ It can be seen that the flashover voltage calculated decreases with an increase in the water melted from snow conductivity.

## 7-2 Future Trends

A comprehensive study was done on the snow electrical behaviors and static modeling of arc inside snow, for future clarification and better understanding on the related matters, the following points could be suggested:

- It is suggested to further investigate the AC and DC conductivity of snow, by taking into account the type of voltage , liquid water content through the snow and surrounding humidity.
- It is also proposed to measure the snow conductivity under high voltage.
- It is also proposed to carry out a series of experiments to control snow density and its water melted conductivity, in order to find some mathematical relationships to have uniform density and conductivity distribution.
- Calculation of snow residual resistance is not easy matter. To calculate the snow residual resistance with accuracy, the arc trajectory should be recorded. Special equipments should therefore be implemented to record and analyze arc trajectory.
- The proposed model was validated without airgap, it suggests that, this model can be developed and used under ultra high voltage for non-completed snow-covered insulators.

# CHAPTER 8:

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