

Production of Artificial Snow at Varying Temperature Conditions and Comparison of its Microstructure with Natural Snow

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for the degree of

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by

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Certificate

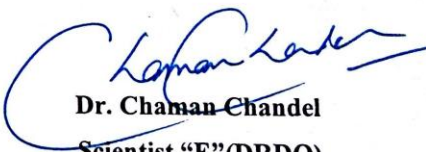
I hereby declare that the thesis entitled “**Production of Artificial Snow at Varying Temperature Conditions and Comparison of its Microstructure With Natural Snow**” is an authentic record of my own work carried out as per the requirements for the award of the degree of **Master of Engineering in Thermal Engineering at Thapar University, Patiala** under the supervision of **Dr. Madhup Kumar Mittal, (Assistant Professor)** Mechanical Engineering Department, Thapar University, Patiala and **Dr. Chaman Chandel, (Scientist-E)** Snow and Avalanche Study Establishment, Chandigarh during July, 2015 to July, 2017. No part of the matter embodied in this thesis report has been submitted to any other university or institute for the award of any degree.

Date: 14/07/2017


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It is certified that the above statement made by the student is correct to the best of my /our knowledge and belief.


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Dedicated
To
My Parents

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Nishant Kumar

Abstract

This research work presents the investigation of the effects of temperature on the production rate of snow. For the production of snow, a wooden prototype of snow making machine was built having three main units named as water basin, nucleation chamber and moisture trap. After fabrication, the machine was kept inside the cold laboratory, where a low temperature surrounding environment was provided. This machine is based on the common supersaturation principle of blowing cold unsaturated air over a heated water basin that increases the temperature and moisture content of air. The moist air stream is directed into the nucleation chamber, where it gets cooled and the process of nucleation of ice crystals is started on the stretched nylon wire. During the experiments, the temperature of the cold laboratory was varied from -20°C to -35°C , whereas the temperature of the water basin was maintained at 25°C . The snow crystals formed inside the nucleation chamber were mainly dendritic in nature. The temperature variation and the production rate of snow was measured at all laboratory temperatures ranges from (-20°C to -35°C) with 5°C temperature decrement. The average values of snow production rate inside the nucleation chamber at all the give values of laboratory temperatures were found to be 72 g/h, 108.76 g/h, 142.64 g/h and 178.53 g/h. After measuring the temperature variation and production rate, microtoming of the Artificial snow sample and natural snow sample was done by the use of microcomputer tomography machine (SKYSCAN, 1173) and various morphometric parameters such as structural thickness, structural separation, and total porosity were compared. After performing experiments on the existing design of artificial snow making machine, a new design of the nucleation chamber of snow making machine was proposed in ordered to overcome the limitations of existing design.

Keywords: Snow making machine, Snow crystals, Nucleation chamber, Production rate of snow

Contents

| | |
|---|------------|
| Certificate..... | i |
| Acknowledgement..... | iii |
| Abstract..... | iv |
| Contents | v |
| List of Figures..... | vii |
| List of Tables | x |
| Nomenclature | xi |
| Chapter-1 Introduction | 1 |
| 1.1 Introduction | 1 |
| 1.2 Formation of Snow | 3 |
| 1.3 Process of Nucleation..... | 4 |
| 1.4 Classification of Snow Crystals | 4 |
| 1.4.1 Hexagonal Plate type | 9 |
| 1.4.2 Columns and Needles | 10 |
| 1.4.3 Stellar plates and dendrites | 9 |
| 1.4.4 Capped Column | 10 |
| 1.4.5 Rimed Snowflakes and Graupels..... | 11 |
| 1.5 Morphology Diagram of Snow Crystals | 11 |
| 1.6 Research Objectives | 12 |
| Chapter-2 Literature Review | 13 |
| 2.1 Introduction | 13 |
| 2.2 Literature Review | 14 |
| Chapter-3 Experimental Setup and Procedure..... | 20 |
| 3.1 Fabrication of Artificial Snow Making Machine | 20 |
| 3.2 Formation of Snow Crystal in the Cold Laboratory..... | 23 |
| 3.3 Instrumentation and Measurement | 26 |
| 3.3.1 Data Logger | 26 |
| 3.3.2 Kestrel Pocket Weather Meter..... | 27 |

| | |
|--|-----------|
| Chapter-4 Experimental Results and Discussion..... | 28 |
| 4.1 Introduction | 28 |
| 4.2 Experimental Results | 29 |
| 4.2.1 Temperature Variation across Nucleation Chamber at Laboratory temperature of -20°C..... | 29 |
| 4.2.2 Production Rate of Snow at Laboratory Temperature of -20°C..... | 31 |
| 4.2.3 Temperature Variation across Nucleation Chamber at laboratory temperature of -25°C..... | 33 |
| 4.2.4 Production Rate of Snow at Laboratory Temperature of -25°C..... | 34 |
| 4.2.5 Temperature Variation across Nucleation Chamber at laboratory temperature of -30°C..... | 36 |
| 4.2.6 Production rate of snow at laboratory temperature of -30°C. | 37 |
| 4.2.7 Temperature Variation across Nucleation Chamber at laboratory temperature of -35°C..... | 38 |
| 4.2.8 Production Rate of Snow at Laboratory Temperature of -35°C..... | 39 |
| 4.2.9 Microstructure of snow from microcomputer tomography (μ CT)..... | 43 |
| Chapter-5 Proposed Design of Snow Making Machine..... | 46 |
| 5.1 A New Design of Nucleation Chamber for Snow Making Machine | 46 |
| 5.2 Nucleation Chamber Design | 47 |
| 5.2.1 Design of Roller Belt Assemble | 48 |
| 5.2.2 Sprocket Chain Mechanism..... | 49 |
| 5.3 Mathematical Analysis..... | 51 |
| 5.4 CFD Simulation of Nucleation Chamber | 52 |
| 5.4.1 Preprocessing..... | 52 |
| 5.4.2 Solver Setup..... | 54 |
| 5.4.3 Post processing | 54 |
| Chapter-6 Conclusion and Future Scope..... | 56 |
| 6.1 Conclusion..... | 56 |
| 6.2 Future Scope..... | 57 |
| References..... | 58 |
| Web References:..... | 60 |
| Appendix: A..... | 61 |

List of Figures

| Figure No. | Title of the Figure | Page No. |
|-------------------|--|-----------------|
| Figure 1.1 | Flow diagram of different types of snow | 3 |
| Figure 1.2 | Hexagonal plates | 9 |
| Figure 1.3 | Columns and Needles | 9 |
| Figure 1.4 | Stellar plates and dendrites | 10 |
| Figure 1.5 | Capped columns | 10 |
| Figure 1.6 | Rimed snowflakes and Graupels | 11 |
| Figure 1.7 | Morphology Diagram of snow crystals | 12 |
| Figure 2.1 | Temperature profile during the process of supercooling | 19 |
| Figure 3.1 | Schematic diagram of geometric model of snow making machine | 20 |
| Figure 3.2 | Snapshot of nucleation chamber of snow making machine | 21 |
| Figure 3.3 | Inside view of the nucleation chamber during initial stage | 21 |
| Figure 3.4 | Wooden Prototype of Artificial Snow Making Machine | 22 |
| Figure 3.5 | Growth of snow crystals on the nylon wires after first experiment | 23 |
| Figure 3.6 | Deposition of snow on the front side of the honeycomb mesh | 24 |
| Figure 3.7 | Brush for harvesting the snow from the nylon wire into snow box | 24 |
| Figure 3.8 | Dendritic snow crystals grown in a downward direction | 25 |
| Figure 3.9 | Multi branches snow crystal under suspended condition | 25 |
| Figure 3.10 | Dendritic snow crystals grown in downward direction. | 25 |
| Figure 3.11 | Dendritic snow crystals | 25 |
| Figure 3.12 | Data acquisition by data Taker DT800 | 26 |
| Figure 3.13 | Data logger CR1000 | 27 |
| Figure 3.14 | Kestrel Pocket Weather Meter | 27 |
| Figure 4.1 | Schematic diagram of snow making machine | 28 |
| Figure 4.2 | Temperature variation across the nucleation chamber at laboratory temperature of -20°C | 30 |
| Figure 4.3 | Average temperature variation across each sensor at laboratory temperature of -20°C | 31 |
| Figure 4.4 | Production rate of snow (g/h)at laboratory temperature of -20°C | 32 |
| Figure 4.5 | Production rate of snow (cm ³ /h)at laboratory temperature of -20°C | 33 |
| Figure 4.6 | Temperature variation across the nucleation chamber at laboratory | |

| | | |
|-------------|--|----|
| | temperature of -25°C | 33 |
| Figure 4.7 | Average temperature variation across each sensor at laboratory temperature of -25°C | 34 |
| Figure 4.8 | Production rate of snow (g/h)at laboratory temperature of -25°C | 35 |
| Figure 4.9 | Production rate of snow (cm ³ /h)at laboratory temperature of -25°C | 36 |
| Figure 4.10 | Temperature variation across the nucleation chamber at laboratory temperature of -30°C | 36 |
| Figure 4.11 | Average temperature variation across each sensor at laboratory temperature of -30°C | 37 |
| Figure 4.12 | Production rate of snow (g/h)at laboratory temperature of -30°C | 37 |
| Figure 4.13 | Production rate of snow (cm ³ /h)at laboratory temperature of -30°C | 38 |
| Figure 4.14 | Temperature variation across the nucleation chamber at laboratory temperature of -35°C | 39 |
| Figure 4.15 | Average temperature variation across each sensor at laboratory temperature of -35°C | 39 |
| Figure 4.16 | Production rate of snow (g/h)at laboratory temperature of -35°C | 40 |
| Figure 4.17 | Production rate of snow (cm ³ /h) at laboratory temperature of -35°C | 40 |
| Figure 4.18 | Average value of snow production rate inside the nucleation chamber at different laboratory temperatures | 41 |
| Figure 4.19 | Average density of snow inside the Nucleation Chamber at different laboratory temperature | 41 |
| Figure 4.20 | Average density of snow inside the Nucleation Chamber at different laboratory temperature. | 42 |
| Figure 4.21 | Snow fall rate (cm/h) inside the nucleation chamber at different laboratory temperature. | 43 |
| Figure 4.22 | Schematic diagram of microcomputer tomography machine | 43 |
| Figure 4.23 | Gray scale images (image resolution = 8.56) (a) artificial snow sample (b) Gray scale image of natural snow sample | 44 |
| Figure 4.24 | Binary scale images (image resolution = 8.56) (a) artificial snow sample (b) Gray scale image of natural snow sample | 45 |
| Figure 5.1 | Proposed design of new snow making machine | 46 |
| Figure 5.2 | Design of nucleation chamber | 47 |

| | | |
|-------------|---|----|
| Figure 5.3 | Exploded view of Nucleation Chamber | 48 |
| Figure 5.4 | Design of roller belt assemble for nucleation chamber | 48 |
| Figure 5.5 | Design of rubber frame | 49 |
| Figure 5.6 | Design of sprocket chain mechanism | 50 |
| Figure 5.7 | Schematic diagram of mixing of two working fluids | 51 |
| Figure 5.8 | Geometric model of nucleation chamber | 53 |
| Figure 5.9 | Meshing of geometric model of nucleation chamber | 53 |
| Figure 5.10 | Contour result of temperature variation across the nucleation chamber | 55 |

List of Tables

| Table No. | Name of the table | Page No. |
|------------------|---|-----------------|
| Table 1.1 | Metrological Classification of Snow Crystals | 5-8 |
| Table 4.1 | Distance between two consecutive temperature sensors | 29 |
| Table 4.2 | Specifications of SKYSCAN 1173 | 44 |
| Table 4.3 | Comparison of Morphometric parameters between snow sample of snow making machine and Natural snow | 45 |
| Table 5.1 | Simulation Parameters | 54 |

Appendix A

| | | |
|----------|---|----|
| Table A1 | Temperature variation across the snow making machine at laboratory temperature of -20°C | 61 |
| Table A2 | Temperature variation across the snow making machine at laboratory temperature of -25°C | 62 |
| Table A3 | Temperature variation across the snow making machine at laboratory temperature of -30°C | 63 |
| Table A4 | Temperature variation across the snow making machine at laboratory temperature of -35°C | 64 |

Nomenclature

| | |
|------------------|---|
| T_{lab} | Temperature of laboratory ($^{\circ}\text{C}$) |
| T_w | Temperature of water basin ($^{\circ}\text{C}$) |
| T_{nuc} | Temperature in nucleation chamber ($^{\circ}\text{C}$) |
| V_{air} | Velocity of air (m/s) |
| RH | Relative humidity (%) |
| H | Height of snow fall in an hour |
| \dot{V}_{snow} | Volumetric production rate of snow per hour (cm^3/hr) |
| A | Inside area of snow box (cm^2) |

Chapter 1

Introduction

1.1 Introduction

India is home of wide variety of climatic regions, ranging from hot and subtropical humid in south to cold and temperate in the Himalayan north (Chang, 1967). In India, the six Himalayan states named as Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, Northern West Bengal and Arunachal Pradesh experience heavy snowfall. According to Indian metrological department, the year's coldest months are December and January. In the cold region, when the favorable atmospheric temperature conditions are reached, snowfall takes place. Snowfall is very common in the high mountainous regions.

In the mountain regions of Himalaya's, landslide, snow avalanche's and glacial floods are the major natural hazards that result catastrophic effects on the life of people living in that areas as well as the transportation, roads and costly infrastructure such as hydropower installations. Out of these natural hazards, snow avalanche is limited to the vast snow bound area of Himalayas. This hazard is most frequent in the snow bound area. The snow avalanche occurs due to failure of weakness/weak layer present in the snowpack. The weak layer properties such as elastic modulus, failure strength, crack propagation propensity etc. depends upon the snow microstructure (Chandel et al., 2014). So it becomes very important to characterize the microstructural and micromechanical properties of snow. The mechanical properties of snow are the function of temperature, density, internal microstructure, wetness and rate of loading (Johnson and Schneebeli, 1999). Out of these independent parameters, mechanical properties are mainly dependent on the snow microstructure (Srivastava et al., 2016). The snow microstructure evolution further depends on the environmental conditions encountered by the snowpack as well as on the initial condition, when snow precipitation takes place. Hence the initial condition of the snow is extremely important to the study the evolution of snow microstructure.

Snow is porous in nature and made of germ of ice, air and small amount of impurities like dust particles. Snow formation takes place, when water vapor deposits on aerosol particles present in the upper atmosphere directly into ice, bypassing the liquid phase (Libbrecht, 2007). So the snow crystals are vapor grown ice crystals. In nature, various type of snow crystals are formed, some of the common types are plate type, hexagonal solid and

hollow prism, needles and dendrites. The growth and crystal habits of these different types of snow crystal depend upon the ambient conditions such as temperature, pressure, supersaturation and wind velocity of air in the atmosphere (Gold and Power, 1954; Nakaya, 1954; Hallett and Mason, 1958 and Kobayashi, 1958). Since in the atmosphere, these conditions are unsteady and nonuniform. Hence, in order to study the influence of the ambient parameters on the formation of snow crystals, it becomes very imperative to perform experiments in the laboratory under some controlled condition of temperature, pressure and supersaturation. But in actual practice, it is not easy to simulate all the ambient conditions that occurred inside the clouds during the formation of snow crystals. In the laboratory, the other challenging task is to provide a method for the close observation of the snow crystals.

Significant work has been done by many researcher (Nakaya, 1954; Hallett and Mason, 1958; Kobayahsi, 1961; lamb and Scott, 1972; keller, 1980, Sato and kikuchi, 1985 and libbrecht, 2006) to understand the habit of the snow crystal. In their work, the snow crystals were grown inside the diffusion chamber which were optimized to control and measure growth velocities of individual crystal in order to understand the formation of the individual snow crystal. Since their study was focused on the individual snow crystals, very small amount of snow is produced. In order to produced snow in a sufficient amount, a different method or approach was needed. The first time, the idea of reproducing the snow in a sufficient amount came from Nakamura (1978) who built a machine, where snow crystals were grown on nylon wires in a stream of supersaturated air. Recently Schleefer et al. (2014) have also made snowmaking machine based upon the idea of Nakamura (1978).

The present work is aimed to investigate the temperature distribution and production rate of snow across the nucleation chamber at different values of laboratory temperature. The experiments were performed on the wooden prototype of snow making machine, which has similar design as proposed by Schleefer et al. (2014). In our study, a set of experiments is performed by varying the laboratory temperature from (-20°C to -35°C) with 5°C temperature decrement. After measuring the temperature distribution and production rate, microtoming of the Artificial snow sample and natural snow sample is done by the use of microcomputer tomography machine (SKYSCAN, 1173) and various morphometric parameters such as structural thickness, structural separation, and total porosity are compared. After performing experiments on the existing design of artificial snow making machine, a new design of the nucleation chamber of snow making machine is proposed in order to overcome the limitations of existing design.

1.2 Formation of Snow

The formation of snow in the atmosphere depends on many variables such as ambient temperature, the degree of supersaturation, up thrust wind velocity and the presence of supercooled water droplets. The whole process of the formation of snow inside the cloud starts with the upward movement of warm moist air. As warm moist air rises, it starts expanding that results in a decrease in the temperature and pressure. A point is reached when the water vapor in the moist air starts condensing and forms countless water droplets. This results in the formation of clouds. Each water droplet requires a nucleus for the condensation, usually dust particles called nucleating agents. As the cloud temperature drops below freezing point, dust particles play a great role in the formation of snow crystals (Libbrecht, 2007).

The snow crystal is the initial stage in the growth of snow having a diameter less than $75\mu\text{m}$. The snow crystals are formed when water vapor changes its form directly into ice, bypassing the liquid phase. Snowflake is a more common word used to describe the different types of winter precipitation. Snowflake is a single crystal or aggregations of snow crystals that are complex and intricate shapes. Figure 1.1 show the flow diagram of the formation of different types of snow.

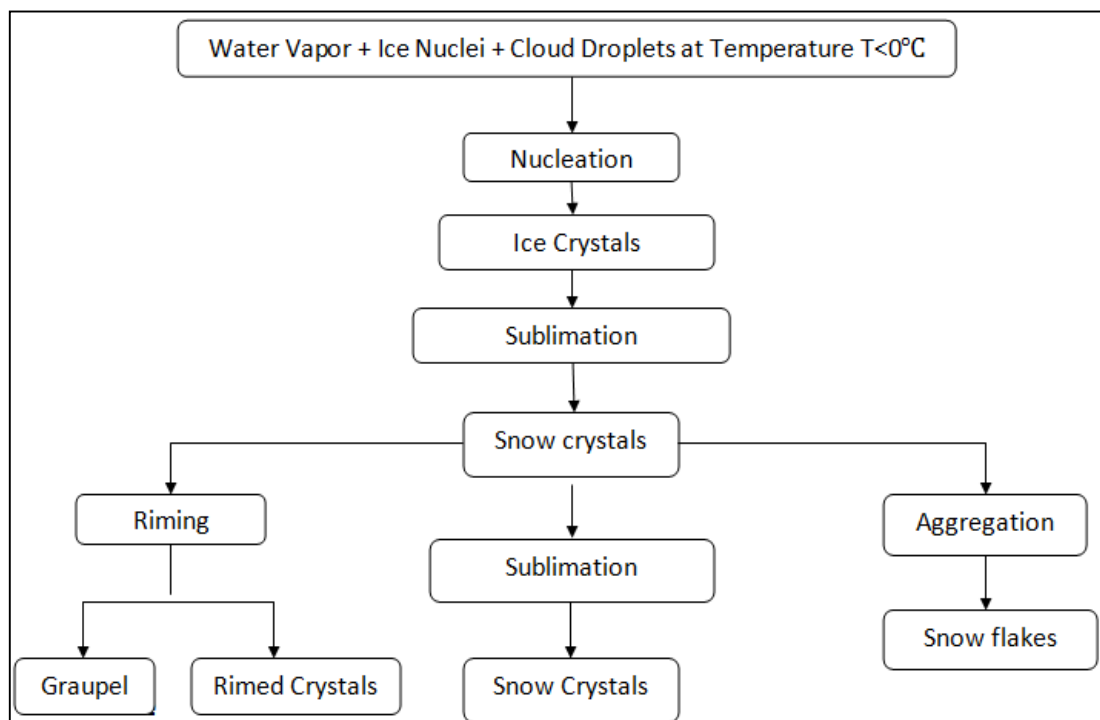


Figure 1.1: Flow diagram of the formation of different types of snow (Gray and Male, 1981).

1.3 Process of Nucleation

In the atmosphere, several thousands of minute size aerosol particles are present having size ranges from 0.01 to 1 μ m. These are the particles around which the water vapors condense when the air is supersaturated. These particles are called condensation nuclei. The particles that starts the formation of ice crystals by the freezing of the water droplets deposited as vapor on to the particle surface called “ice” nuclei (Gray and Male, 1981; Vali, 1966). As the temperature falls below freezing point, all the water droplets do not freeze immediately. Instead, they remain in liquid form called supercooled state of water (Gholaminejad and Hosseini, 2013). Pure water droplets can be supercooled to about -40°C. At a temperature below -40°C, there is the direct freezing of water droplets in the absence of any aerosol particle (Libbrecht, 2007).




















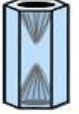

These aerosol particles are found in a large variety of chemical composition. Each aerosol particle is identified by a particular activation temperature at which the ice formation can be initiated. Most aerosol particles have an activation temperature is in the range of -5°C to -10°C, which are classed as efficient nucleating agents. The nucleating agents having a temperature range below -20°C are referred to as poor nucleating agents (Gray and Male, 1981). The formation of ice crystal by this process called as heterogeneous nucleation, because all the cloud droplets do not freeze immediately. The major sources of ice nuclei are dust from earth surface, sea salt aerosols like bromine oxide, a strong ozone depleting molecule, forest fires etc. clay silicate is one of the common and efficient nucleating agents. Only a very few aerosol particles are active as ice nuclei about one in 10⁹ at -10°C. The number of active nuclei increases as the temperature decreases approximately by a factor of 10 with a temperature step of -4°C (Gray and Male, 1981).

1.4 Classification of Snow Crystals





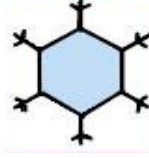
















It was Dr. U. Nakya (Magono and Chung. 1966) who first made the classification of natural snow crystals after the experimental investigation of the artificial snow crystals in the form of $T_a - s$ diagram. But this classification was roughly applicable to the natural snow crystals. So the $T_a - s$ diagram was further studied and improved by Nakya, Hallat and Mason, (1958) and Kobayashi, (1958). But, the classification was not sufficient enough to describe the different types of snow crystal formed in nature. The nakya classification was modified and some classifications were added by Magono and Lee, (1966). The number of classification increased from 36 to 80, which is still used as a general classification of natural snow crystals.

The classification of natural classification by Magono and Lee is shown in the tabular form in Table 1.1.

Table 1.1 Metrological Classification of Snow Crystals. (Magono and Chung, 1966)

| Snow crystal Image | Name | Snow crystal Image | Name | Snow crystal image | Name |
|---|---|---|--|---|---|
|  | N1a Elementary needle |  | N2c Combination of long solid columns |  | C1g Solid thick plates |
|  | N1b Bundle of elementary needles |  | C1a pyramid |  | C1h Thick plate of skeletal form |
|  | N1c Elementary sheath |  | C1b Cup |  | C1i Scroll |
|  | N1d Bundle of elementary sheaths |  | C1c Solid bullet |  | C2a Combination of Bullets |
|  | N1e Long solid Column |  | C1d Hollow bullet |  | C2b Combination of columns |
|  | N2a Combination of needles |  | C1e Solid column |  | P1a Hexagonal plates |
|  | N2b Combination of sheaths |  | C1f Hollow column |  | P1b Sector Plate |


















Continued

| | | | | | |
|---|--|---|---|--|---|
|  | P1c Broad branch |  | P2d Dendrite with sectorlike ends |  | P4a Broad branch with 12 branches |
|  | P1d Stellar |  | P2e Plate with simple extensions |  | P4b Dendrite with 12 branches |
|  | P1e Ordinary dendrite |  | P2f Plate with sector extensions |  | P5 Malformed crystal |
|  | P1f Fernlike dendrite |  | P2g Plate with dendrite extensions |  | P6a Plate with spatial branches |
|  | P2a Stellar with plates at ends |  | P3a Two branches |  | P6b Plate with spatial dendrites |
|  | P2b Stellar with sectorlike ends |  | P3b Three branches |  | P6c Stellar with spatial plates |
|  | P2c Dendrite with plates at ends |  | P3c Four branches |  | P6d Stellar with spatial dendrites |

Continued.

| | | | | | |
|--|--|--|--|--|--|
| | P7a Radiating assemblage of plates | | CP3a Stellar with needles | | R1a Rimed needle |
| | P7b Radiating assemblage of dendrites | | CP3b Stellar with columns | | R1b Rimed column |
| | CP1a Column with plates | | CP3c Stellar with scrolls at ends | | R1c Rimed plate or sector |
| | CP1b Column with dendrites | | CP3d Plate with scrolls at ends | | R1d Rimed stellar |
| | CP1c Multiple capped column | | S1 Side planes | | R2a Densely rimed Plate or sector |
| | CP2a Bullet with plates | | S2 Scale like side planes | | R2b Densely rimed Stellar |
| | CP2b Bullet with dendrites | | S3 Side planes with bullets and columns | | R2c Stellar with rimed spatial branches |

Continued

| | | | | | |
|---|---|---|------------------------------|---|-----------------------------------|
|  | R3a Grapule-like snow of hexagonal type |  | I2 Rimed particle |  | G4 Minute stellar |
|  | R3b Grapule-like snow of lump type |  | I3a Broken branch |  | G5 Minute assemblage of plates |
|  | R3c Grapule-like with nonrimed Extension |  | I3b Rimed broken branch |  | G6 Irregular germ |
|  | R4a Hexagonal grauple |  | I4 Miscellaneous | | |
|  | R4b Lump grauple |  | G1 Minute column | | |
|  | R4c Conelike graupel |  | G2 Germ of Skeletal form | | |
|  | I1 Ice particle |  | G3 Minute hexagonal plate | | |

The snow crystals are commonly classified into five basic crystal habits such as hexagonal plate type, hexagonal solid prism type, column type, needles, and dendrites. Different irregular shapes of snow crystals also formed in the atmosphere due to the variation in the temperature and supersaturation along the path in the atmosphere. Some of the snow crystals or snowflakes are defined below.

1.4.1 Hexagonal Plate type

A hexagonal plate type snow crystal is the most basic form of snow crystal that is formed when the temperature is in the range of ($0^{\circ}\text{C} - -3^{\circ}\text{C}$). With the increase in the value of supersaturation, sectored plate and dendritic plates are formed that are shown in the Fig. 1.2.

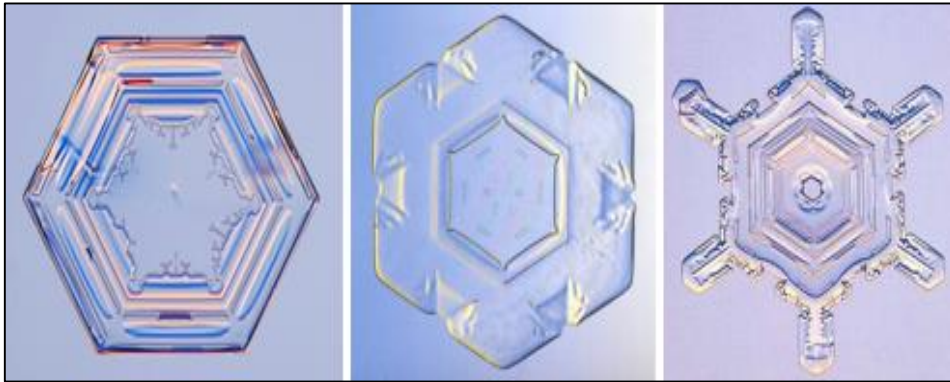


Figure 1.2: Hexagonal plate (Snowcrystals.com, 2016)

1.4.3 Stellar plates and dendrites

These are the most recognizable and complex form of snow crystals. These crystals are formed at a lower temperature of about ($-15^{\circ}\text{C} - -20^{\circ}\text{C}$) with a higher value of supersaturation. Some of these shapes are shown in the Fig. 1.3.

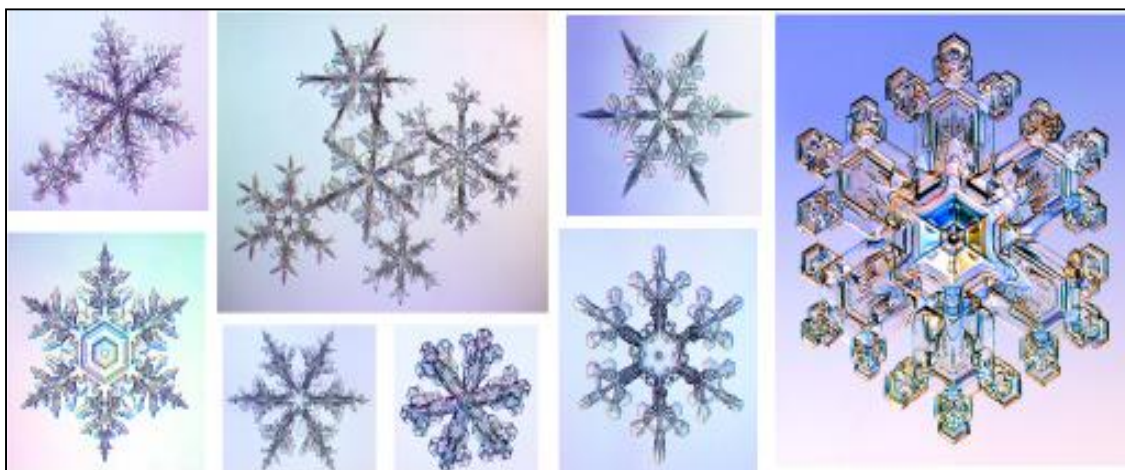


Figure 1.3: Stellar plates and Dendrites. (Snowcrystals.com, 2016)

1.4.2 Columns and Needles

Columnar type snow crystals appear, when the temperature is around -6°C . At a small value of supersaturation solid column appears. With the increase in the value of supersaturation, hollow column and needle-like snow crystals are formed that are shown in the Fig. 1.4.



Figure 1.4: Column and Needle.(Snowcrystals.com, 2016)

1.4.4 Capped Column

Capped column is a combination of plate type and column type shown in Fig. 1.5. First, a column is formed at a temperature of $-6^{\circ}\text{C} - -8^{\circ}\text{C}$. After the formation of the column, plates are grown at a temperature of -15°C . These plates are grown parallel to each other and grown at the ends of the column. These plates can be simple hexagonal or stellar plates type.

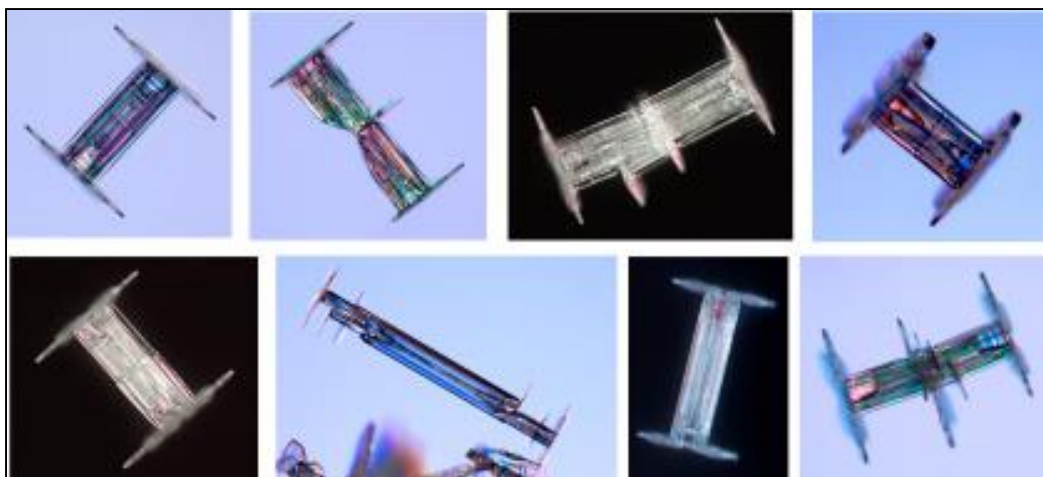


Figure 1.5: Capped Columns. (Snowcrystals.com, 2016)

1.4.5 Rimed Snowflakes and Graupels

In the atmosphere, the snowflakes are formed inside the clouds. When the size of the snowflakes is sufficient enough, they start falling. During snow fall, the snow crystals have to travel through regions with varying concentration of tiny water droplets. As the snow crystals travel through such regions, the snow crystals collide with water molecules and water molecules freeze onto the surfaces. These snowflakes are called rimed snowflakes. When these crystals are completely covered with rimes are called graupels. Some of the rimed snowflakes and graupels are shown in the Fig. 1.6.

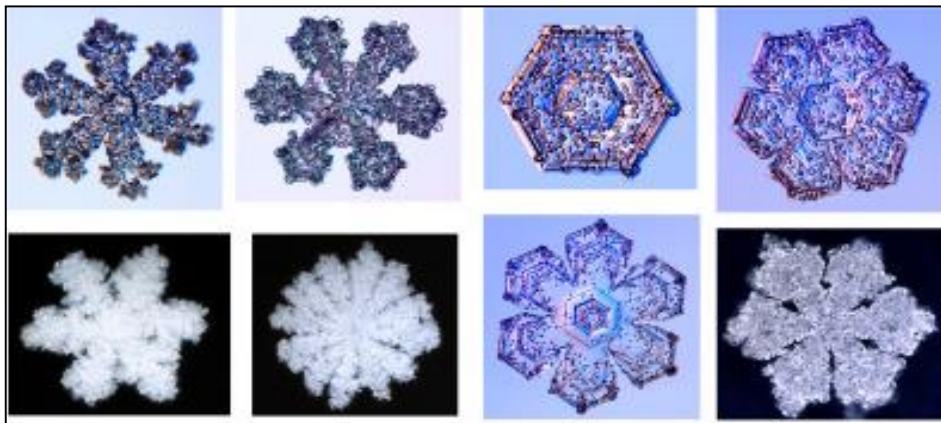


Figure 1.6: Rimed Snowflakes and Graupels. (Snowcrystals.com, 2016)

1.5 Morphology Diagram of Snow Crystals

The formation of snow in the atmosphere depends on many variables such as ambient temperature, the degree of supersaturation, up thrust wind velocity. Out of these temperature and supersaturation are the main parameters in the formation of snow crystals. It has been observed by the researcher and now generally conceded that the changes in the crystal structure are controlled mainly by the temperature of the environment. A higher value of supersaturation influenced only the secondary features of the snow crystals such as the development of dendritic form, fast growth, and more complexity.

It was the physicist Ukichiro Nakaya of the University of Hokkaido in Japan, who grown artificial snow crystals in the laboratory. He was the first to present the habits of snow crystals as a function of temperature and supersaturation. Figure 1.7 shows the behavior of crystal structure as the function of temperature and supersaturation, which is known as snow crystal morphology diagram.

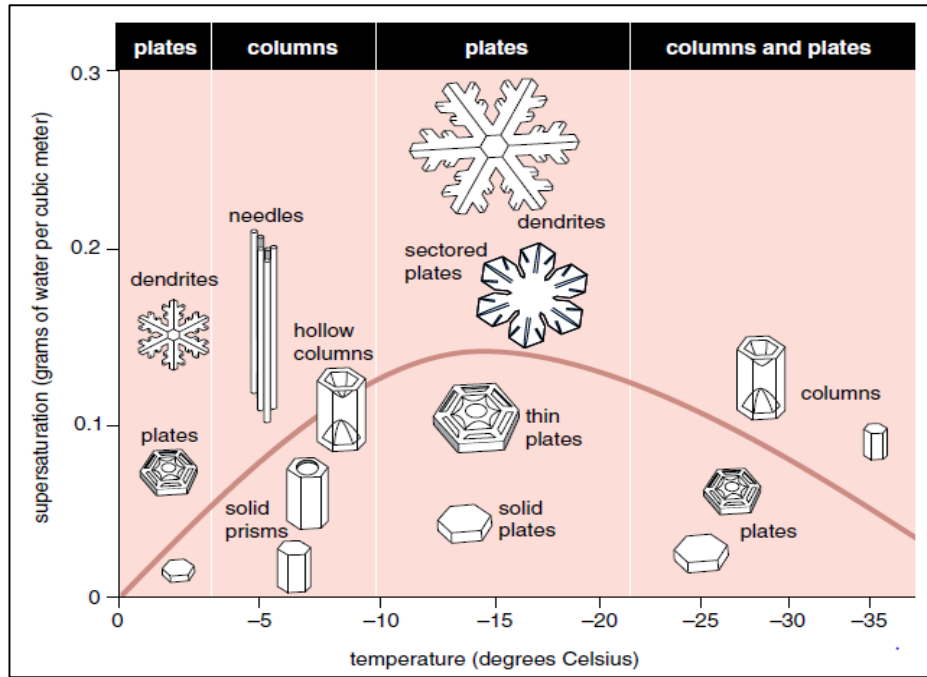


Figure 1.7: Morphology diagram of snow crystals. (Libbrecht, 2007)

From the diagram, one can predict that the ice crystals are a plate type ranges from (0°C – -3°C), prisms type (-3°C – -8°C) then again plate type(-8°C – -25°C). As the temperature below -25°C, mainly short column crystals are grown. At all temperature values, for the low value of supersaturation, prism-like crystals are formed. As the supersaturation increases, the complexity of crystal increases. Why snow crystals grow in this fashion remains an unsolved puzzle. the growth behavior of ice depends upon molecular structure and dynamics at the crystal surface.

1.6 Research Objectives

The aim of this research work is mainly to investigate the effect of temperature on the production rate of snow. This aim is accomplished by fulfilling the following specific research objectives.

1. To fabricate the wooden prototype of existing snow making machine.
2. To produce and study the growth of artificial snow in the nucleation chamber of snowmaking machine under varying temperature conditions.
3. To compare the microstructure of artificial snow with natural snow.
4. To propose a new design of artificial snow making machine.

Chapter 2

Literature Review

2.1 Introduction

A detailed history of understanding the structure of snow crystals was made as early as 1550. It was Johann Kepler first to examine snow crystals with the scientific eye. In 1611, Kepler penned an article entitled “The cornered snowflakes” in which he attempted to understand the flower-like structure of snowflakes. In his study, Kepler realized the formation of complex crystal structure in nature. How these complex crystal structures are formed was a worth scientific question. It is one of the questions in which scientists are still investigating today. The famous proverb “no two snowflakes are alike” probably started on January 15, 1885 in Jericho Vermont. A 20-year-old named Wilson Bentley was sitting outside his farmhouse holding a sheet of black fabric and a turkey feather, waiting for a snowflake to fall in just the right spot. When it did, he put that snowflake under a microscope attached to an enormous camera. Wilson Bentley had the first photograph of a snowflake ever taken. Wilson Bentley produced over 6000 spectacular pictures of snowflakes with wide variations in the forms that exist in nature.

Despite these earlier studies, after the use of x-ray diffraction techniques, it had become possible to understand the crystalline structure. In 1932, Ukichiro Nakaya and his fellow workers had started working on the formation of snow crystals in the laboratory for the first time. They started observing and documenting the range of snow crystals but latterly Nakaya realized that laboratory experiments were necessary to investigate under what conditions these snow crystals appeared.

Nakaya performed an experiment in his laboratory under controlled conditions of temperature and supersaturation, in which he was able to produce snow crystals, which were very much alike with those found in the atmosphere. In his book and various research papers contains hundreds of photomicrographs not only of the artificial snow crystals but also of natural snow crystals. After performing a number of experiments in the laboratory, Nakaya found that the snow crystal habit is primarily dependent on temperature not on excess vapor density (supersaturation). After nakaya, many researchers have worked to understand the growth and habit of the snow crystal.

Marshall and Langleben (1954) have made the investigations of the Nakaya laboratory experiments and contradict the statement made by Nakaya. According to their investigation, the habit of crystal growth is determined principally by the excess of the ambient vapor density over that of equilibrium with ice crystals. Kobayashi (1957) performed some experiments on snow crystal habit in the diffusion chamber with the objective of examining the theory given by Marshall and Langleben (1954) on the snow crystal habit. It was found that the snow crystal habit is primarily determined not by the excess vapor density but by the ambient temperature.

2.2 Literature Review

Nakaya (1954) has discussed about the formation of the different types of snow crystals and the conditions under which these snow crystals are formed. He has also contrasted the difference in the snow crystal and ice crystal. During the experiments he founds that the needle, irregular needles and cup crystals are formed in the supersaturated region above water saturation. He also presented the $T_a - W$ diagram for the formation of rimed crystals.

Kobayashi (1957) had performed some experiments on snow crystal habit in the diffusion chamber with the objective of examining the theory given by Marshall and Langleben 1953 on the snow crystal habit. Marshall and Langleben (1953) investigated the experiments of Nakaya, they found that the snow crystal habit is primarily depended upon the excess vapor density over that in equilibrium with the growing ice crystal. And this theory was based on the assumption that the Nakaya's supersaturation must be relative to water supersaturation, but according to Nakaya, it was not the case. To examine this theory, Kobayashi performed experiments in the diffusion chamber free from cloud droplets. And from the results, it was found that the snow crystal habit is primarily determined by the ambient temperature, not by the excess vapor density.

Koboyashi (1958) had performed a series of experiments on the growth and habit of artificial snow crystals at low ambient pressure. The experiments were performed inside the diffusion chamber and convective chamber. During the observation, $T_a - P$ diagram was established. At the starting of the experiment, the pressure was reduced to about 10^{-2} mm Hg and the temperature at the bottom of the chamber was maintained at -30°C . Initially, the experiments were performed inside the diffusion chamber at low ambient pressure and then gradually

recovered the pressure to 1 atmospheric pressure. In the diffusion chamber only solid hexagonal columns were formed. From the $T_a - P$ diagram, column crystals were formed at a pressure lower than 100 mm Hg. Sector and dendritic crystals begin to form, when the pressure is above 300 mm Hg and temperature in the range of -10°C to -20°C .

Hallett et al. (1958) have worked on the snow crystal habit and performed a number of experiments to find out the influence of the temperature and supersaturation. They grew the ice crystals in a cold chamber in which the temperature and supersaturation can be varied independently with the temperature ranges from 0 to -30°C . They found out that the large variations in the crystal habit are mainly controlled by the temperature of the environment. Large variations in the supersaturation influence only the secondary feature of the crystals such as a dendritic form. In the cold chamber, the ice crystals grew in the presence of a cloud of supercooled droplets, when the environment is saturated with respect to water and supersaturated with respect to the ice. The degree of supersaturation determined solely by the temperature. So it was very difficult to determine whether the changes in the crystal habit were being produced by the change in temperature or by change in supersaturation.

So to resolve this point, Shaw and Mason (1955) performed experiments on the growth of the ice crystals formed under some controlled conditions in which the temperature and supersaturation can be varied independently. They found out that the change in the crystal habit controlled mainly by the temperature of the plate, the supersaturation has not much effect.

The results obtained by the Shaw and Mason were at variance with the suggestion, made by the Weickmann (1950) and Marshall and Langbein (1954), that the crystal habit is principally determined by the excess of ambient vapor density over that at equilibrium with the ice crystal at its own temperature. It was found out that the conditions for crystal growth on the metal surface may not have exactly the same as those for the air. To meet this point, J. Hallett and Mason have performed experiments to understand the problem in more detail.

Nakaya (1959) had performed experiments in Mauna Loa during the winter of 1956-57 in order to understand the nature of the snow crystals. In Mauna Loa the concentration of the aerosol particle is very small compared to other places. So it was supposed that the shape of the snow crystals might be different from that observed in other places. But this expectation was wrong. The number of condensation nuclei was measured by using the General Electric

condensation nuclei meter at various altitudes as well as at 4000m, and it was found that the number of nuclei was very small in this district. The number above (1828 m) was very small on fine days, being 100-200 per cm^3 . Around 170 micrographs of the snow crystals were taken at the summit. He has also shown that how the ice pellets are formed in the cold climates. In Mauna Loa, Nakaya had also found a new crystal, which was an intermediate state of the column and the needle.

Kobayashi (1961) have performed an experiment to examine the growth of snow crystals at low supersaturation. In his results, he found that at low supersaturation, the c/a ratio reaches to a value of 1.4 for prisms and 0.8 for plates. To produce such a small supersaturation, he used convective mixing chamber in which a known volume of air (about 2 liters) passed from the chamber through the dried methanol and moisture content is measured by titration with Karl Fischer reagent. At small values of supersaturation of about 3%, solid column and very thick plates occurred at a temperature range of -8°C to -23°C .

Rottener and Vali (1974) have studied the growth of snow crystals at smaller value of excess vapor density. The crystals were grown inside the diffusion chamber at the center of two parallel plates, in which the top plate was kept warmer than the bottom plates. During the process they assume the linear variation in the temperature and the vapor pressure across the two plates. The experiments were conducted at five different temperature. The growth of the snow crystal was primarily determined by the magnitude of vapor density excess. At low value of vapor density excess, thin plates, thick plates and column crystals were formed. Dendritic crystals were grown at higher value of supersaturation, they have also mentioned that their study does not agree with the observations made by Nakaya (1954), particularly the dendritic crystal growth at a supersaturation ratio less than unity with respect to water.

Keller (1982) has investigated the effect of air velocity on the growth rate of the ice crystal grown from the water vapor inside the diffusion chamber with temperature and supersaturation ranging from 0°C - 35°C , 2 – 40% over the ice surface. He performed experiments to observe the effect on the growth rate of snow crystal along the a -axis and c -axis as the air velocity is increased or decreased without changing the temperature and supersaturation. During the observation, he found the dendritic crystal habit, when the air

velocity was 7 cm s^{-1} , as the surrounding environment reaches stationary conditions, dendritic crystal starts changing to plate type.

Libbrecht (2006) has discussed about a technique for the accurate measurement of the growth rate of snow crystals. Vapor diffusion and attachment kinetics are the two main factor for the growth of the snow crystals. Different types of systematic errors occurred during the measurements of growth of the snow crystals are also discussed. He has also discussed about the various other factors such as neighboring crystals, temperature gradient in the growth chamber and chemical contamination on the growth of the snow crystal.

Satyawali et al. (2008) have presented a sequential variations in the microstructure and thermal conductivity of snow samples under the influence of a temperature gradient. Temperature gradients from 28 to 45 K m^{-1} were applied to snow samples having a density range 180 – 320 kg m^{-3} . In order to investigate changes in snow microstructure and effective thermal conductivity with time, four experiments were performed inside the cold laboratory in a designed heat flux apparatus. For the measurement of effective thermal conductivity (ETC) and microstructure, snow samples were sieved in the cold laboratory. To check the microstructure of the natural sieved snow, a snow sample of size $3 \times 3 \times 3 \text{ cm}^3$ was cut for the microtoming. Microtoming was done in a microcomputer tomographic machine (μ CT) (Leica, Germany), in their study, they found that the effective thermal conductivity was increasing with increase in grain size and bond radius. Since they found that microstructure of snow changes very slowly with time that leads to slow change in the effective thermal conductivity (ETC) of snow.

Style et al. (2008) have shown theoretically and confirm experimentally that the frost flowers can be formed on solid, pure ice sublimating into an unsaturated atmosphere. They also have derived general regime diagram showing the various vapor related phenomena and performed various experiments to confirm frost flower formation. They also come up to a very important result is that frost flowers forms on ice surfaces that are sublimating, unlike hoar frost condensing from the supersaturated atmosphere to which frost flowers can be compared. Domine et al. (2005) have also been observed that frost flower can be formed on freshwater lakes so they have ignored the influence of salt and considered the evolution of a pure ice and

air above it. They have considered the Clausius- clapeyron equation to find out the humidity of the air and the phase behaviour of its water content.

Bones and Adam (2009) have designed a low cost, small snow making systems based on the ideal of Nakamura 1978. During the experiments, they have grown different type of snow crystals such as plate, column, needle and rime over the hemp strings inside the chimney under some controlled conditions of temperature and supersaturation. Air is passed over the humidifier by the help of cross flow fan to carry water vapor from the humidifier. To control the temperature of air inside the chimney and the humidifier, a thermostat is used. During their experiments, they have performed experiments ranging from 0°C to -35°C. In the results, they have obtained plate to dendrite crystals in the range 0°C to -4°C , column to needle between -4 °C to -10°C, plate to dendrite crystals between -10 °C to -21°C, column or plate type between -21°C to -35°C.

Gholaminejad and Hosseini (2013) have studied the phenomenon of supercooling. They have worked on the various parameters that affect the stability of supercooling including freezer temperature and water initial temperature. During their experiments, they found out that when the freezer temperature is in between -4 °C to -8 °C . The phenomenon of supercooling takes place for a longer time and is independent of water initial temperature. This is due to the fact of lack of nucleation sites. With a further decrease in temperature of the freezer (-10°C to -12°C). Supercooling becomes unstable and nucleation happens. In the present case, the cold liquid bath is used as the freezing compartment with ethylene glycol as freezing media. Distilled water has been used so that the dissolved impurities could not influence the water supercooling.

To know whether the supercooling occurs or not, a sample of 500 ml of distilled water with initial temperature 65°C was placed in the freezer temperature of -8°C. The temperature profile obtained during the experiment is shown in Fig. 2.1.

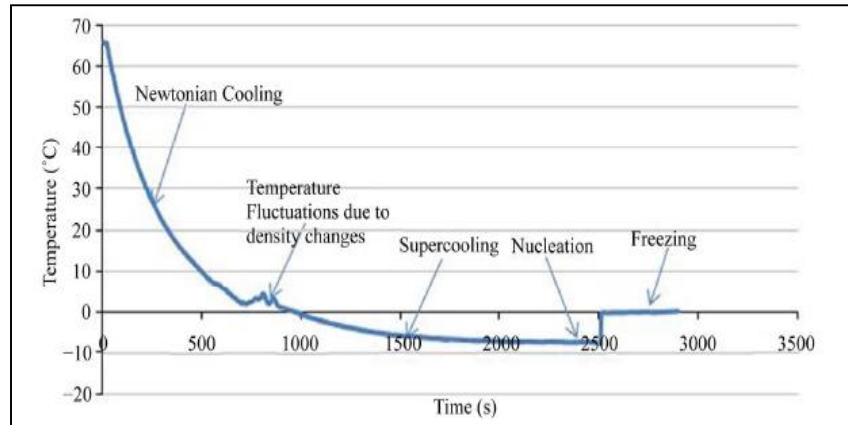


Figure 2.1: Temperature profile during the process of supercooling (Gholaminejad et al., 2013)

Freezer temperature was varied in the range of -4°C to -12°C to study its effect on supercooling. The results are as follows: For freezer temperature ranges from -4°C , -6°C and -8°C no nucleation observed, water remained in the supercooled state for as long as 5 hours. When the temperature of the freezer reached -10°C , nucleation happens and it was random and was higher for hot water. For freezer temperature -12°C , nucleation always happened irrespective of water inlet temperature.

Schleef et al. (2014) have made an improved design of snow making machine, in which natural identical snow crystals were produced. This machine is based on the common supersaturation principle of blowing cold unsaturated air over a heated water basin that increases the temperature and moisture content of air. This moist airstream is directed into the nucleation chamber, where it gets cooled and the process of nucleation of ice crystals is started on the stretched nylon wires. An automatic brush rack mechanism is made for harvesting the snow crystals regularly. The main snow crystals grown inside the nucleation chamber are dendrite and needle types in nature. After the formation of the snow crystals, samples of snow were prepared for determining the microstructure by the use of microcomputer tomographic machine. This machine is capable to produce sufficient amount of snow for laboratory experiments.

Chapter 3

Experimental Setup and Procedure

3.1 Fabrication of Artificial Snow Making Machine

The idea of production of snow by snow making machine was first given by Nakamura (1978). Following this idea, Schleef.et al. (2014) have built a machine called snow-maker. For the production of artificial snow, a wooden prototype of the existing design (Schleef.et al., 2014) have been built. Initially the geometric model of the wooden prototype was designed in Solidworks 2015. The schematic diagram of geometric model of snow making machine is shown in Fig. 3.1.

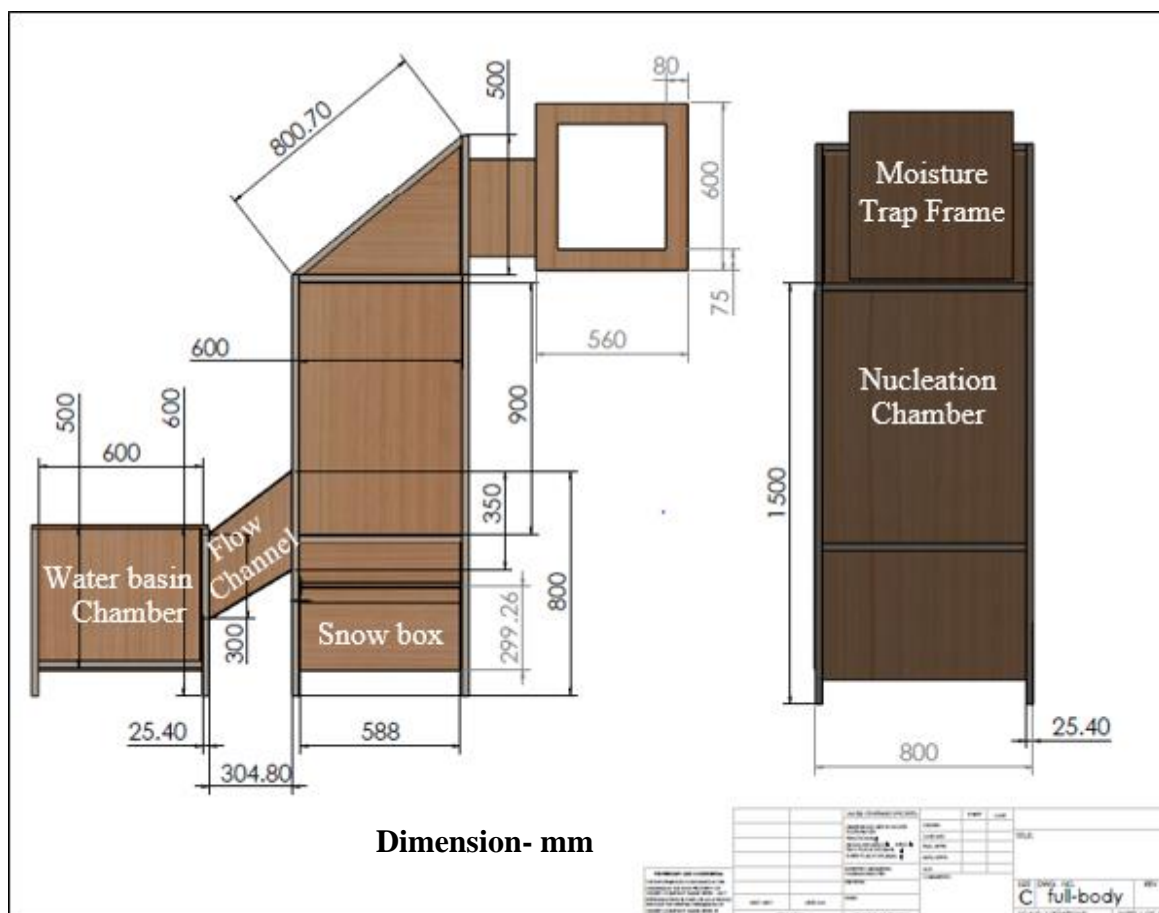


Figure 3.1: Schematic diagram of geometric model of snow making machine.

The snow making machine is divided into three sections named as a water basin, Nucleation Chamber and moisture trap. After the design of the geometric model of the snow making

machine, a wooden prototype of snow making machine was built in the workshop of SASE (Snow and Avalanche Study Establishment) by the help of this geometric model of snow making machine.

To carry the weight of snow making machine, the wooden frame is used across the snow making machine of size 2.54 cm \times 2.54 cm. The size of the water basin chamber is 60 cm \times 80 cm \times 50 cm. Figure 3.2 and Figure 3.3 show the initial stages of the fabrication of snow making machine.



Figure 3.2: Snapshot of nucleation chamber of snow making machine.



Figure 3.3: Inside view of the nucleation chamber during initial stage.

In the water basin chamber, the water is filled in a steel water tray of size 78 cm \times 57 cm with 15.5 cm of depth of water basin. An electronic box is mounted at the front side of the water basin to control the supply of all the electronic equipments. In the water basin, a heater coil of 2 kW is used to increase the temperature of the water. A three phase motor of 5 W and 1300 RPM is used to run the cross flow fan.

The water basin and nucleation chamber are connected by a rectangular diverging flow channel. The inlet and outlet cross sections of the diverging flow channel are 30 cm \times

80 cm, 35 cm × 80 cm respectively. The size of the nucleation chamber is approximately 60 cm × 80 cm × 90 cm. Inside the nucleation chamber, approximately 688 nylon wires of size 0.6mm are placed across the nucleation chamber (Rows = 16, Column = 43). The nylon threads were tightened by the help of nails of size 2.5 cm.

At the bottom of the nucleation chamber, a rectangular snow box of size 58.8 cm × 80 cm × 30 cm is placed to collect the snow after harvesting snow crystals from the nucleation chamber by the help of a manual brush. A small rectangular opening at the top of the nucleation chamber allows the moist air to pass through the moisture trap, so that remaining moisture could be trapped with a very small change in the relative humidity of the cold chamber. The material used in the moisture trap is made of cotton. The wooden prototype of snow making machine is shown in the Fig. 3.4.



Figure 3.4: Wooden prototype of artificial snow making machine.

After the fabrication of wooden prototype of snow making machine, in order to perform experiments, the snow making machine was carried inside the cold laboratory.

3.2 Formation of Snow Crystal in the Cold Laboratory

The study of the formation of snow crystal was carried out in the cold laboratory of SASA (Snow and Avalanche Study Establishment). The cold laboratory has three chambers with different temperature range. The experiments were performed in a third chamber having minimum achievable temperature is -45°C . During the first experiment, the temperature of the laboratory was maintained at -20°C and relative humidity of 38%. The temperature of the water basin was maintained at $25^{\circ}\text{C} \pm 2^{\circ}\text{C}$. After maintaining all the required conditions, the cross flow fan was started. In the first attempts, the very small growth of snow crystals was noticed on the nylon wires in the nucleation chamber. Figure 3.5 show the very small amount of growth of snow crystals on the nylon wires.



Figure 3.5: Growth of snow crystals on the nylon wires after the first experiment

The reason for the very small growth is that we had placed a honeycomb mesh inside the water basin with a submersible pump to allow the water to sprinkle over the honeycomb mesh with an expectation that when the high-temperature water will come in contact with low-temperature unsaturated air, it will increase the temperature and moisture content of the moist air. So when this air will reach in the low-temperature nucleation chamber, the temperature of the air will reduce and the process of supersaturation will take place. But this expectation was wrong. There was a problem because of the addition of honeycomb mesh. There was found blockage on the front side of honeycomb mesh due to the formation of snow-like crystals. So because of this, no air was crossing the honeycomb mesh. This blockage may be due to the presence of impurities in the water, the water was not filtered and deionized. So as the air came in the contact with the sprinkled water, the unsaturated air

stream became saturated and due to the presence of impurities in the water, which can act as nucleating agents could be the main cause of snow like crystal formation. Figure 3.6 shows the deposition of the snow on the front side of the honeycomb mesh.

At the end of the experiment, due to the horizontal position of the nails along the wall of the nucleation chamber. The nylon wires get off from the nails in long-running experiments. To overcome this, the direction of the nail was changed from horizontal to vertical by attaching wooden pieces across the wall of nucleation chamber.

Before starting the new experiments, following Observations and problems of the previous experiment were resolved.

1. Removal of honey comb mesh so that sufficient amount of air could pass over the water basin.



Figure 3.6: Deposition of snow on the front side of the honeycomb mesh.

2. A brush-like arrangement with an extension rod is made of wooden material in order to remove snow crystals manually. Figure 3.7 shows the manual brush-like arrangement.



Figure 3.7: Brush for harvesting the snow from the nylon wire into snow box.

After setting up all the problems, different sets of experiments were performed at different laboratory temperatures ($-20^{\circ}\text{C} - -35^{\circ}\text{C}$). In all the experiments, the temperature of the water basin was kept at ($25^{\circ}\text{C} \pm 2^{\circ}\text{C}$). The snow crystals formed were mainly dendritic in nature and the crystals were growing in the downward direction against the direction of flow of air. Figure 3.8, Figure 3.10 and Figure 3.11 shows the dendritic form of snow crystals on the nylon wires. Whereas, Figure 3.9 shows multi branching dendritic form of snow crystals under suspended condition inside the nucleation chamber.

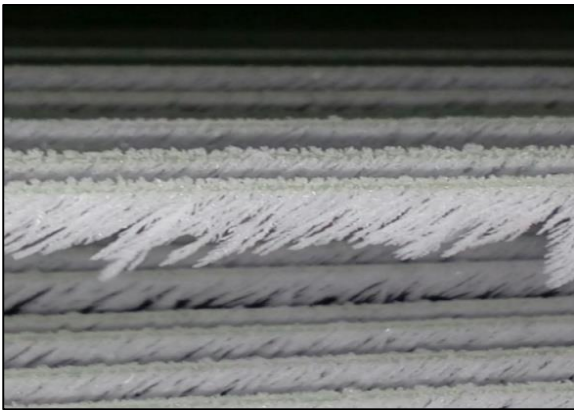


Figure 3.8: Dendritic snow crystals grown in a downward direction.



Figure 3.9: Multi branches snow crystal under suspended condition.



Figure 3.10: Dendritic snow crystals grown in downward direction.

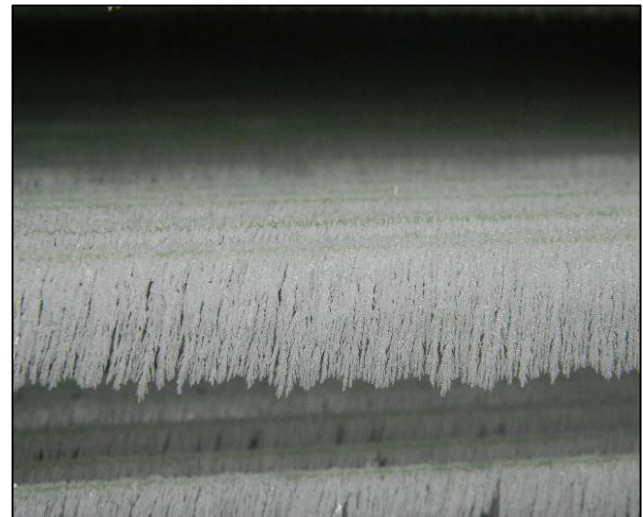


Figure 3.11: Dendritic snow crystals.

3.3 Instrumentation and Measurement

During the experiment, a number of instruments were used to measure the various parameters such as temperature, the velocity of air and relative humidity. A detailed description of these devices are explained below.

3.3.1 Data Logger

The data logger is a device which is used to automatic log the data at preset interval by the use of sensors. In our experiments, Data Taker DT 800 was used. Data taker DT800 is capable of measuring various parameters such as frequency, temperature, humidity, etc. the software used to communicate with DT800 are Delogger, Delogger Pro, De Transfer and De plot. Out of these, Delogger is used for communication, which has a graphical interface that eliminates the requirement of data logger programming. To measure the temperature at different positions across the snow making machine, T – type thermocouples were used. The connections of these sensors with the data taker DT800 are shown in Fig. 3.12.



Figure 3.12: Data acquisition by data Taker DT800.

To measure the relative humidity of the air after mixing with the water vapors in the water basin, the condition of the moist air was measured by RH/AT sensor and data logged by using the data logger CR 1000, which is shown in Fig. 3.13.



Figure 3.13: Data logger CR1000.

3.1.2 Kestrel Pocket Weather Meter

Kestrel pocket weather meter is a hand-held weather meter, which is used to measure the various parameters such as wind velocity, relative humidity, air and water temperature, dew point, heat stress index etc. In our experiments, the kestrel pocket weather meter is used to measure the velocity of air from the fan. The flow velocity was found to be 1.2 m/s at the starting of the experiments and it reduced with time form 1.2 m/s to 0.9 m/s due to the formation of frost on the blades of the fan. To make the flow velocity constant the frosting was removed from the blades during half an hour time interval. During the experiments, the pocket weather meter was also used to measure the condition of the relative humidity of the moist air in the cold laboratory. Fig. 3.14 shows the Picture of Kestrel Pocket Weather Meter.



Figure.3.14: Kestrel Pocket Weather Meter.

Chapter 4

Experimental Results and Discussion

4.1 Introduction

After the design of the snow making machine, the experiments were performed in the cold laboratory SASE (Snow and Avalanche Study Establishment). The various parameters measured during the experiments are temperature of the laboratory (T_{lab}), temperature of water basin (T_w), Temperature in nucleation chamber (T_{nuc}) velocity of air (V_{air}) and relative Humidity (Rh). The temperature, velocity of air and relative humidity at different positions are measured by the use of T- type thermocouple, Kestrel pocket weather meter and hygroclip AT/RH sensor respectively.

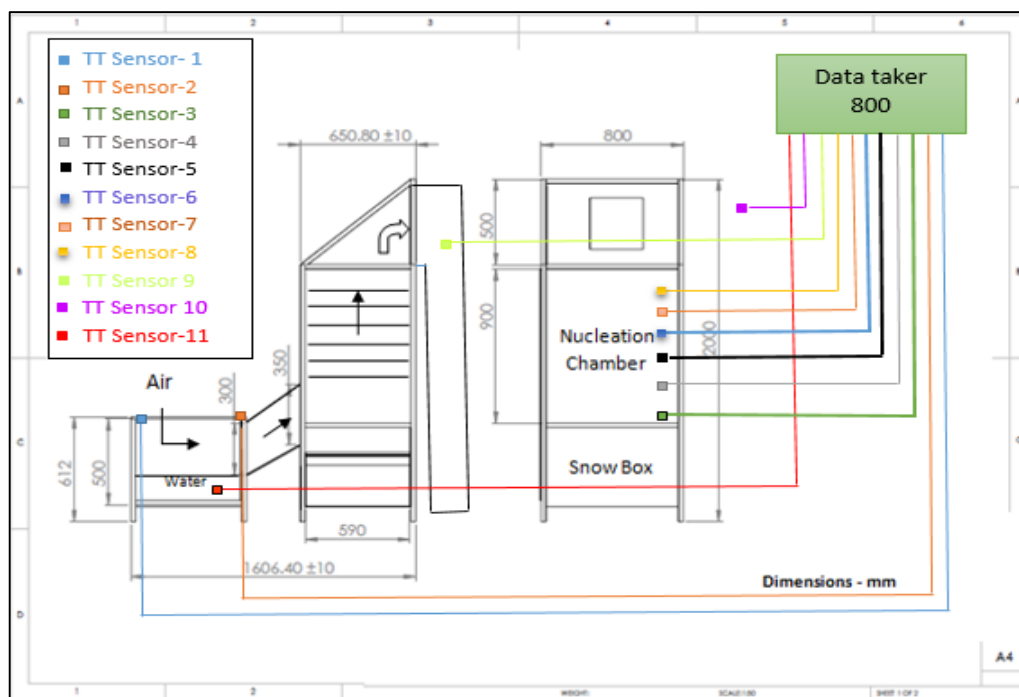


Figure 4.1: Schematic diagram of snow making machine.

To measure the temperature variation across the snow making machine, eleven thermocouples (T- type) were placed at different positions. T – Type thermocouple is very commonly used for low temperature applications. The material of T- type thermocouple is copper and constantan. The data was collected at a rate of one minute by the use of datataker DT800. The schematic diagram of snow making machine is shown in Fig. 4.1.

The distance between the two consecutive temperature sensors is shown in the Table 4.1. In the table, only 8 temperature sensors consecutive distances are mentioned. The TT- Sensor 9, 10 and 11 were placed in the moisture trapper, laboratory (T_{lab}) and water basin (T_w). The positions of these three temperature sensors were not fixed.

Table-4.1: Distance between two consecutive temperature sensors.

| Sr. No. | Temperature Sensors | Distance between two consecutive sensors (cm) |
|---------|---------------------------|---|
| 1 | TT Sensor-1 & TT Sensor-2 | 62 |
| 2 | TT Sensor-2 & TT Sensor-3 | 29 |
| 3 | TT Sensor-3 & TT Sensor-4 | 25 |
| 4 | TT Sensor-4 & TT Sensor-5 | 14.5 |
| 5 | TT Sensor-5 & TT Sensor-6 | 15.5 |
| 6 | TT Sensor-6 & TT Sensor-7 | 15 |
| 7 | TT Sensor-7 & TT Sensor-8 | 15 |

4.2 Experimental Results

In our experimental setup, the snow crystals are formed inside the nucleation chamber and as we know that, the snow crystals are formed when the water vapor in the atmosphere condenses directly into ice, bypassing the liquid phase. Since it a process of desublimation that leads to variation in temperature across the nucleation chamber. Hence in ordered to measure the temperature variation during the growth of snow crystals inside the nucleation chamber, T- type thermocouples were used at eleven different positions across the snow making machine. These thermocouples were used to measure the temperature of the cold laboratory (T_{lab}), temperature of water (T_w), and temperature variation across the nucleation chamber (T_{nuc}). Variation in the temperature across the nucleation chamber was measured, when the laboratory temperature (T_{lab}) was varied from -20°C to -35°C and the temperature of the water basin (T_w) was kept at $25^{\circ}\text{C} \pm 2^{\circ}\text{C}$.

4.2.1 Temperature Variation across Nucleation Chamber at Laboratory

Temperature of -20°C

The experiment was performed on 28 January 2017 in the cold laboratory of SASE, Manali (Snow and Avalanche Study Establishment). Before starting the experiment, the water basin

was filled with water. The temperature of the water (T_w) and the temperature of the cold laboratory (T_{lab}) was maintained at $(25^\circ\text{C} \pm 2^\circ\text{C})$ and $(-20^\circ\text{C} \pm 2^\circ\text{C})$ respectively. The relative humidity of the air was measured at various positions inside the cold laboratory by the use of kestrel pocket weather meter and an average value of the relative humidity was measured to be in the range of 60–70%. After maintaining the required conditions, the cross flow fan was started to allow the low temperature airstream to pass over the water basin. The velocity of the air directly after the fan was 2 m/s and almost vanishes inside the nucleation chamber. During this process, as the low temperature air passes over the water basin, it gets mixed with the high temperature water vapors that increases the temperature and moisture content of the air. After passing through the water basin, the air is passed into the nucleation chamber through the rectangular flow channel. At the inlet of the rectangular flow channel, the relative humidity of the air was measured and it was found to be fully saturated. As the air passes over the nylon wires inside the nucleation chamber, the process of formation of snow crystals is started. Since it a process of desublimation that leads to the variation in temperature across the nucleation chamber. The temperature variation across the nucleation chamber at laboratory temperature of -20°C is shown in Fig. 4.2.

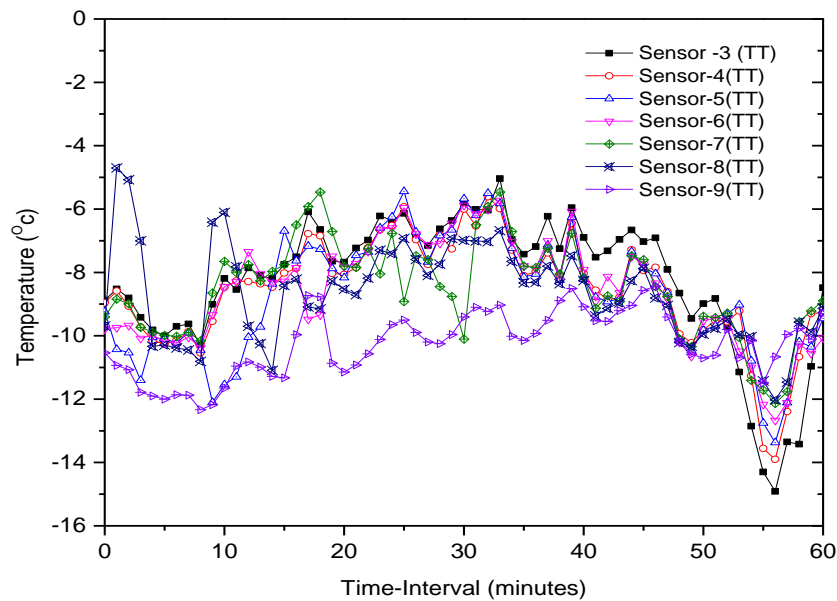


Figure 4.2: Temperature variation across the nucleation chamber at laboratory temperature of -20°C

The data collected of the temperature variation across the snow making machine by the data taker DT 800 is shown in the Appendix-A, Table-A1. The positions of the different T- type sensors are shown in the schematic diagram of a snow making machine (4.1). From Figure

4.2 Sensor-3(TT) to Sensor-9(TT) show the temperature variation across the nucleation chamber. In this graph, the temperature variation trending lines across the sensor-3(TT) to Sensor-8(TT) are overlapping. So in order to find out the trend of the temperature variations across the nucleation chamber, the average values of the temperature variations are measured across each sensor, which are shown in the Fig. 4.3.

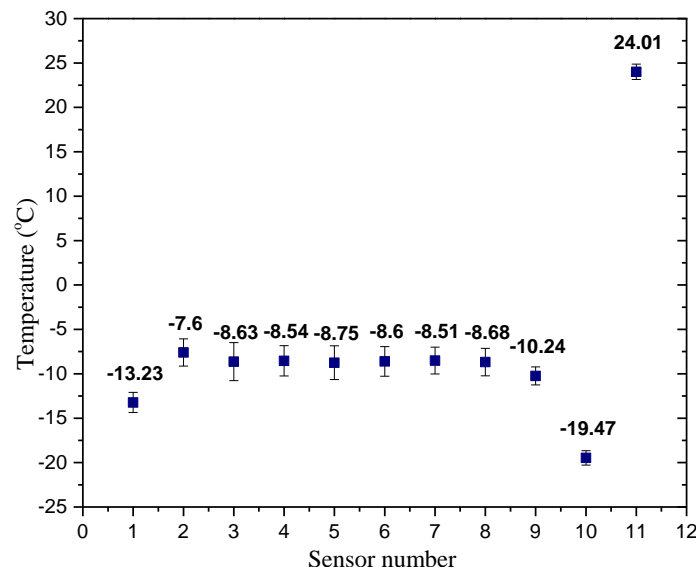


Figure 4.3: Average temperature variation across each Sensor at laboratory temperature of -20°C

Since the value of the temperature variation should increase along the length of the nucleation chamber due to the process of desublimation, but from the graph, it can be seen that the values of the temperatures are decreasing along the length of the nucleation chamber (-8.63°C to -10.24°C). The region behind the decrease in the temperature could be because of two heat transfer processes occurring inside the nucleation chamber.

1. Transfer of heat to the surrounding air in the nucleation chamber during the process of desublimation of water vapors into snow crystals.
2. Heat transfer from the nucleation chamber to the surrounding low temperature air of the laboratory.

So the net effect of these two processes is what is seen in the Fig. 4.3.

4.2.2 Production Rate of Snow at Laboratory Temperature of -20°C

After measuring the temperature variation across the nucleation chamber of snow making machine, the Production rate of snow is measured both in the snow box and moisture trap.

During the experiment, the density of the snow is also measured for each sample taken from the snow box and moisture trap. At -20°C the average value of the densities of snow in the snow box and moisture trap are $(0.147 \pm 0.01) \text{ g/cm}^3$ and $(0.145 \pm 0.01) \text{ g/cm}^3$ respectively. The variation in the production rate of snow at laboratory temperature of -20°C is shown in the Fig. 4.4

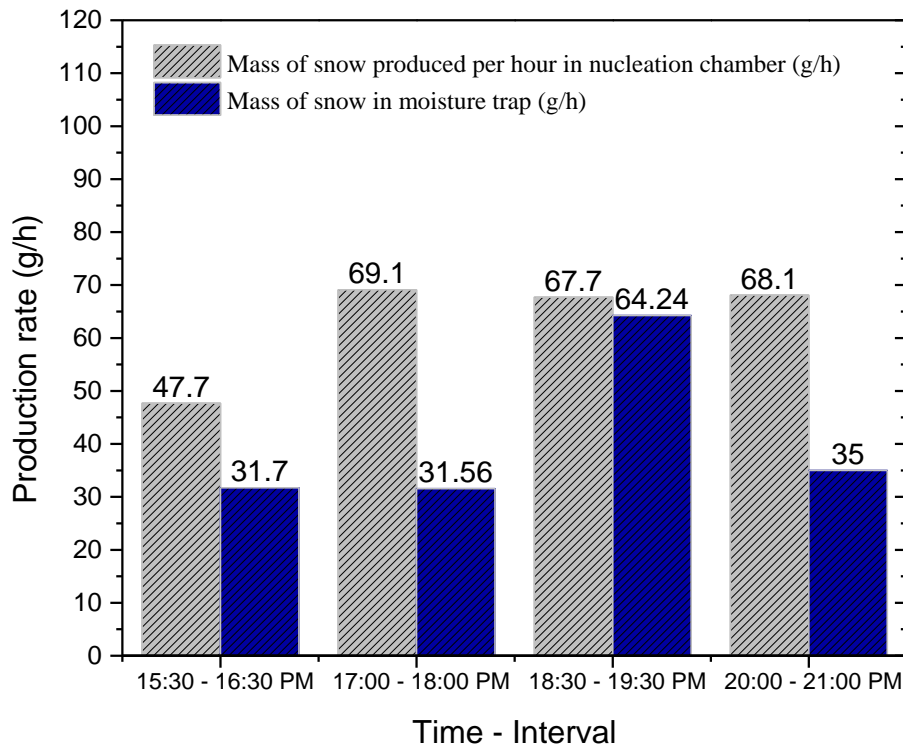


Figure 4.4: Production rate of snow (g/h) at laboratory temperature of -20°C .

At laboratory temperature of -20°C , the value of the production rate of snow (g/h) in the nucleation chamber is increasing after the first hour of operation. The reason for the increase in the amount of snow during the second hour of operation is the presence of small grains of ice crystals over the nylon wires after harvesting the snow during the first hour, these ice crystals act as nucleation sites that fastened the growth of snow crystals during 2nd hour of operation. After 2nd hour the production rate is becoming constant for the remaining time intervals. Whereas, in the moisture trap, the amount of snow produced is constant for first two hours of operation but then increasing and decreasing during the next hours.

The total volumetric production rate of snow is calculated and obtained values are plotted as shown in the Fig. 4.5. After measuring the temperature variation and production rate of snow

at laboratory temperature of -20°C , similar experiments were repeated by maintaining the laboratory temperature at -25°C , -30°C and -35°C .

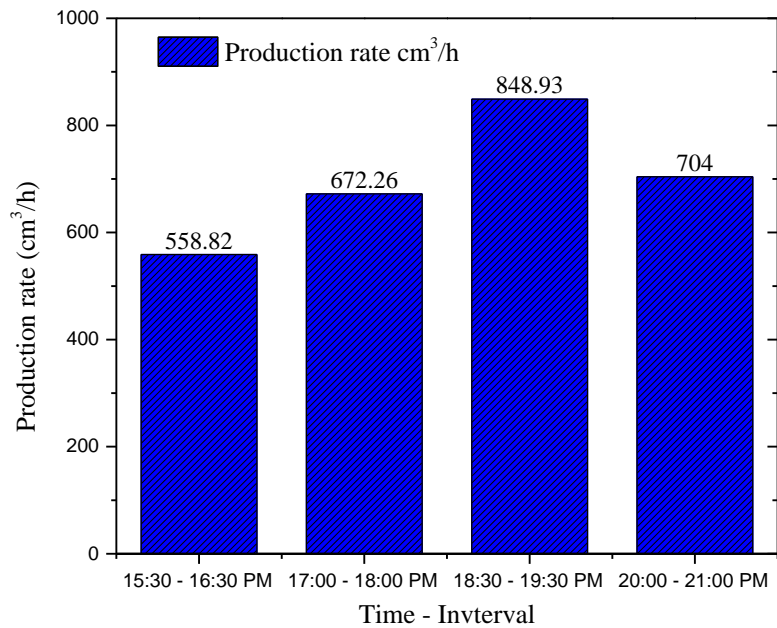


Figure 4.5: Production rate of snow (cm^3/h) at laboratory temperature of -20°C .

4.2.3 Temperature Variation across Nucleation Chamber at laboratory temperature of -25°C

The temperature variation across the snow making machine at laboratory temperature of -25°C is shown in the Fig. 4.6.

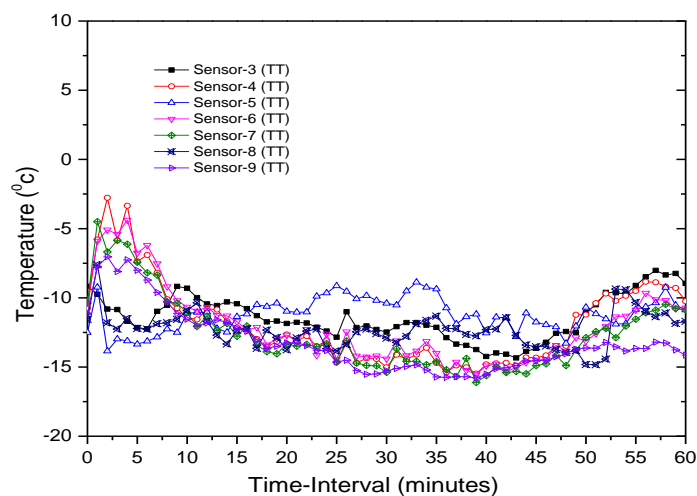


Figure 4.6: Temperature variation across the nucleation chamber at laboratory temperature of -25°C .

The data collected of the temperature variation across the snow making machine by the data taker DT 800 is shown in the Appendix-A Table-A2. To determine the trend of the temperature variations across the nucleation chamber, the average values of the temperature variations are measured across each sensor, which are shown in the Fig. 4.7.

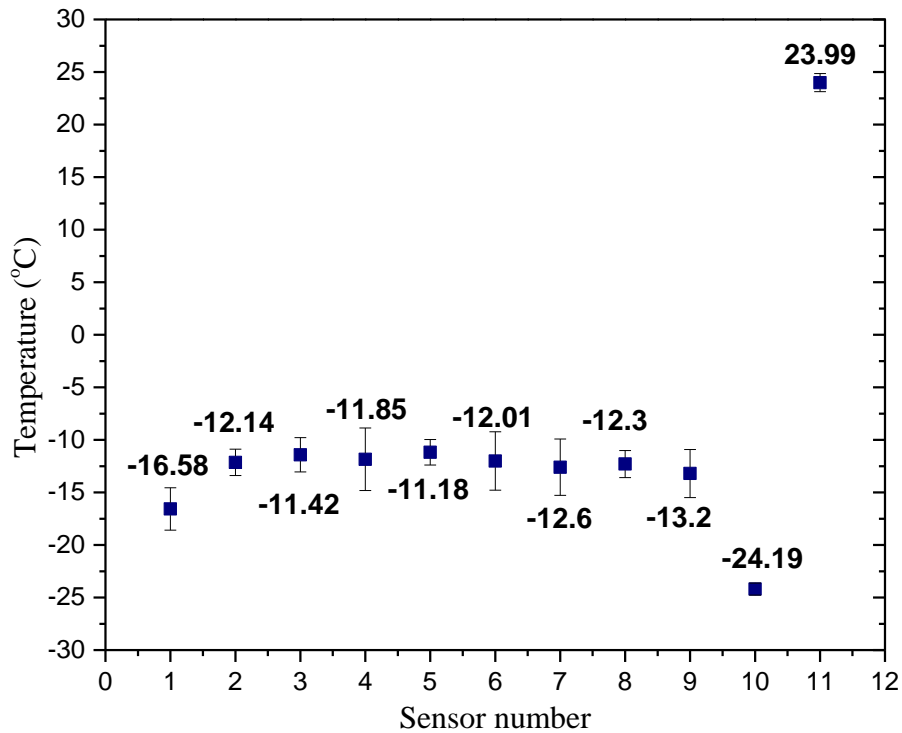


Figure 4.7: Average temperature variation across each Sensor at laboratory temperature of -25°C .

4.2.4 Production Rate of Snow at Laboratory Temperature of -25°C

To measure the production rate of snow across the nucleation chamber and moisture trap, the weight of the snow boxes with snow and without snow were measured by the use of Mettler Toledo weighing machine. The obtained values of production rates of snow at laboratory temperature of -25°C inside the nucleation chamber and moisture trap are shown in the Fig. 4.8. Figure 4.8 shows that the amount of snow produced inside the nucleation chamber is of considerable amount as compared to snow collected in the moisture trap.

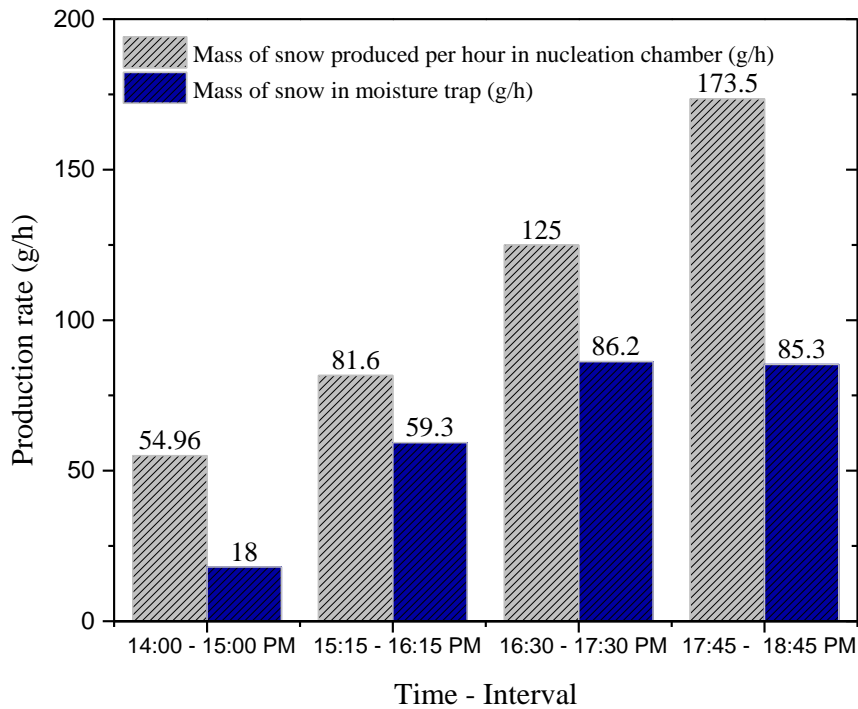


Figure 4.8: Production rate of snow (g/h) at laboratory temperature of -25°C .

From the graph, it can be seen that the production rate is increasing with each time interval. The reason for the increase in the production rate during the second hour of operation is the presence of small grains of ice crystals over the nylon wires after harvesting the snow crystals during the first hour, these ice crystals act as nucleation sites that fastened the growth of snow crystals during the 2nd hour of operation. In the 3rd and 4th hour of operation, the growth rate is further increasing. This increase in growth rate could be because of this reason.

The relative humidity of the air present in the cold laboratory is increasing with time because the air after passing through the water basin, nucleation chamber and moisture trap, is again mixing back with the air present in the laboratory. So the net moisture content of the air present in the laboratory is increasing with time that causes the increase in the production rate of snow with each time interval. In our design of snow making machine, the W/H ratio of the water basin is low.

In the moisture trap, the values of mass of snow are increasing during 14:00 PM to 17:30 PM and then becoming constant. To measure the density of the snow, a sample of 100 cm^3 was taken and its weight was measured by the use of Mettler Toledo weighing machine. After measuring the density, the volumetric production rate is calculated and obtained values are shown in the Fig. 4.9.

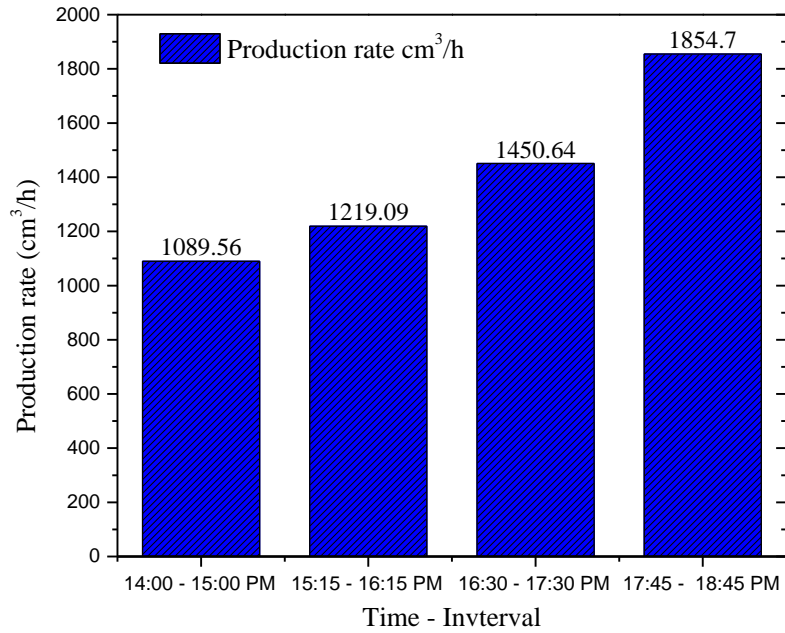


Figure 4.9: Production rate of snow (cm³/h) at laboratory temperature of -25°C.

4.2.5 Temperature Variation across Nucleation Chamber at laboratory temperature of -30°C

The temperature variation across the snow making machine at laboratory temperature of -30°C is shown in the Fig. 4.10.

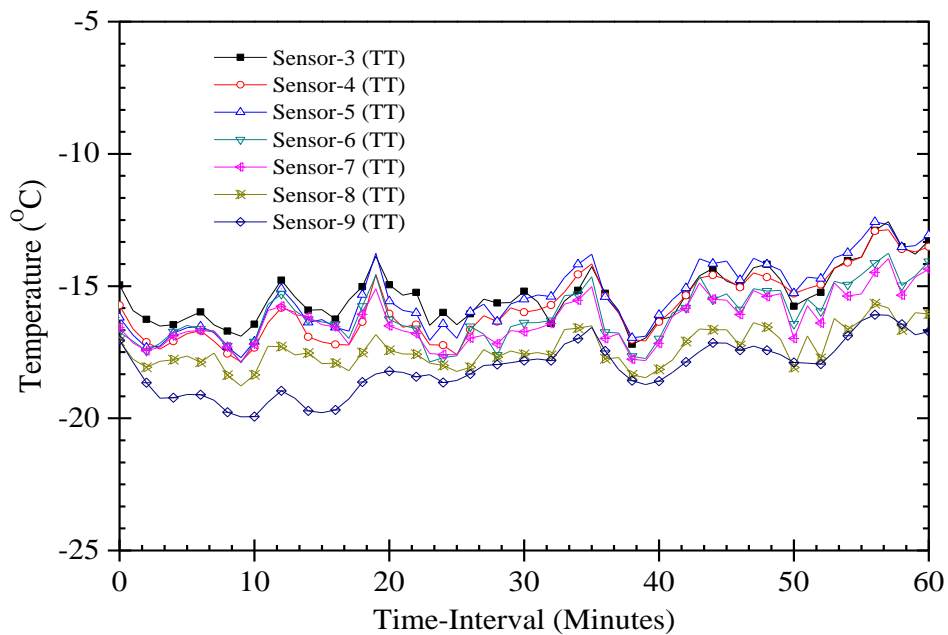


Figure 4.10: Temperature variation across the nucleation chamber at laboratory temperature of -30°C.

The data collected of the temperature variation across the snow making machine by the data taker DT 800 is shown in the Appendix-A Table-A3. To determine the trend of the temperature variations across the nucleation chamber, the average value of the temperature variation are measured across each sensor, which are shown in the Fig. 4.11.

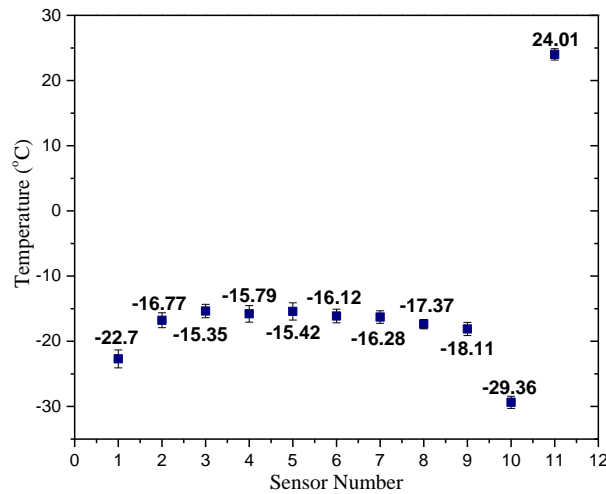


Figure 4.11: Average temperature variation across each sensor at laboratory temperature of -30°C.

4.2.6 Production rate of snow at laboratory temperature of -30°C.

After measuring the temperature variation across the nucleation chamber at laboratory temperature of -30°C, the production rate of snow are determined. The production rates of snow across the nucleation chamber and moisture trap are shown in Fig. 4.12.

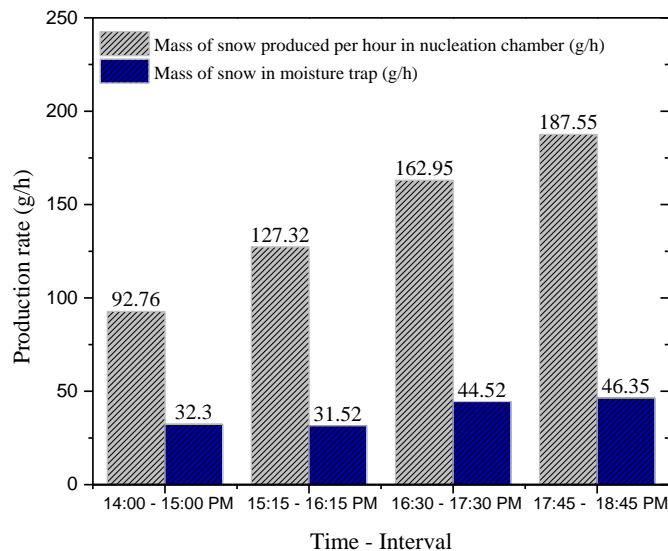


Figure 4.12: Production rate of snow (g/h) at laboratory temperature of -30°C.

From the Fig. 4.12, it can be seen that, as the temperature of the laboratory is decreasing, the mass of the snow produced per hour across the nucleation chamber is increasing with time and at the same moment, the values of mass of snow produced across the moisture trap are reducing. The production rate of snow inside the nucleation chamber is increasing because of the increase in the relative humidity of the air with time that increase the mass content of air for a constant value of volume flow rate. The total volumetric production rate of snow are calculated and obtained values are plotted as shown in Fig. 4.13.

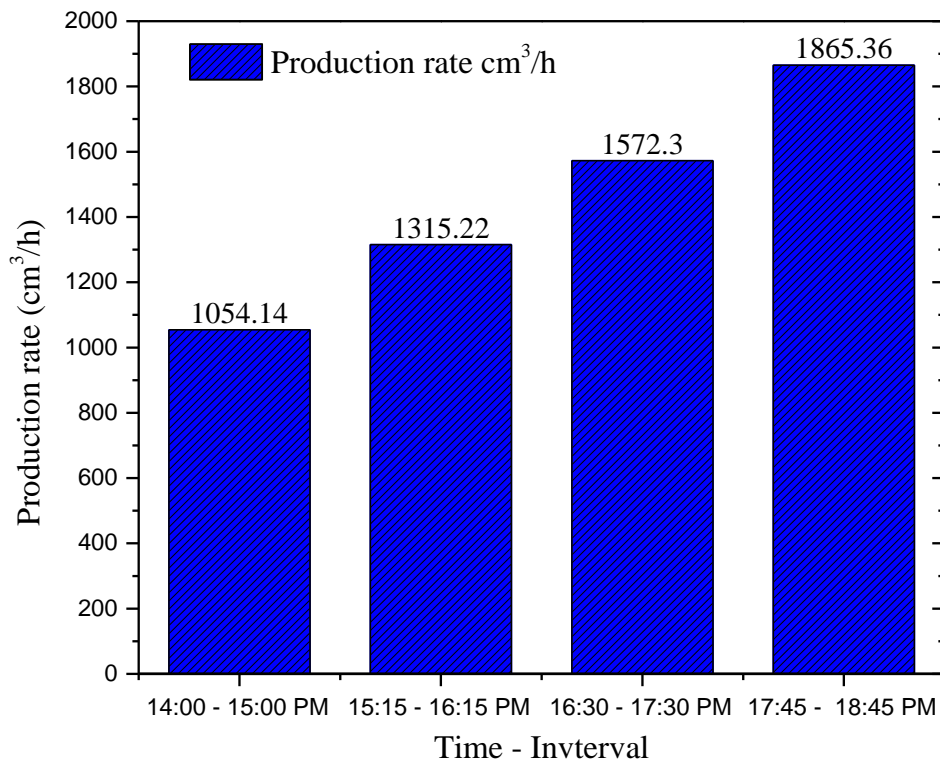


Figure 4.13: Production rate of snow (cm³/h) at laboratory temperature of -30°C

4.2.7 Temperature Variation across Nucleation Chamber at laboratory temperature of -35°C.

The temperature variation across the snow making machine at laboratory temperature of -35°C is shown in Fig. 4.14.

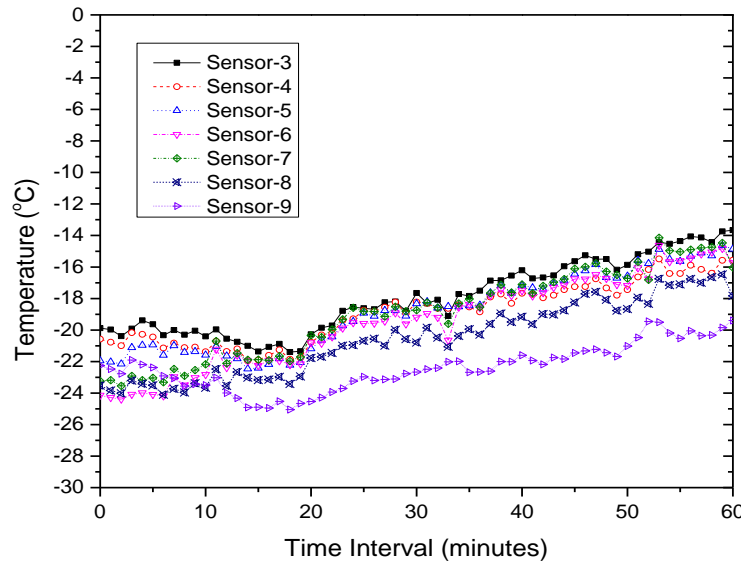


Figure 4.14: Temperature variation across the nucleation chamber at laboratory temperature of -35°C .

The data collected of the temperature variation across the snow making machine by the data taker DT 800 is shown in the Appendix-A Table-A4. To determine the trend of the temperature variations across the nucleation chamber, the average value of the temperature variation was measured across each sensor, which are shown in the Fig. 4.15.

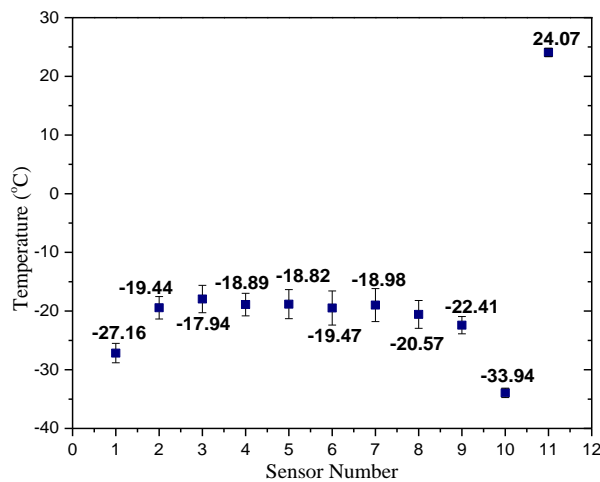


Figure 4.15: Average temperature variation across each Sensor at laboratory temperature of -35°C .

4.2.8 Production Rate of Snow at Laboratory Temperature of -35°C .

The production rate of snow across the nucleation chamber and the moisture trap are shown in the Fig. 4.16. From the graph, it can be predicted that, between two consecutive time intervals, the differences in values of the production rate of snow across the nucleation

chamber and moisture has been reduced. The average value of snow produced in the nucleation chamber and moisture trap at laboratory temperature of -35°C are 178.53 g/h and 49.4 g/h .

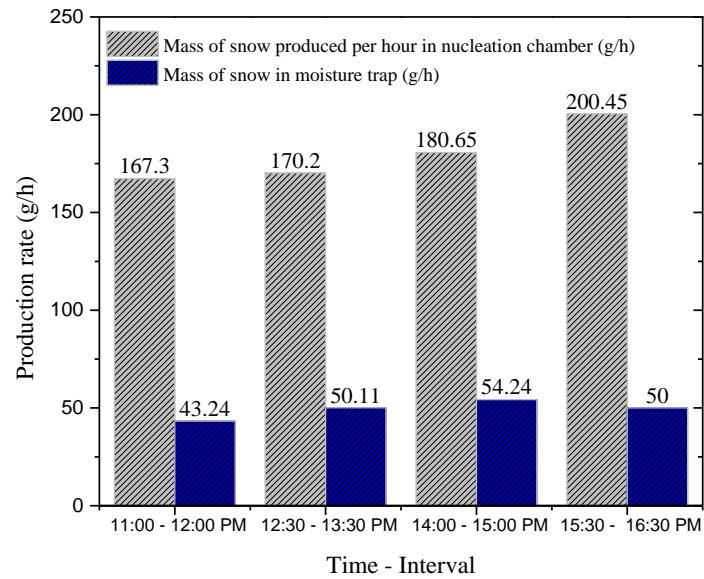


Figure 4.16: Production rate of snow (g/h) at laboratory temperature of -35°C .

After measuring the density of snow for each sample of nucleation chamber and moisture trap for all time- intervals, the total volumetric production rate of snow (cm^3/h) are calculated, which are shown in the Fig. 4.17.

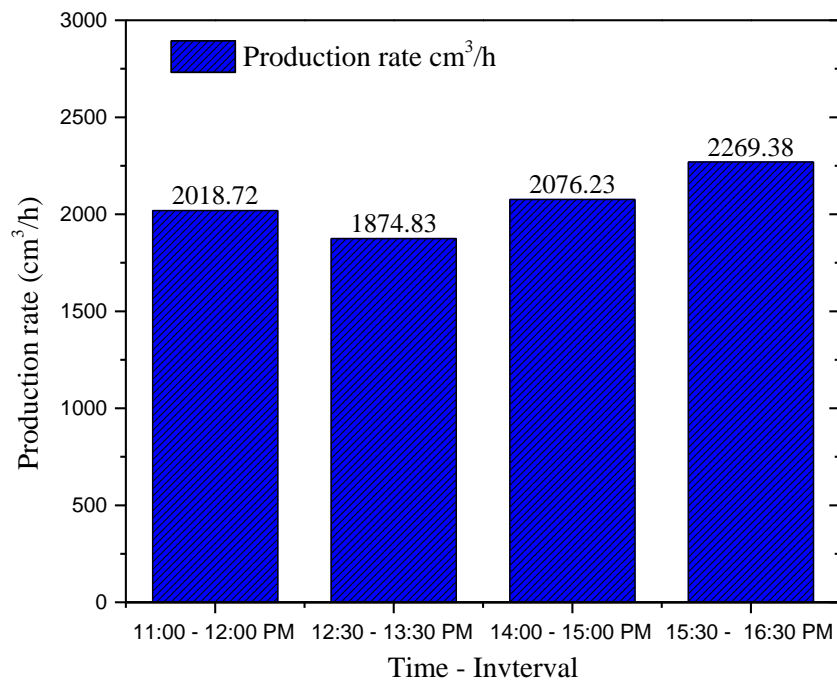


Figure 4.17: Production rate of snow (cm^3/h) at laboratory temperature of -35°C .

The average values of the Production rate of snow inside the nucleation chamber at different laboratory temperatures are measured, which are shown in the Fig. 4.18.

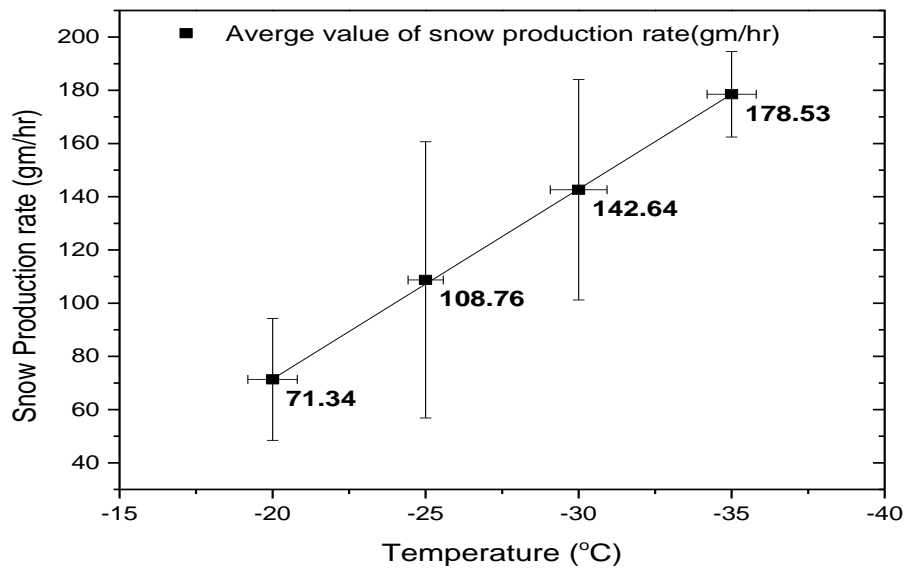


Figure 4.18: Average value of snow production rate inside the nucleation chamber at different laboratory temperatures.

The density of the snow produced inside the nucleation chamber is reduced as the laboratory temperature is varied from -20°C to -35°C . The average values of density of snow inside the nucleation chamber at different laboratory temperatures are shown in Fig. 4.19.

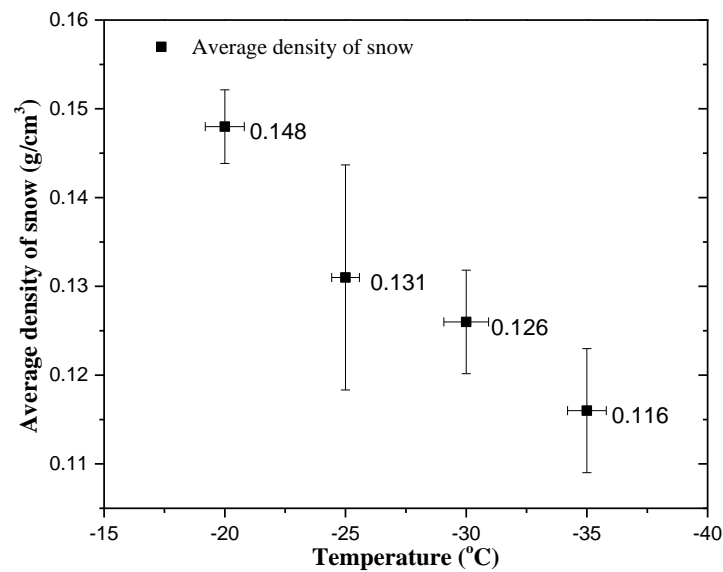


Figure. 4.19: Average density of snow inside the Nucleation Chamber at different laboratory temperatures.

The average density of snow inside the moisture trap at different laboratory temperatures ranging from -20°C to -35°C are shown in the Fig. 4.20.

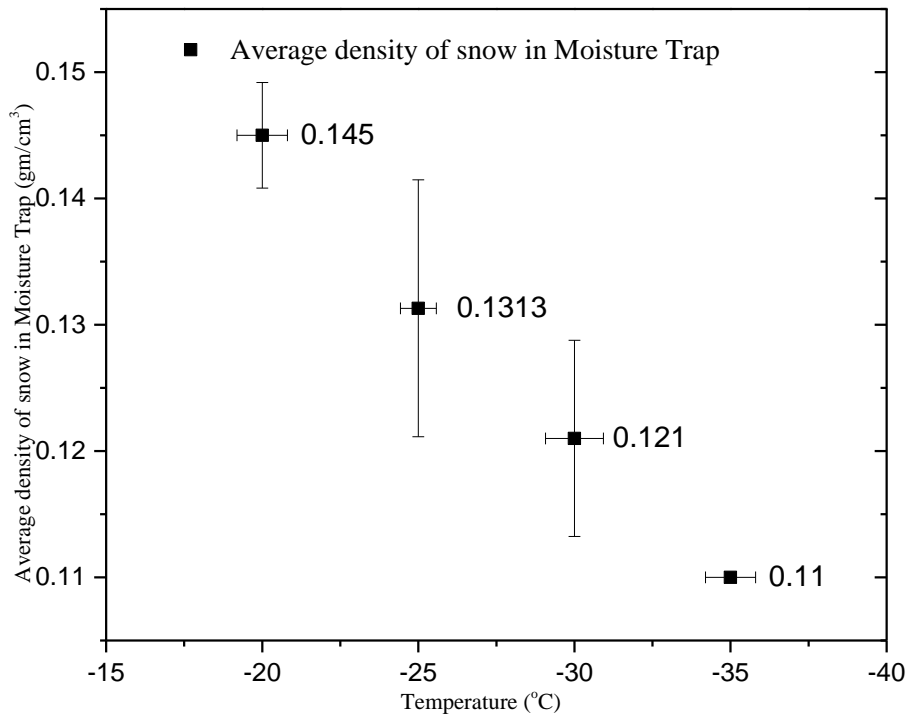


Figure 4.20 Average density of snow inside the moisture trap at different laboratory temperature.

After measuring the production rates (g/h) at different laboratory temperatures from -20°C to -35°C, with 5°C temperature difference, the snowfall rate inside the rectangular snow box of area (77.7 cm × 47.2 cm) is calculated from the data obtained during the experiments.

To calculate the snowfall rate, the volume production rate was equated with the volume of the snow box and height of snow was calculated.

$$H = \frac{\dot{V}_{snow}}{A} \quad (4.1)$$

Where H= Height of the snow fall in an hour (cm/h)

\dot{V}_{snow} = Volumetric production rate of snow per hour (cm³/h)

A = Inside area of snow box (cm²)

The calculated values of the snowfall rate (cm/h) at different laboratory temperatures are shown in the Fig. 4.21.

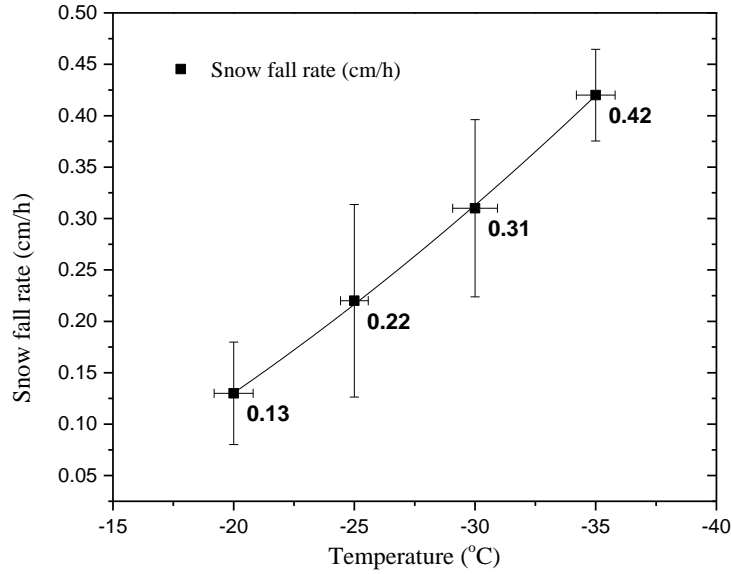


Figure 4.21: Snow fall rate (cm/h) inside the nucleation chamber at different laboratory temperatures.

4.2.9 Microstructure of snow from microcomputer tomography (μCT)

An X- Ray (radiography) system produces two dimensional shadow images of complete internal three dimensional structures, but in a single two dimension shadow projection system, the depth information is completely mixed. Only X- ray tomography system allow us to visualize and measure complete three dimensional object structures. An automated polycot machine “SKYSCAN 1173”, (Germany) is used for the microtoming of the snow sample. The minimum operating temperature of this machine is -15°C . The schematic diagram of microcomputer tomography (μCT) is show in the Fig. 4.22.



Figure 4.22: Schematic diagram of microcomputer tomography machine.

Specifications of SKYSCAN 1173

The specification of the SKYSCAN 1173 are given in the Table 4.2

Table 4.2: Specifications of SKYSCAN 1173.

| | |
|---------------------|--|
| X- ray source | 40-130KV , < 5 μ m spot size |
| Maximum object size | Diameter = 140mm , length = 200mm |
| Spatial resolution | < 4-5 μ m detail detectability, 7-8 μ m low contrast resolution. |
| Optical stages | Cooling , Heating, Compression/Tension |

Microtoming of Artificial and Natural Snow Samples

After aging, samples of snow were sieved by the use of a mechanical siever of size 1.4mm in a sample holder of Size (diameter=15mm and height of 30mm). It is a very common method of sample preparation for microstructural parameters (Satyawali et al., 2008; Schleef and Lowe, 2013 and Schleef et al., 2014). After the samples preparation, samples were placed inside the machine for scanning. During scanning, a projection image of the snow sample is formed. This projection image is reconstructed to form a gray scale image. A gray scale image of both type of snow sample are shown in the Fig. 4.23.

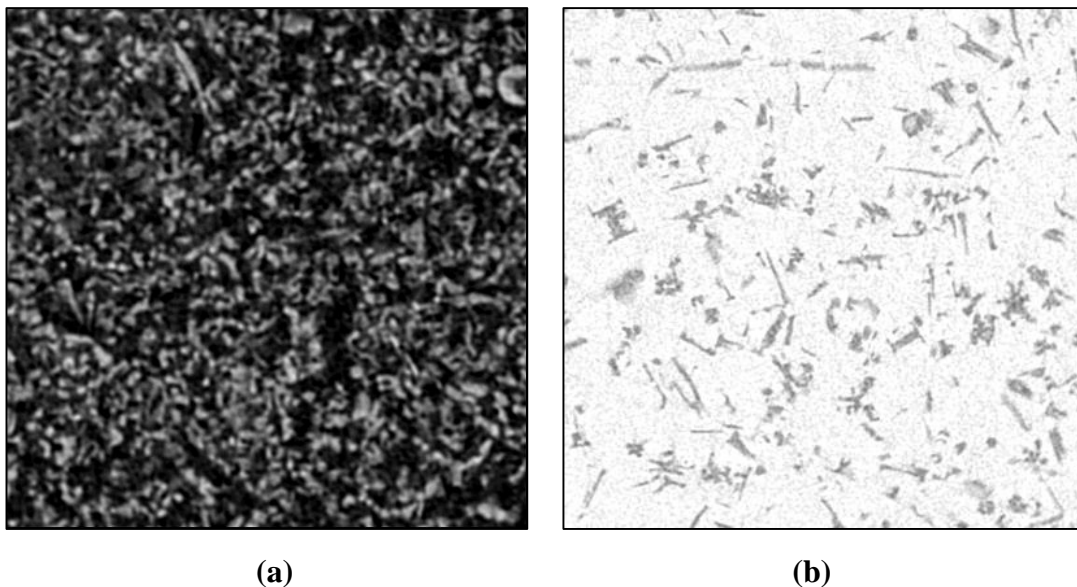


Fig. 4.23 Gray scale images (image resolution = 8.56) (a) artificial snow sample and (b) natural snow sample.

These gray scale image is in Tagged Image File Format (TIFF), which was loaded in image-Pro Plus (IPP) 4.0 software, where gray scale image is converted into a binary image. The binary scale image of the snow sample is shown in the Fig. 4.24.

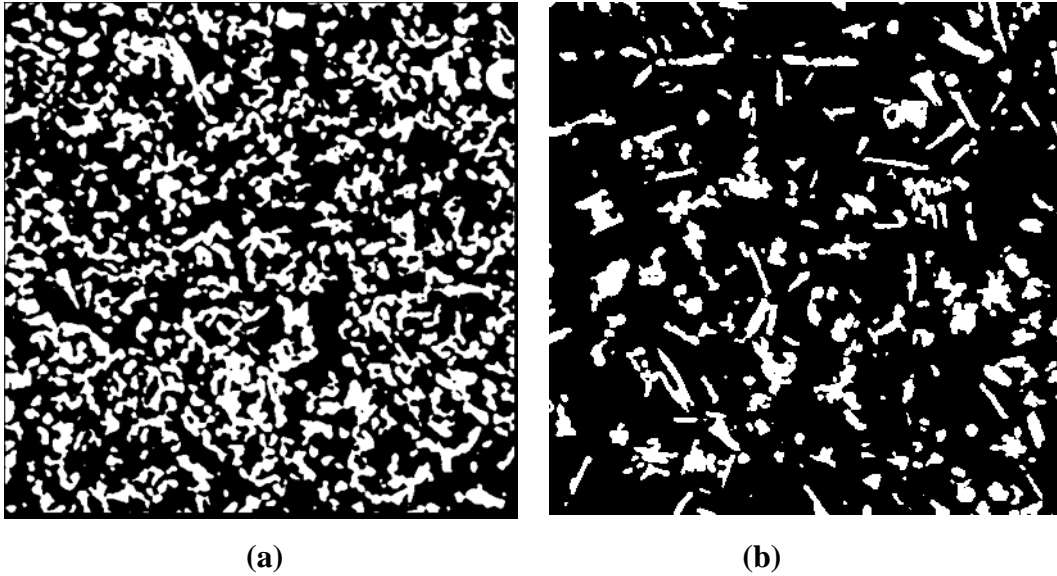


Fig. 4.24 (a) Binary scale images (image resolution = 8.56) (a) artificial snow sample and (b) natural snow sample.

The morphometric parameters of snow such as structural thickness, structural separation, and porosity of artificial snow sample are compared with the natural snow. The resulting values are shown in the Table - 4.3.

Table-4.3 Comparison of Morphometric parameters between snow sample of snow making machine and Natural snow.

| Description | Snow sample of Snow making machine (30 day age) | Natural snow (30 day age) | Unit |
|-----------------------|--|----------------------------------|-------------|
| Resolution | 8.56 | 8.56 | μm |
| Structural thickness | 0.113 | 0.232 | mm |
| Structural separation | 0.167 | 0.295 | mm |
| Total porosity | 64.03 | 63.91 | % |
| Percent object volume | 36.8 | 35.96 | % |

schematic. The snow is formed by mixing airstreams in the mixing chamber, one is coming from the refrigeration unit and the other coming from the humidifier. The air coming from the refrigeration unit will be unsaturated and at low temperature (T_1), whereas, the air coming from the humidifier section will be saturated and at a higher temperature (T_2). Before mixing, the mass flow rate of these two streams will be adjusted in such a way that after mixing, the supersaturated atmosphere will be formed. After mixing, the supersaturated air will be passed through the nucleation chamber.

5.2 Nucleation Chamber Design

A nucleation chamber of size ($L= 2000\text{mm}$, $W = 1700\text{mm}$ and $H=3500\text{mm}$) is shown in Fig. 5.2. In this figure, Top view, Front view, Side view and Isometric view are shown. In the nucleation chamber, five roller belt assemblies, each at a distance of 333.34mm is placed across the nucleation chamber. The belt used on the roller will be designed in such a way that the nylon wire mesh can be attached to the belt. At the bottom of each roller belt assembly, a thread cutter will be placed, which will be used to harvest the snow. After harvesting, the snow will be collected in the snow box.

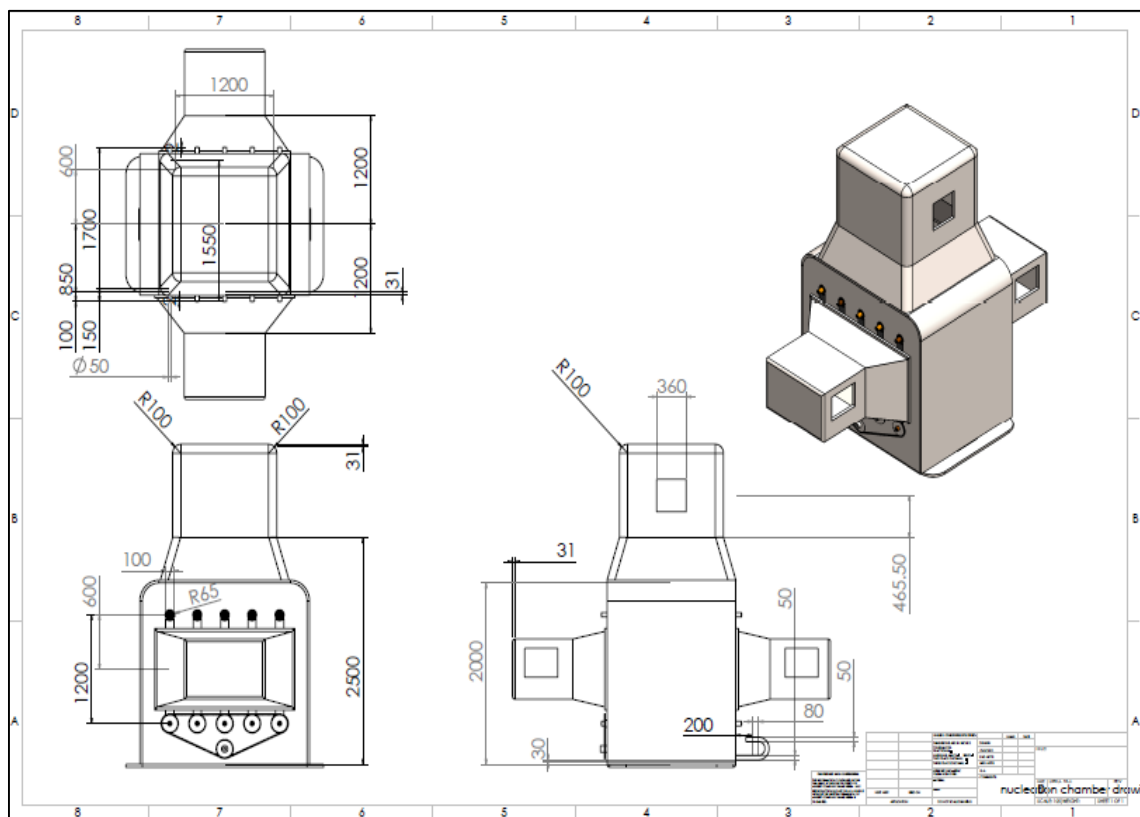


Figure 5.2: Design of Nucleation Chamber.

The exploded view of the nucleation chamber of snow making machine is shown in Fig. 5.3.

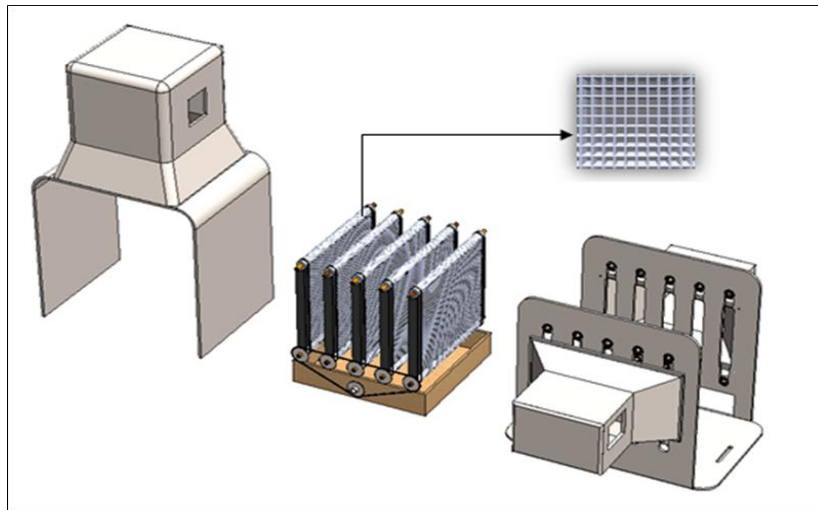


Figure 5.3: Exploded view of Nucleation Chamber.

The designs of various components used in the nucleation chamber for the production of snow are described below.

5.2.1 Design of Roller Belt Assemble

In the previous design of the snow making machine, the nylon wires were fixed and placed in the horizontal direction across the nucleation chamber. Whereas in the new design, the nylon wire mesh is mounted on the roller belt assembly, which is rotated by the sprocket chain assembly. The design of roller belt assembly is shown in the Fig. 5.4.

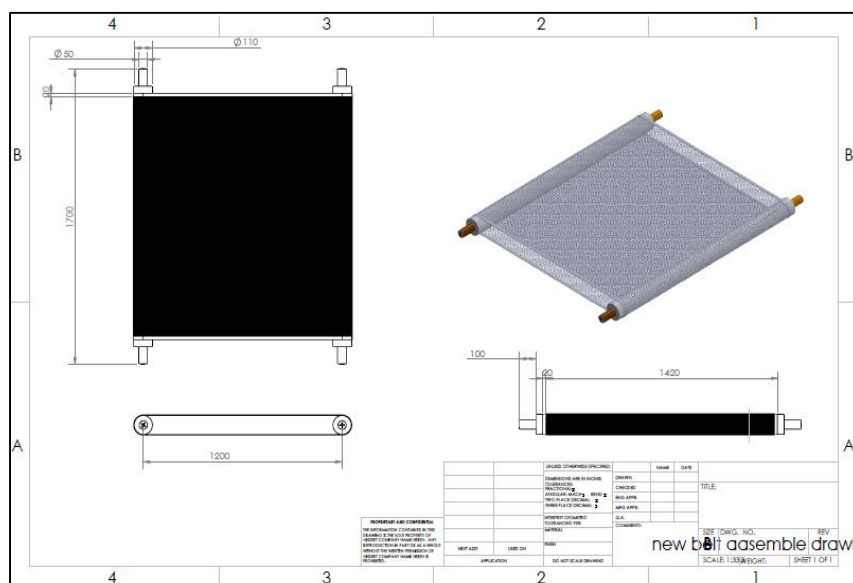


Figure 5.4: Design of Roller Belt Assemble for Nucleation Chamber.

In the roller belt assembly design, two rollers of 50mm shaft diameter are placed at a distance of 1200 mm. The length of the shaft is 1700mm. In this design, a 5× 5 nylon wire mesh (0.6mm wire diameter) is mounted over the hubs of the shafts. At low temperature, most of the ferrous metals show the transition from ductile to brittle. So it becomes very important to select a material that can have high structural strength and toughness in that regime. So for low-temperature application, 300 stainless steel series (304 LN, 316LN), the 15NiMn6 material can be used for shaft and hub.

After mounting the five roller belt assemblies across the nucleation chamber, the space between the two adjacent sides of the nylon wire mesh is separated by the use of the rubber frame to promote the directional flow of air. The design of the rubber frame is shown in the Fig. 5.5.

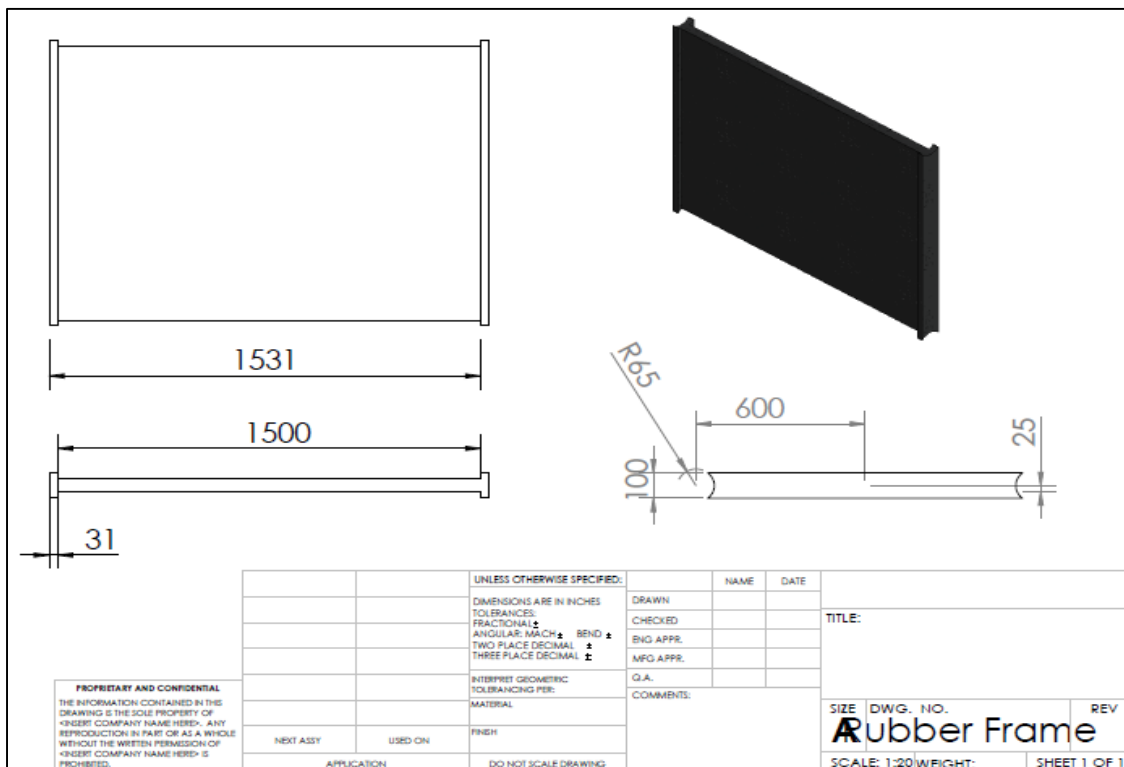


Figure 5.5: Design of Rubber Frame.

5.2.2 Sprocket Chain Mechanism

In order to rotate the five roller belt assemblies, sprocket chain mechanism is used. The design of the sprocket chain mechanism is shown in the Fig. 5.6. Cold Resistant Roller Chain RS 80-KT-1 can be used as a material for the chain for low temperature.

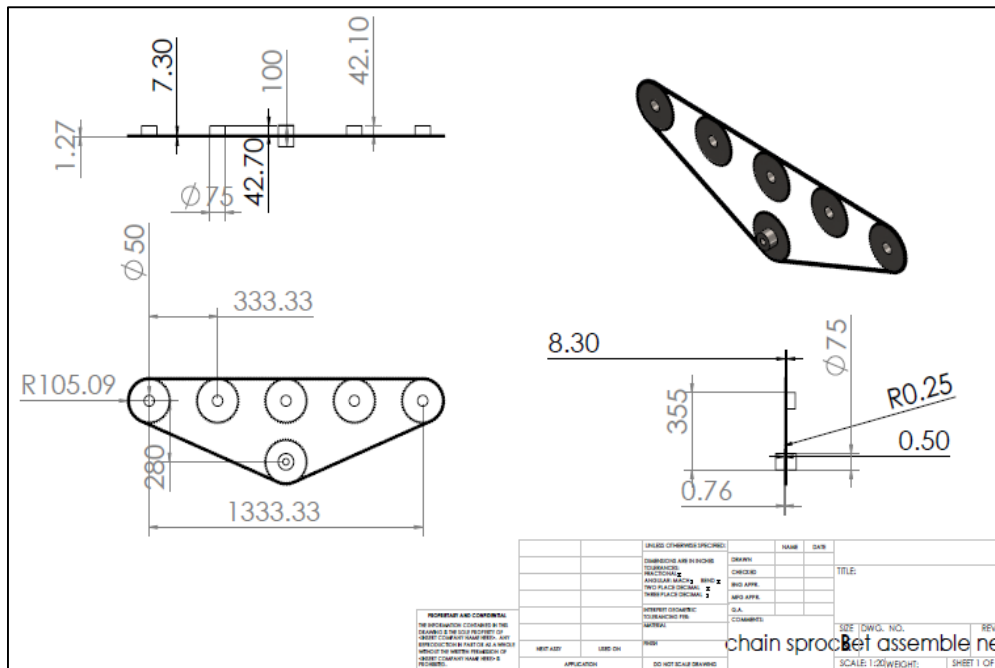


Figure 5.6: Design of Sprocket Chain Mechanism.

Advantages of proposed design of snow making machine

The advantages of the newly designed snow making machine are as such.

- In the previous design of snow making machine, the nylon wires were fixed at a particular position inside the nucleation chamber. Whereas in the new design, the nylon wire mesh is mounted over the roller so that each nylon wire can be moved across the nucleation chamber from top to bottom. The speed of rotation of the roller will be designed in such a way that each point on any thread will take an hour to complete the cycle, that results in the growth of snow crystal under dynamic condition. In this design, the snow crystals will be subjected to varying temperature conditions across the nucleation chamber.
- A cutter is placed at the bottom of each roller belt assemble, so no manual effort is required to harvest the snow from snowmaking machine.
- In this design, it is possible to analyze the formation of snow crystals under suspended form during the mixing of the two air streams in the mixing chamber.

5.3 Mathematical Analysis

In the new design of snow making machine, the two air streams are being mixed in the mixing section. In order to grow the snow crystals on the nylon wire mesh inside the nucleation chamber, the surrounding air must be supersaturated. To ensure such condition in the nucleation chamber, the mass flow rate of the two streams, one from the refrigeration unit and the other from the humidifier unit are adjusted. The schematic diagram of mixing of two air streams is presented in Fig. 5.7.

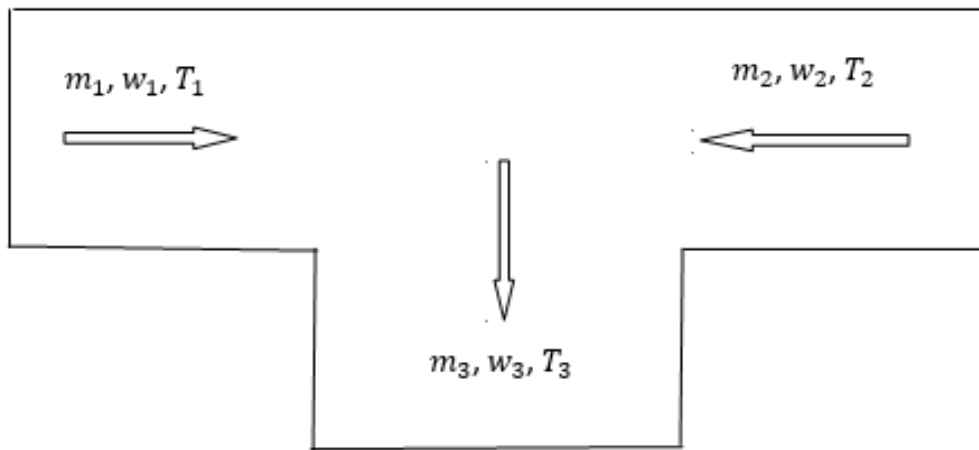


Figure 5.7: Schematic diagram of mixing of two working fluids.

From the schematic diagram, let m_1 mass of air coming from the refrigeration unit maintained at a temperature of (T_1) and specific humidity (w_1), whereas the air of mass (m_2) coming from the humidifier unit is maintained at a temperature (T_2), specific humidity (w_2). Since it is an adiabatic mixing process so from the mass balance equation. The value of specific humidity (w_3) after mixing process can be written as:

$$w_3 = \frac{m_1 \times w_1 + m_2 \times w_2}{m_1 + m_2} \quad (5.1)$$

From energy balance equation, the final temperature of the air after mixing can be written as:

$$T_3 = \frac{m_1 \times T_1 + m_2 \times T_2}{m_1 + m_2} \quad (5.2)$$

To measure the specific humidity (w) of moist air under saturated condition for a temperature range of $173.15 \leq T \leq 273.15$, the saturated vapor pressure over ice is calculated by the use of an equation given by Sonntag and Heinze (1982).

Over liquid water

$$\ln(P_W) = -6094.4642T^{-1} + 21.1249952 - 2.724552 \times 10^{-2} \times T + 1.6853396 \times 10^{-5} \times T^2 + 2.4575506 \times \ln(T). \quad (5.3)$$

Over ice

$$\ln(P_{ice}) = -5504.4088 \times T^{-1} - 3.5704628 - 1.7337458 \times 10^{-2} \times T + 6.5204209 \times 10^{-6} T^2 + 6.1295027 \times \ln(T). \quad (5.4)$$

After measuring the saturation pressure over ice, the specific humidity (w) can be obtained by this equation.

$$W = \frac{0.622 \times P_{ice}}{P_{atm.} - P_{ice}} \quad (5.5)$$

In our design, the air coming from the humidifier unit will be at a temperature of -10°C and fully saturated, whereas the air coming from the refrigeration unit can be adjusted to a temperature range of up to -50°C.

5.4 CFD Simulation of Nucleation Chamber

Computational fluid dynamic (CFD) is the branch of fluid mechanics that is used for the prediction of fluid flow behaviors by finding out the numerical solution of the governing equations. The simulation of the nucleation chamber is performed in ANSYS® FLUENT® v1. In CFD analysis, basically three steps are followed that are explained below.

5.4.1 Preprocessing

The objective of the simulation of nucleation chamber is to measure the temperature distribution across the nucleation chamber. First, the simple geometry of the nucleation chamber is imported in Ansys 2015 in IGES format from Solidworks 2015. The geometric model of nucleation chamber is shown in the Fig. 5.8.

After importing the geometry, the entire domain is discretized into small control volumes where the various form of Navier stroke equations such as conservation of momentum and energy equations are solved by the help of some iterative methods. An automatic mesh is generated with the relevance value of 100.

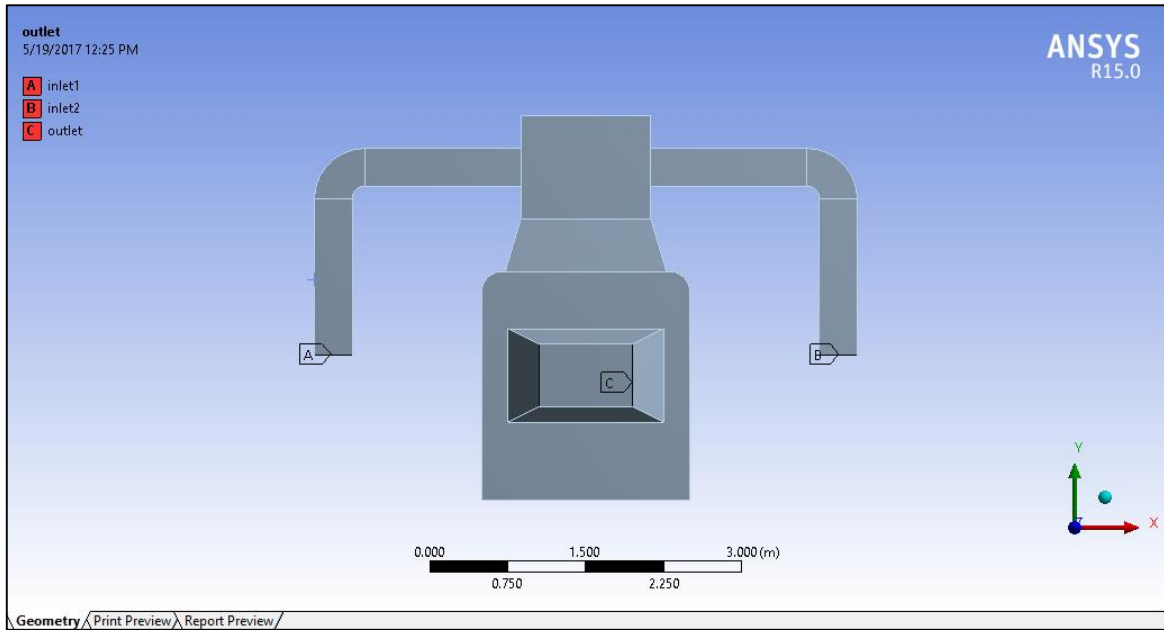


Figure 5.8: Geometric model of nucleation chamber.

The meshing of the nucleation chamber is shown in the Fig. 5.9. In this meshing, most of the cells are hexahedral. After meshing following statistics are obtained.

| | |
|-------------------------------------|------------------------|
| Average value of Aspect ratio | 1.0554 |
| Average value of orthogonal quality | 0.996 |
| Average value of skewness | 9.278×10^{-3} |

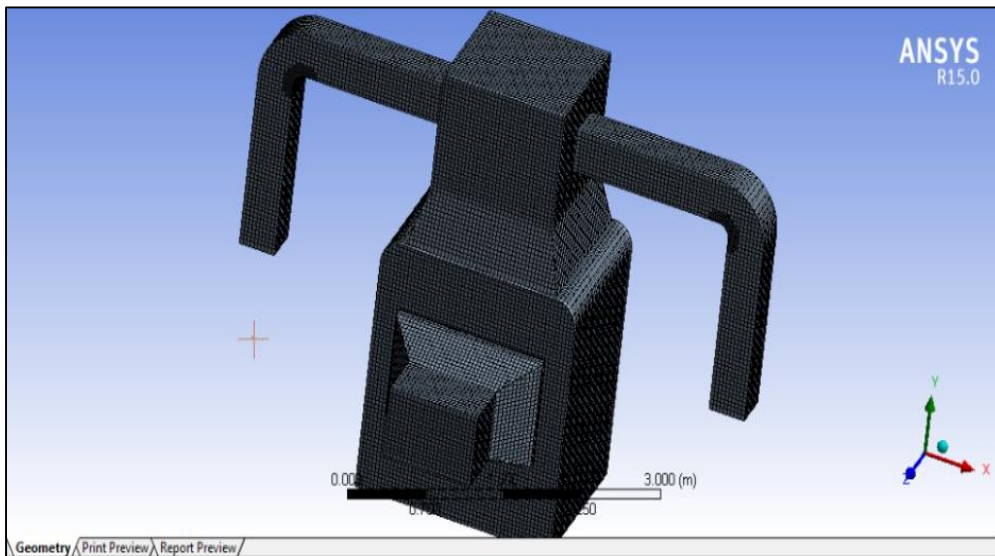


Figure 5.9: Meshing of geometric model of nucleation chamber.

5.4.2 Solver Setup

The simulation parameters used for the study of the temperature distribution across the nucleation chamber of the snow making machine are given in Table 5.1.

Table 5.1: Simulation Parameters

| Parameters | Values |
|----------------------------|--------------------------------------|
| Solver type | Pressure based |
| Velocity formulation | Absolute |
| Time | Steady |
| Model | Energy, k- ϵ (2- equation) |
| Near wall treatment | Standard wall treatment |
| Pressure Velocity coupling | Phase coupled simple |

Boundary conditions

The inlet boundary condition is velocity inlet in which velocity and temperature are given as 2m/s and 223.15 K for inlet 1 and 2m/s and 263.15K for inlet 2 respectively. The outlet boundary condition is pressure out in which pressure is set as zero Gauge pressure.

Convergence Criterion

Convergence criterion is based on the residual values of continuity, flow variables in x, y and z direction, kinetic energy and turbulent energy dissipation rate. The solution is assumed to be converged, when sum of the residual values falls below a specified convergence criterion. In the present simulation work, the residual values of all the flow variables are assigned values of 10^{-5} for better convergence results. The convergence results are obtained at 1500 iterations.

5.4.3 Post processing

In Post processing, the obtained results are plotting into various contour and vector form. The variation in the temperature distribution across the nucleation chamber is shown in the Fig. 5.10. As it can be seen from the result of contour, the temperature distribution across the nucleation chamber is similar to the expected results. High temperature can be seen in the right side of the nucleation chamber, which is close to high temperature inlet of the snow making machine.

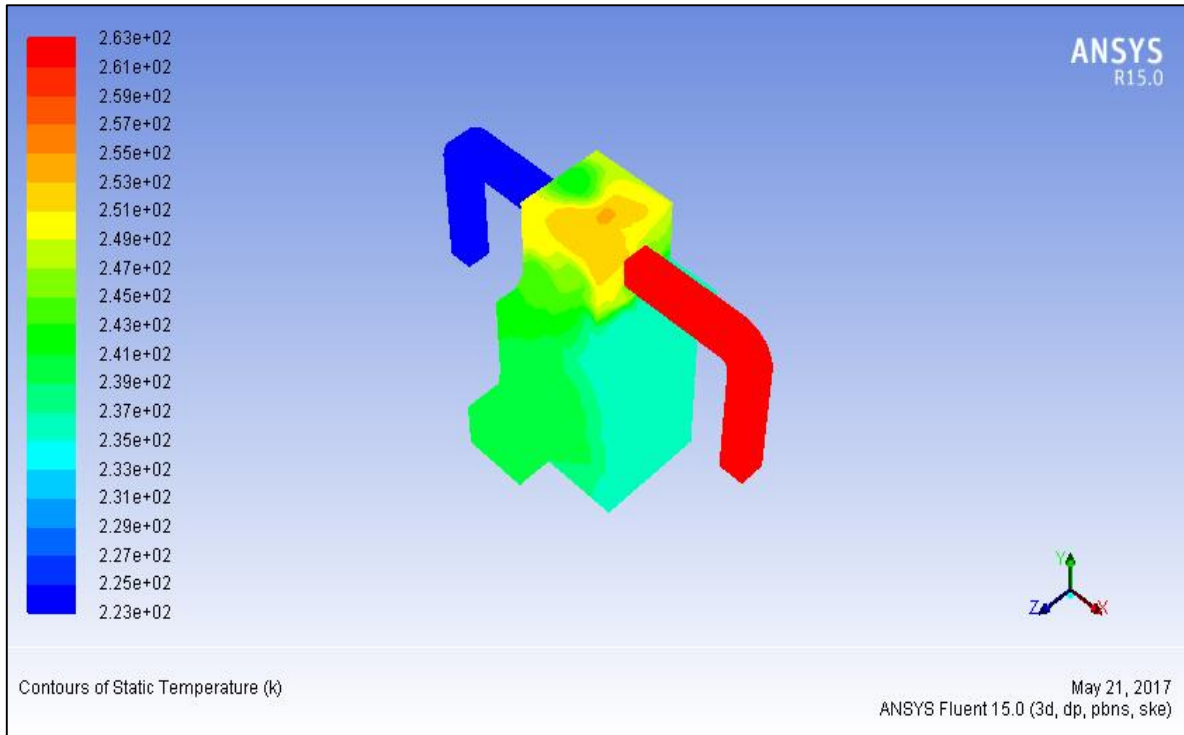


Figure 5.10: Contour results of temperature across the nucleation chamber.

Chapter 6

Conclusion and Future Scope

6.1 Conclusion

The following conclusions have been determined from this study.

1. The temperature variation across the nucleation chamber is measured by varying the laboratory temperature from -20°C to -35°C and keeping the temperature of the water basin at $25^{\circ}\text{C} \pm 2^{\circ}\text{C}$. In all the experiments, it has been found out that the average values of temperature variations are decreasing along the length of the nucleation chamber.
2. The production rate of snow is measured at different values of laboratory temperatures ranging from -20°C to -35°C . The average values of snow production rate inside the nucleation chamber at all the given values of laboratory temperatures are found to be 72 g/h, 108.76 g/h, 142.64 g/h and 178.53 g/h. After measuring the production rate, microtoming of the artificial snow sample and natural snow sample is done by the use of microcomputer tomography machine (SKYSCAN, 1173) and various morphometric parameters such as structural thickness, structural separation, and total porosity are compared.
3. The density of the snow has reduced as the laboratory temperature was varied from -20°C to -35°C . The average values of density of snow inside the nucleation chamber at all given values of laboratory temperatures are found to be 0.1478 gm/cm^3 , 0.131 gm/cm^3 , 0.126 gm/cm^3 and 0.117 gm/cm^3 .
4. The average values of snow fall rate (cm/h) inside the nucleation chamber are 0.13 cm/h, 0.22 cm/h, 0.31cm/h and 0.42 cm/h for all the given values of laboratory temperatures ranging from -20°C to -35°C .
5. A new design of snow making machine is proposed, in which a nucleation chamber with five roller belt assemblies each at a distance of 333.34 mm is placed across the nucleation chamber. These roller belt assemblies are rotated by the help of sprocket chain assemblies. To visualize the temperature variation across the nucleation chamber, simulation of the nucleation chamber is performed in ANSYS® FLUENT® v1.

6.2 Future Scope

1. The morphology diagram provides a handy explanation for the formation of odd-looking snow crystal forms that stand the dependency on temperature and supersaturation. But still researchers cannot explain many of the features of the morphology diagram such as:
 - Why snow crystals grow as thin plates or slender columns depending on temperature.
 - Morphologies depend on the detailed molecular structure and dynamics of the different ice surfaces. There remains a bit of mystery in the formation of a snowflake.
2. The process of formation of snow in the present design of snow making machine takes place at standard atmospheric pressure and the snow crystals grown are mainly dendritic in nature. In order to produce different type of snow crystals such as plate type, hexagonal hollow and solid prism etc. a method is needed by which the experiment can be performed at different values of pressure.
3. In this design, there is no method available to measure the supersaturation parameter across the nucleation chamber. There is one more challenging task in this design is to provide a method for the close observation of snow crystals.

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Web References:

<http://www.snowcrystals.com/guide/guide.html> [Accessed 15 Dec. 2016].

Appendix: A

Table A1: Temperature variation across the snow making machine at laboratory temperature of -20°C.

| Time (minutes) | Sensor-1(°C) | Sensor-2(°C) | Sensor-3(°C) | Sensor-4(°C) | Sensor-5(°C) | Sensor-6(°C) | Sensor-7(°C) | Sensor-8(°C) | Sensor-9(°C) | Sensor-10(°C) | Sensor-11(°C) |
|----------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|---------------|---------------|
| 0 | -10.2547 | -9.45408 | -8.87672 | -8.962 | -9.24099 | -9.77931 | -9.40615 | -9.69522 | -10.53496 | -19.30386 | 25.47889 |
| 1 | -10.97773 | -9.39548 | -8.52178 | -8.58913 | -10.42861 | -9.73995 | -8.84156 | -4.70184 | -10.93484 | -19.21571 | 24.36102 |
| 2 | -13.7843 | -9.40747 | -8.80561 | -9.06353 | -10.53333 | -9.67221 | -8.98962 | -5.07597 | -11.0711 | -19.70882 | 24.41941 |
| 3 | -14.34114 | -10.26885 | -9.41667 | -9.72352 | -11.4029 | -10.08074 | -9.734 | -7.00196 | -11.78162 | -19.66711 | 25.31776 |
| 4 | -14.77613 | -10.51632 | -9.81563 | -10.16019 | -10.05196 | -9.97782 | -9.88511 | -10.32964 | -11.8991 | -19.80143 | 25.95184 |
| 5 | -14.80072 | -10.02073 | -10.00387 | -10.25578 | -10.09807 | -10.19404 | -9.98564 | -10.29392 | -12.00266 | -19.50655 | 24.32324 |
| 6 | -14.52503 | -10.23255 | -9.70296 | -10.14882 | -10.22297 | -10.23215 | -10.01763 | -10.38471 | -11.85944 | -19.15114 | 23.32987 |
| 7 | -14.66852 | -10.82796 | -9.62851 | -9.87281 | -9.90967 | -10.04684 | -9.89345 | -10.45014 | -11.87282 | -19.45035 | 22.82038 |
| 8 | -15.69759 | -10.77019 | -10.29745 | -10.54085 | -10.45023 | -10.37648 | -10.15984 | -10.8101 | -12.3353 | -20.16683 | 24.61675 |
| 9 | -15.014 | -9.71146 | -9.00831 | -9.54469 | -12.10267 | -9.32596 | -8.64901 | -6.41633 | -12.17731 | -20.05881 | 22.72168 |
| 10 | -14.23995 | -8.56324 | -8.1884 | -8.47438 | -11.53942 | -8.44665 | -7.64964 | -6.10413 | -11.64941 | -19.53187 | 23.98619 |
| 11 | -13.47678 | -8.46243 | -8.54012 | -8.26955 | -11.29744 | -8.29496 | -8.00607 | -7.81731 | -10.9579 | -18.78315 | 24.95346 |
| 12 | -13.33048 | -8.22111 | -7.86014 | -8.29075 | -10.04391 | -7.34645 | -7.75394 | -9.69997 | -10.82739 | -18.85427 | 23.74932 |
| 13 | -13.96898 | -8.32207 | -8.09944 | -8.36081 | -9.71878 | -8.04548 | -8.26307 | -10.24572 | -10.98743 | -19.59432 | 22.25752 |
| 14 | -14.18711 | -8.4828 | -8.19435 | -8.47091 | -8.35896 | -8.31454 | -7.96511 | -11.09268 | -11.28209 | -20.13877 | 22.70196 |
| 15 | -13.962 | -8.75579 | -7.74532 | -8.02106 | -6.69046 | -8.27896 | -7.7492 | -8.41464 | -11.32633 | -19.85081 | 23.38298 |
| 16 | -12.59843 | -7.84082 | -7.50617 | -7.87559 | -7.63081 | -7.85001 | -6.50035 | -8.21315 | -9.96513 | -18.98277 | 24.17201 |
| 17 | -12.65561 | -6.84103 | -6.08821 | -6.77877 | -7.16841 | -9.48113 | -5.9183 | -9.09015 | -8.72909 | -18.9749 | 24.84803 |
| 18 | -12.88818 | -6.99499 | -6.64953 | -6.8453 | -7.26775 | -9.33847 | -5.4645 | -9.15327 | -8.76754 | -20.06563 | 23.57215 |
| 19 | -13.83302 | -8.27043 | -7.64625 | -8.0319 | -7.87701 | -7.48831 | -6.70986 | -8.27148 | -10.86523 | -20.74661 | 24.15758 |
| 20 | -14.46075 | -9.09283 | -7.67314 | -8.06382 | -8.16571 | -7.82782 | -7.79971 | -8.53186 | -11.14324 | -20.94998 | 24.9035 |
| 21 | -14.00157 | -8.6285 | -7.23038 | -7.84909 | -7.46176 | -7.71718 | -7.84631 | -8.70042 | -10.92022 | -20.22475 | 23.54186 |
| 22 | -13.32877 | -7.22215 | -6.97914 | -7.22444 | -7.35364 | -7.33818 | -7.23789 | -8.18232 | -10.56707 | -19.48194 | 23.12434 |
| 23 | -12.65035 | -7.30005 | -6.22049 | -6.65447 | -6.59561 | -6.6347 | -8.04713 | -7.29778 | -10.11708 | -18.83833 | 23.89556 |
| 24 | -12.37167 | -6.96265 | -6.35538 | -6.51863 | -6.24545 | -6.59513 | -6.76631 | -7.40665 | -9.64827 | -18.15013 | 23.64899 |
| 25 | -11.66874 | -6.1229 | -6.13702 | -5.92927 | -5.4422 | -5.95473 | -8.91816 | -6.92875 | -9.50253 | -18.79128 | 24.58691 |
| 26 | -12.54171 | -7.597 | -6.87188 | -6.96516 | -6.72246 | -6.78839 | -7.47254 | -7.58949 | -9.893 | -20.18947 | 23.69856 |
| 27 | -13.57082 | -7.15037 | -7.1519 | -7.74703 | -6.72703 | -7.11963 | -7.59536 | -8.09315 | -10.19506 | -20.49719 | 23.1946 |
| 28 | -13.14661 | -7.36072 | -6.62479 | -6.81919 | -6.83747 | -7.0865 | -8.44865 | -7.73796 | -10.24721 | -20.16896 | 24.0189 |
| 29 | -13.01394 | -6.86038 | -6.3638 | -7.25814 | -6.65745 | -6.44792 | -8.75965 | -6.92717 | -9.95974 | -19.40013 | 23.57927 |
| 30 | -12.19821 | -6.27183 | -5.82623 | -5.99892 | -5.67111 | -5.88234 | -10.10224 | -6.98679 | -9.40445 | -18.6596 | 24.16785 |
| 31 | -11.37542 | -5.52957 | -6.00727 | -6.53402 | -6.19525 | -6.15326 | -6.50035 | -7.00499 | -9.10109 | -18.2232 | 23.62928 |
| 32 | -12.41679 | -6.20375 | -6.03499 | -5.61343 | -5.50004 | -6.01279 | -5.9183 | -7.02646 | -9.23481 | -19.16568 | 25.82838 |
| 33 | -12.0186 | -6.79661 | -5.03847 | -5.98558 | -5.82143 | -5.72332 | -5.4645 | -6.6808 | -9.02878 | -20.14131 | 24.32932 |
| 34 | -13.75361 | -7.53059 | -6.95605 | -7.23969 | -7.23493 | -7.03246 | -6.70986 | -7.6532 | -10.01462 | -20.64153 | 23.82227 |
| 35 | -13.80954 | -7.73445 | -7.4251 | -8.10331 | -8.14792 | -7.79353 | -7.79971 | -8.33135 | -10.14801 | -20.26205 | 23.12343 |
| 36 | -13.73016 | -7.42419 | -7.183 | -7.97511 | -8.04945 | -7.86472 | -7.84631 | -8.30975 | -9.92438 | -19.46799 | 22.63244 |
| 37 | -13.15746 | -6.14958 | -6.22783 | -7.38515 | -7.13226 | -7.00221 | -7.23789 | -7.80124 | -9.5083 | -18.75686 | 23.28054 |
| 38 | -12.6655 | -5.74653 | -7.24989 | -8.09897 | -8.24185 | -8.23792 | -8.04713 | -8.35526 | -8.88892 | -18.0055 | 24.94644 |
| 39 | -12.47165 | -6.00697 | -5.95893 | -6.44855 | -6.25855 | -6.07339 | -6.76631 | -7.47211 | -8.50576 | -18.25134 | 23.95152 |
| 40 | -13.24325 | -6.70226 | -6.89494 | -8.03168 | -8.21433 | -7.90593 | -8.16461 | -8.2536 | -9.08355 | -19.92748 | 24.5153 |
| 41 | -14.42543 | -7.10535 | -7.5219 | -8.56114 | -8.77673 | -8.90864 | -9.12822 | -9.37514 | -9.52569 | -20.65632 | 24.3971 |
| 42 | -14.052 | -7.04131 | -7.31936 | -8.86664 | -8.91984 | -8.12912 | -8.7375 | -9.13283 | -9.54444 | -20.51101 | 23.6056 |
| 43 | -13.42486 | -6.6647 | -6.95976 | -8.78281 | -8.83343 | -8.64085 | -8.91816 | -8.96445 | -9.20225 | -19.68447 | 23.35168 |
| 44 | -12.8388 | -6.33923 | -6.66157 | -7.28372 | -7.3409 | -7.50298 | -7.47254 | -8.26106 | -9.04188 | -18.83231 | 22.41555 |
| 45 | -12.72667 | -5.9632 | -7.02571 | -7.94006 | -7.84941 | -7.72148 | -7.59536 | -7.87251 | -8.56719 | -18.19948 | 23.95773 |
| 46 | -12.42196 | -6.65084 | -6.91127 | -7.84218 | -8.03895 | -8.34075 | -8.44865 | -8.80793 | -8.43765 | -17.99673 | 24.58159 |
| 47 | -13.69153 | -7.79356 | -7.90473 | -8.60465 | -8.64018 | -8.82799 | -8.75965 | -9.04159 | -9.40515 | -19.49706 | 25.01787 |
| 48 | -14.26111 | -8.63179 | -8.65342 | -9.94362 | -10.11371 | -10.20883 | -10.10224 | -10.21441 | -10.16685 | -20.73409 | 24.52852 |
| 49 | -14.79331 | -9.20795 | -9.45455 | -10.22168 | -10.46859 | -10.64946 | -10.33995 | -10.33371 | -10.58175 | -20.5901 | 24.56421 |
| 50 | -14.46251 | -8.92406 | -8.98514 | -9.81296 | -9.82473 | -9.52543 | -9.3845 | -9.949 | -10.70169 | -20.02735 | 25.4623 |
| 51 | -14.10673 | -9.03943 | -8.82193 | -9.51809 | -9.6879 | -9.44561 | -9.42591 | -9.76937 | -10.61007 | -19.30532 | 23.57927 |
| 52 | -10.32188 | -5.20071 | -9.72275 | -9.55655 | -9.30843 | -9.45285 | -9.28423 | -9.48234 | -9.79781 | -18.3071 | 24.16785 |
| 53 | -11.22902 | -5.23151 | -11.14297 | -9.21899 | -9.0204 | -10.48239 | -10.05505 | -9.97017 | -10.69422 | -17.97258 | 23.62928 |
| 54 | -12.41679 | -5.71737 | -12.85488 | -11.26491 | -10.79016 | -10.99482 | -11.40706 | -10.02707 | -10.14218 | -18.93053 | 25.82838 |
| 55 | -12.0186 | -6.31136 | -14.30074 | -13.55517 | -12.75066 | -12.16611 | -11.71586 | -11.42503 | -11.48564 | -20.1337 | 24.32932 |
| 56 | -13.75361 | -6.65474 | -14.9132 | -13.90145 | -13.36926 | -12.67034 | -12.13505 | -12.02396 | -10.6659 | -20.28399 | 23.82227 |
| 57 | -13.80954 | -7.09173 | -13.35312 | -12.39554 | -12.10883 | -12.11069 | -11.76339 | -11.46196 | -9.95924 | -19.73431 | 23.12343 |
| 58 | -13.73016 | -5.86788 | -13.4203 | -10.66527 | -10.18577 | -10.25668 | -9.55429 | -9.56927 | -9.76277 | -19.38054 | 22.63244 |
| 59 | -13.15746 | -5.25599 | -10.96735 | -9.29864 | -10.34781 | -10.55603 | -9.21836 | -9.87876 | -10.10594 | -18.77322 | 23.28054 |
| 60 | -13.69153 | -5.16933 | -8.48431 | -9.26193 | -9.45106 | -10.06833 | -8.89571 | -9.13503 | -9.29353 | -18.11501 | 24.94644 |

Table A2: Temperature variation across the snow making machine at laboratory temperature of -25°C.

| Time (minutes) | Sensor-1 (TT) | Sensor-2 (TT) | Sensor-3 (TT) | Sensor-4 (TT) | Sensor-5 (TT) | Sensor-6 (TT) | Sensor-7 (TT) | Sensor-8 (TT) | Sensor-9 (TT) | Sensor-10 (TT) | Sensor-11 (TT) |
|----------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|----------------|----------------|
| 0 | -15.36724 | -9.54158 | -9.17359 | -10.75235 | -12.50189 | -10.19717 | -10.37788 | -11.55965 | -11.1435 | -25.03014 | 23.38298 |
| 1 | -12.95352 | -10.02488 | -9.74808 | -5.7884 | -9.23568 | -5.89741 | -4.49466 | -7.60967 | -7.75215 | -24.50498 | 22.82038 |
| 2 | -10.2922 | -11.72128 | -10.81155 | -2.77205 | -13.84797 | -5.08476 | -6.68249 | -11.80365 | -7.03798 | -24.17565 | 24.61675 |
| 3 | -13.71284 | -12.85926 | -10.8477 | -5.85668 | -12.97972 | -5.40471 | -5.83804 | -12.25839 | -8.0992 | -23.18312 | 22.72168 |
| 4 | -10.92388 | -12.62549 | -11.70175 | -3.349 | -13.11556 | -4.37734 | -6.13005 | -11.50554 | -7.25868 | -24.27207 | 23.98619 |
| 5 | -13.78952 | -12.37513 | -12.15045 | -7.36329 | -13.35295 | -6.76605 | -7.4378 | -12.21432 | -8.01306 | -24.58181 | 24.95346 |
| 6 | -15.30136 | -12.51343 | -12.24919 | -6.90889 | -13.1313 | -6.21262 | -8.19141 | -12.26466 | -8.72013 | -24.17796 | 23.74932 |
| 7 | -15.39712 | -12.92659 | -10.97443 | -8.1949 | -12.83864 | -7.52715 | -8.35353 | -11.86989 | -9.60682 | -24.13097 | 22.25752 |
| 8 | -16.48283 | -12.99601 | -10.53614 | -10.1051 | -12.25819 | -9.19516 | -10.28448 | -11.80022 | -10.29841 | -23.78561 | 22.70196 |
| 9 | -17.36724 | -9.54158 | -9.17359 | -10.75235 | -12.50189 | -10.19717 | -10.37788 | -11.55965 | -11.1435 | -25.03014 | 23.38298 |
| 10 | -18.14779 | -10.23995 | -9.30761 | -11.44036 | -11.11493 | -10.66964 | -11.07332 | -10.91907 | -11.54548 | -25.30861 | 24.17201 |
| 11 | -17.57339 | -10.01647 | -9.98541 | -11.55594 | -11.05468 | -10.9522 | -12.06803 | -10.35616 | -12.00798 | -24.8525 | 24.84803 |
| 12 | -17.0015 | -10.41665 | -10.44505 | -10.81155 | -11.03823 | -10.67803 | -11.31953 | -11.70474 | -11.81155 | -24.1552 | 23.57215 |
| 13 | -16.7554 | -10.66625 | -10.56326 | -10.8477 | -12.21837 | -11.25314 | -12.34436 | -12.69759 | -11.59039 | -23.29215 | 24.15758 |
| 14 | -16.51103 | -10.72421 | -10.29994 | -11.70175 | -12.48541 | -11.29388 | -11.85335 | -13.32824 | -11.7837 | -23.15606 | 24.9035 |
| 15 | -17.43322 | -11.53386 | -10.4259 | -12.15045 | -11.36238 | -11.71443 | -12.78418 | -12.34464 | -12.22487 | -23.92819 | 23.54186 |
| 16 | -17.40122 | -10.84622 | -10.78407 | -12.24919 | -11.17276 | -12.34184 | -12.03871 | -12.2336 | -12.41902 | -24.31856 | 23.12434 |
| 17 | -18.11537 | -11.72128 | -11.29165 | -12.97443 | -10.49305 | -12.13297 | -13.40405 | -13.64612 | -13.03378 | -24.84062 | 25.47889 |
| 18 | -18.20375 | -12.85926 | -11.7376 | -13.53614 | -10.62614 | -13.39718 | -13.895 | -12.32841 | -13.65821 | -24.69122 | 24.36102 |
| 19 | -18.13359 | -12.62549 | -11.68152 | -13.17359 | -10.38586 | -12.94218 | -14.04649 | -12.86819 | -13.50157 | -24.2868 | 24.41941 |
| 20 | -17.54509 | -12.37513 | -11.85831 | -12.64805 | -10.98101 | -12.68808 | -13.3406 | -13.75793 | -13.25338 | -23.43633 | 25.31776 |
| 21 | -17.88907 | -12.51343 | -11.77196 | -13.11171 | -11.04452 | -13.13255 | -13.49739 | -12.89637 | -13.27598 | -23.57034 | 25.95184 |
| 22 | -17.88017 | -12.92659 | -11.82525 | -12.76626 | -11.03037 | -12.27128 | -13.36383 | -12.4031 | -13.45352 | -23.64765 | 24.32324 |
| 23 | -18.03918 | -12.99601 | -11.12327 | -13.50535 | -9.88542 | -14.15337 | -13.52493 | -12.25755 | -13.78603 | -23.87979 | 23.32987 |
| 24 | -18.00413 | -13.06982 | -12.40709 | -13.08744 | -9.64812 | -12.6063 | -13.31153 | -13.67596 | -13.81513 | -23.98319 | 23.12343 |
| 25 | -18.8273 | -13.00144 | -12.84316 | -14.66579 | -9.13449 | -14.45497 | -14.64621 | -13.83888 | -14.6274 | -23.99339 | 22.63244 |
| 26 | -18.69117 | -12.5667 | -11.01162 | -13.23739 | -9.5332 | -12.45535 | -13.11558 | -13.36992 | -14.51253 | -25.17839 | 23.28054 |
| 27 | -19.29064 | -13.63236 | -12.15336 | -14.6967 | -10.07841 | -14.20191 | -14.71406 | -12.46455 | -15.26298 | -25.06855 | 24.94644 |
| 28 | -18.74786 | -13.41729 | -12.03335 | -14.36862 | -9.83811 | -14.26496 | -14.88763 | -12.25222 | -15.52535 | -24.08282 | 23.95152 |
| 29 | -18.93579 | -14.16782 | -12.28496 | -14.42305 | -10.19078 | -14.19137 | -14.91141 | -12.58246 | -15.50444 | -25.39169 | 24.5153 |
| 30 | -18.29233 | -13.71299 | -12.47971 | -15.01566 | -10.39246 | -14.41378 | -15.38556 | -12.91108 | -15.28196 | -24.5538 | 24.3971 |
| 31 | -17.54422 | -13.04195 | -12.0851 | -14.11812 | -10.5249 | -13.10271 | -13.6877 | -13.21958 | -15.09884 | -23.94386 | 23.6056 |
| 32 | -17.30229 | -13.12975 | -11.78988 | -14.4354 | -9.50788 | -14.17739 | -14.58849 | -12.78096 | -14.95508 | -23.31065 | 23.35168 |
| 33 | -17.50663 | -13.28844 | -11.78997 | -14.10328 | -8.87443 | -13.83989 | -14.58706 | -11.87656 | -14.84423 | -23.5067 | 22.41555 |
| 34 | -18.25739 | -13.08511 | -11.97436 | -13.61929 | -9.23827 | -13.14677 | -14.83739 | -11.62487 | -15.21621 | -24.60335 | 23.95773 |
| 35 | -18.88325 | -14.46689 | -12.13646 | -14.70688 | -9.36411 | -14.00189 | -14.60505 | -11.31922 | -15.71953 | -25.04904 | 24.58159 |
| 36 | -18.43336 | -14.28997 | -12.88067 | -15.36599 | -10.73501 | -15.44257 | -15.19959 | -12.21108 | -15.74351 | -24.54618 | 25.01787 |
| 37 | -18.43079 | -14.19682 | -13.34301 | -14.88711 | -11.88655 | -14.63771 | -15.68592 | -12.23024 | -15.69588 | -24.03127 | 24.52852 |
| 38 | -18.28302 | -14.08683 | -13.43344 | -15.02589 | -11.37171 | -15.24188 | -14.37651 | -12.64367 | -15.70656 | -24.15011 | 24.56421 |
| 39 | -18.56622 | -12.96851 | -13.74247 | -15.47779 | -11.17931 | -15.5377 | -16.11337 | -12.7464 | -15.7968 | -23.51148 | 25.4623 |
| 40 | -18.08559 | -12.864 | -14.23676 | -14.816 | -12.54487 | -14.90748 | -15.62372 | -12.29419 | -15.51872 | -24.44672 | 23.57927 |
| 41 | -17.94791 | -12.61283 | -13.98617 | -14.73905 | -11.39853 | -14.78758 | -14.97978 | -12.25636 | -15.1208 | -24.21124 | 24.16785 |
| 42 | -17.66629 | -12.66269 | -14.07321 | -14.70225 | -11.44229 | -15.31877 | -15.3988 | -11.43847 | -15.05757 | -23.62086 | 23.62928 |
| 43 | -17.76126 | -12.44648 | -14.34567 | -14.89729 | -12.80585 | -15.04544 | -15.31772 | -12.71287 | -14.89642 | -24.16736 | 25.82838 |
| 44 | -16.29269 | -11.97418 | -13.86656 | -14.31708 | -11.10017 | -14.67617 | -15.49449 | -13.40547 | -14.56668 | -24.52798 | 24.32932 |
| 45 | -16.63782 | -12.77947 | -13.64626 | -14.33177 | -11.75611 | -14.48728 | -14.89674 | -13.53312 | -14.55476 | -24.62921 | 23.82227 |
| 46 | -16.40461 | -12.96543 | -13.21639 | -14.16593 | -11.94613 | -14.45114 | -14.77344 | -13.47399 | -14.50683 | -23.84867 | 23.12343 |
| 47 | -15.58354 | -12.16241 | -12.5652 | -13.49711 | -12.09971 | -13.43315 | -14.1615 | -13.73507 | -14.26764 | -23.49475 | 22.63244 |
| 48 | -15.83501 | -12.37976 | -12.43703 | -13.47087 | -13.29221 | -13.84944 | -14.89531 | -13.94122 | -14.03245 | -24.53956 | 23.28054 |
| 49 | -16.7722 | -10.55146 | -12.5045 | -11.22115 | -12.04243 | -12.86681 | -13.77025 | -13.80479 | -13.71135 | -24.81414 | 24.58691 |
| 50 | -16.78117 | -11.56647 | -11.05648 | -11.21269 | -10.68603 | -13.13678 | -12.88291 | -14.8187 | -13.62269 | -23.48783 | 23.69856 |
| 51 | -15.51937 | -11.16357 | -10.50659 | -10.38418 | -11.15631 | -12.58283 | -12.4335 | -14.83193 | -13.63706 | -23.41102 | 23.1946 |
| 52 | -15.40914 | -10.62618 | -9.60764 | -9.69081 | -11.52824 | -12.06957 | -12.2129 | -14.43137 | -13.2261 | -23.68566 | 24.0189 |
| 53 | -14.07908 | -11.22753 | -9.63708 | -10.21937 | -11.90344 | -11.36211 | -12.87491 | -9.35974 | -13.53976 | -23.94879 | 23.57927 |
| 54 | -15.0578 | -10.80971 | -9.73601 | -9.85428 | -11.86485 | -11.31108 | -12.0344 | -9.41055 | -13.84367 | -24.13911 | 24.16785 |
| 55 | -13.57251 | -10.85052 | -9.1056 | -9.50217 | -10.83789 | -10.86775 | -11.54402 | -10.33746 | -13.65349 | -24.79453 | 23.62928 |
| 56 | -13.5303 | -10.71646 | -8.48353 | -8.84263 | -10.64999 | -9.65547 | -11.08484 | -10.9953 | -13.65764 | -24.32145 | 25.82838 |
| 57 | -13.3433 | -10.63296 | -8.0231 | -8.88343 | -10.36658 | -10.12892 | -10.88567 | -11.36295 | -13.20264 | -23.88672 | 24.32932 |
| 58 | -14.07129 | -10.74458 | -8.34878 | -9.19007 | -9.24754 | -10.18607 | -10.46711 | -11.09636 | -13.26617 | -23.6951 | 23.82227 |
| 59 | -14.11565 | -11.58953 | -8.24 | -9.28835 | -10.52938 | -10.76671 | -10.77799 | -11.84761 | -13.76363 | -23.53828 | 24.32932 |
| 60 | -14.9946 | -11.52925 | -8.96359 | -10.24805 | -10.87828 | -10.73038 | -10.87427 | -11.70083 | -14.14161 | -24.19836 | 23.82227 |

Table A3: Temperature variation across the snow making machine at laboratory temperature of -30°C.

| Time (minutes) | Sensor-1 (TT) | Sensor-2 (TT) | Sensor-3 (TT) | Sensor-4 (TT) | Sensor-5 (TT) | Sensor-6 (TT) | Sensor-7 (TT) | Sensor-8 (TT) | Sensor-9 (TT) | Sensor-10 (TT) | Sensor-11 (TT) |
|----------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|----------------|----------------|
| 0 | -17.60826 | -15.72151 | -14.96311 | -15.72685 | -16.18681 | -16.74692 | -16.57245 | -17.07434 | -17.04125 | -29.42281 | 25.47889 |
| 1 | -19.01932 | -17.27228 | -15.92821 | -16.62889 | -16.85205 | -17.08965 | -17.14638 | -17.77016 | -17.88414 | -30.55904 | 24.36102 |
| 2 | -20.39487 | -18.43303 | -16.25982 | -17.11765 | -17.3195 | -17.45283 | -17.44306 | -18.07584 | -18.65697 | -30.86229 | 24.41941 |
| 3 | -22.32665 | -18.10323 | -16.50855 | -17.38501 | -17.26728 | -17.16176 | -17.313 | -17.84851 | -19.24366 | -30.23193 | 25.31776 |
| 4 | -21.78399 | -18.32813 | -16.45679 | -17.08363 | -16.78132 | -16.72691 | -16.88842 | -17.78333 | -19.226 | -29.53333 | 25.95184 |
| 5 | -21.23866 | -17.8245 | -16.21018 | -16.80173 | -16.57427 | -16.48788 | -16.72001 | -17.6417 | -19.09883 | -28.73223 | 24.32324 |
| 6 | -21.4946 | -17.34493 | -15.9798 | -16.68259 | -16.52299 | -16.62671 | -16.6753 | -17.87807 | -19.10612 | -28.63721 | 23.32987 |
| 7 | -22.34802 | -18.05813 | -16.47006 | -17.08352 | -16.76853 | -16.69213 | -16.72624 | -17.5339 | -19.32149 | -29.16125 | 22.82038 |
| 8 | -23.02763 | -18.68255 | -16.70508 | -17.5591 | -17.30654 | -17.26114 | -17.30395 | -18.36655 | -19.76947 | -29.49557 | 24.61675 |
| 9 | -23.03501 | -19.1156 | -16.89495 | -17.86166 | -17.70662 | -17.90782 | -17.87121 | -18.77723 | -19.94222 | -29.52909 | 22.72168 |
| 10 | -22.93492 | -18.44876 | -16.44322 | -17.33303 | -17.09152 | -17.10672 | -17.19945 | -18.35605 | -19.93853 | -28.91981 | 23.98619 |
| 11 | -21.90513 | -17.84596 | -15.53374 | -16.38571 | -15.86258 | -15.70346 | -15.92918 | -17.27887 | -19.39222 | -28.89161 | 24.95346 |
| 12 | -22.3394 | -17.24443 | -14.77586 | -15.82218 | -15.10453 | -15.29876 | -15.76392 | -17.28428 | -18.96085 | -29.38835 | 23.74932 |
| 13 | -22.68195 | -17.69168 | -15.40235 | -15.99282 | -15.66511 | -15.92786 | -16.07733 | -17.60518 | -19.236 | -30.42414 | 22.25752 |
| 14 | -23.70663 | -17.97696 | -15.90927 | -16.92219 | -16.3728 | -16.26377 | -16.1603 | -17.53362 | -19.71984 | -30.97711 | 22.70196 |
| 15 | -23.59324 | -18.23744 | -15.89026 | -17.11093 | -16.26694 | -16.35881 | -16.45912 | -17.93519 | -19.78962 | -30.78317 | 23.38298 |
| 16 | -22.81317 | -17.11536 | -16.24653 | -17.20989 | -16.56334 | -16.43826 | -16.54171 | -17.91318 | -19.68671 | -29.91591 | 24.17201 |
| 17 | -22.37687 | -17.10208 | -15.5315 | -17.22869 | -16.70147 | -16.97863 | -17.19954 | -18.20152 | -19.26343 | -29.22205 | 24.84803 |
| 18 | -21.91039 | -16.27192 | -15.02152 | -16.35104 | -15.32751 | -15.76 | -16.06951 | -17.51488 | -18.63203 | -29.52909 | 23.57215 |
| 19 | -21.46672 | -15.66169 | -13.8715 | -14.55893 | -13.75716 | -14.59079 | -15.09823 | -16.83179 | -18.32238 | -28.09807 | 24.15758 |
| 20 | -21.72322 | -16.54553 | -14.95104 | -16.04757 | -15.57022 | -16.25976 | -16.50273 | -17.42369 | -18.21968 | -28.57378 | 24.90351 |
| 21 | -22.04902 | -16.0725 | -15.34846 | -16.55674 | -15.9228 | -16.49576 | -16.6917 | -17.57029 | -18.26499 | -29.08204 | 23.54186 |
| 22 | -21.7643 | -16.33185 | -15.23653 | -16.46008 | -16.01822 | -16.60936 | -16.7979 | -17.57878 | -18.42976 | -29.27535 | 23.12434 |
| 23 | -22.33134 | -16.44192 | -16.48847 | -17.21971 | -17.05581 | -17.87216 | -17.54669 | -17.91521 | -18.35394 | -29.60538 | 23.89556 |
| 24 | -22.8453 | -16.5961 | -15.99601 | -17.23456 | -16.43369 | -17.70496 | -17.59692 | -18.00527 | -18.64971 | -29.61546 | 23.64899 |
| 25 | -23.00318 | -17.08034 | -16.45711 | -17.59492 | -16.97643 | -17.63388 | -17.59447 | -18.23241 | -18.56789 | -29.66888 | 24.58691 |
| 26 | -22.22343 | -16.83404 | -16.05098 | -16.65265 | -15.97569 | -16.52666 | -16.96611 | -18.07271 | -18.23256 | -29.15008 | 23.69856 |
| 27 | -22.03359 | -15.91563 | -15.49357 | -16.11735 | -15.68592 | -16.81575 | -16.86457 | -17.40328 | -18.00572 | -28.72616 | 23.19465 |
| 28 | -22.11065 | -16.48173 | -15.63867 | -16.3502 | -16.33381 | -17.60745 | -17.18094 | -17.69007 | -17.9642 | -28.89886 | 24.01898 |
| 29 | -22.28926 | -16.44829 | -15.62516 | -15.82199 | -15.67109 | -16.53791 | -16.68228 | -17.45515 | -17.89552 | -28.7342 | 23.57927 |
| 30 | -21.81726 | -15.92675 | -15.19985 | -15.9907 | -15.50154 | -16.39231 | -16.72648 | -17.58665 | -17.81961 | -28.76905 | 24.16785 |
| 31 | -23.30921 | -16.4314 | -15.59441 | -15.89976 | -15.33843 | -16.37757 | -16.60556 | -17.51824 | -17.75554 | -28.82327 | 23.62928 |
| 32 | -23.36802 | -16.90337 | -16.41488 | -15.7233 | -15.39425 | -16.30298 | -16.4166 | -17.61519 | -17.82115 | -28.81506 | 25.82838 |
| 33 | -22.45571 | -16.73659 | -15.56623 | -15.22104 | -14.67383 | -15.36147 | -15.68705 | -16.64611 | -17.18824 | -28.17652 | 24.32932 |
| 34 | -20.55689 | -14.70492 | -15.16195 | -14.55884 | -14.1776 | -15.31595 | -15.53298 | -16.59385 | -16.99533 | -27.40658 | 23.82227 |
| 35 | -22.30442 | -15.2855 | -14.25942 | -14.15875 | -13.78981 | -14.64686 | -15.01928 | -16.50401 | -16.56417 | -28.37911 | 23.12343 |
| 36 | -24.04274 | -16.91418 | -15.27659 | -15.37236 | -15.40574 | -16.74564 | -16.98674 | -17.74703 | -17.45146 | -29.91497 | 22.63244 |
| 37 | -24.42093 | -17.29386 | -15.92711 | -16.02484 | -15.96074 | -16.77008 | -16.79874 | -17.70682 | -18.16166 | -31.02581 | 23.28054 |
| 38 | -25.46734 | -18.36698 | -17.20226 | -17.02805 | -16.95777 | -17.65113 | -17.763 | -18.35581 | -18.57464 | -31.38639 | 24.94644 |
| 39 | -25.12813 | -18.05127 | -16.96544 | -17.07681 | -16.89121 | -17.74162 | -17.81593 | -18.46075 | -18.72783 | -31.20197 | 23.95152 |
| 40 | -24.46267 | -17.73269 | -16.27975 | -16.35341 | -16.08672 | -16.99514 | -17.16235 | -18.15212 | -18.59605 | -30.8301 | 24.51533 |
| 41 | -23.9576 | -17.56851 | -16.15261 | -15.91622 | -15.51015 | -16.00876 | -16.13777 | -17.79218 | -18.26624 | -29.95019 | 24.39717 |
| 42 | -23.35606 | -16.6165 | -15.34122 | -15.35197 | -15.07388 | -15.82156 | -15.84524 | -17.09894 | -17.87143 | -29.04351 | 23.60562 |
| 43 | -22.44728 | -16.06863 | -14.60895 | -14.69765 | -13.96777 | -14.6213 | -14.87909 | -16.62815 | -17.475 | -28.67901 | 23.35168 |
| 44 | -23.4212 | -16.14212 | -14.33235 | -14.58966 | -14.14837 | -15.50949 | -15.4954 | -16.64882 | -17.14824 | -28.8491 | 22.41555 |
| 45 | -23.33201 | -15.79631 | -14.81697 | -14.75122 | -14.05373 | -15.29206 | -15.53797 | -16.65205 | -17.15793 | -28.91718 | 23.95773 |
| 46 | -23.76837 | -16.77987 | -15.00009 | -15.05124 | -14.76952 | -15.89106 | -16.07704 | -17.25691 | -17.42718 | -29.55553 | 24.58159 |
| 47 | -23.31346 | -16.66149 | -14.30881 | -14.4982 | -13.95092 | -15.10178 | -15.16736 | -16.38528 | -17.26768 | -28.36924 | 25.01787 |
| 48 | -24.07997 | -16.99378 | -14.17226 | -14.66623 | -14.17731 | -15.18752 | -15.40028 | -16.55198 | -17.43094 | -29.7405 | 24.52852 |
| 49 | -24.22986 | -16.39693 | -14.7514 | -14.88689 | -14.39219 | -15.15755 | -15.29215 | -17.00233 | -17.5919 | -30.61274 | 24.56421 |
| 50 | -25.25272 | -17.84929 | -15.75896 | -15.2869 | -15.26745 | -16.43723 | -16.98112 | -18.08182 | -17.89301 | -30.83586 | 25.46231 |
| 51 | -24.76612 | -16.91801 | -15.4753 | -15.0939 | -14.66079 | -15.48883 | -15.74701 | -16.88716 | -17.91651 | -30.26053 | 23.57927 |
| 52 | -24.15824 | -17.28081 | -15.24223 | -14.94748 | -14.71268 | -15.95834 | -16.39509 | -17.73607 | -17.94775 | -29.69411 | 24.16785 |
| 53 | -23.66289 | -16.50482 | -14.33335 | -14.32744 | -13.93227 | -14.82248 | -14.87858 | -16.22343 | -17.47423 | -28.90863 | 23.62928 |
| 54 | -22.61476 | -15.19567 | -14.03908 | -14.11917 | -13.73643 | -14.9537 | -15.38071 | -16.64332 | -16.87996 | -28.19995 | 25.82838 |
| 55 | -21.42205 | -14.24626 | -13.90645 | -13.90257 | -13.21003 | -14.5657 | -15.29613 | -16.29699 | -16.31185 | -27.663 | 24.32932 |
| 56 | -21.32835 | -13.90297 | -12.89219 | -12.9258 | -12.5732 | -14.13043 | -14.47914 | -15.67071 | -16.08351 | -27.77229 | 23.82227 |
| 57 | -21.96638 | -14.21125 | -12.56368 | -12.86979 | -12.67766 | -13.75557 | -13.95811 | -15.83658 | -16.10407 | -28.49244 | 23.12343 |
| 58 | -22.6626 | -15.22445 | -13.51373 | -13.60548 | -13.52616 | -14.97782 | -15.34188 | -16.66076 | -16.43853 | -29.16682 | 22.63244 |
| 59 | -23.44148 | -15.77735 | -13.79185 | -13.70856 | -13.47476 | -14.61635 | -14.65854 | -16.00516 | -16.8391 | -29.39306 | 23.28054 |
| 60 | -23.27402 | -15.12507 | -13.28288 | -13.51467 | -13.07016 | -14.07344 | -14.36358 | -16.05796 | -16.7251 | -29.37539 | 24.94644 |

Table A4: Temperature variation across the snow making machine at laboratory temperature of -35°C.

| Time (minutes) | Sensor-1 (TT) | Sensor-2 (TT) | Sensor-3 (TT) | Sensor-4 (TT) | Sensor-5 (TT) | Sensor-6 (TT) | Sensor-7 (TT) | Sensor-8 (TT) | Sensor-9 (TT) | Sensor-10 (TT) | Sensor-11 (TT) |
|----------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|----------------|----------------|
| 0 | -20.76156 | -19.31225 | -19.87837 | -20.57629 | -21.94111 | -24.14236 | -23.2426 | -23.52935 | -22.25239 | -35.63513 | 25.4559 |
| 1 | -21.67849 | -19.78558 | -19.97243 | -20.77524 | -22.02287 | -24.29124 | -23.18256 | -23.83789 | -22.47583 | -35.01693 | 24.1412 |
| 2 | -22.61642 | -20.21576 | -20.38588 | -20.99362 | -22.15067 | -24.38859 | -23.53946 | -24.01581 | -22.77249 | -34.49628 | 24.4151 |
| 3 | -23.05208 | -19.35995 | -19.9124 | -20.17044 | -21.11271 | -24.08389 | -22.90803 | -23.2052 | -21.90157 | -34.14207 | 25.3247 |
| 4 | -25.95898 | -20.58475 | -19.3857 | -20.27129 | -20.96397 | -23.98329 | -23.17848 | -23.41064 | -22.19061 | -34.20347 | 24.9154 |
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