On the Feasibility of Generating and Storing Winter Ice to Meet Water Demands in the Summer

by

Moshe Alamaro

B.S. Aeronautical Engineering (1976)

Technion-Israel Institute of Technology

M.S. Mechanical Engineering (1995)

Boston University

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the Mechanical Engineer's Degree at the Massachusetts Institute of Technology

May 1999

[June 2000]

Signature of Author --------- --------------------------------

Department of Mechanical Engineering

May 16, 1999

Certified by-- -----------------

Dr. Robert S. Langer

Professor of Chemical Engineering

Thesis Supervisor

Accepted by--

Dr. Ain A. Sonin

Chairman, Department Graduate Committee

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Abstract

Summer water shortages have become a problem in Southeastern Massachusetts, communities in Vermont, New Hampshire and Rhode Island, and in a few areas in the Great Plains. This thesis proposes a conceptual system and outlines its feasibility for the production of large masses of ice in the winter within or in the vicinity of existing water reservoirs, thereby increasing their effective capacity without the need for an extensive or permanent water storage infrastructure. Eastern Massachusetts, for example, has an approximate average of 600 cold hours per winter when the temperature is below $-4\ C$. According to this concept, during these subfreezing temperature periods, ice would be produced by spraying water into the air and letting it freeze during free-fall as in the production of artificial snow. The pile of ice would then melt gradually during the spring and summer to provide a continuous supply of water.

This study is the first step toward anticipated development of a pilot system and subsequent implementation. Major engineering issues of such an approach are: atomization and spraying of water and heat transfer between the water drop and the air. A heat transfer model, which considers the drop size, free fall time, atmospheric temperature, humidity and nucleation, has been developed. The goal of the model is to enable the optimization of such an operation so as to minimize the required pumping power. Insulation techniques to preserve the ice for the summer are also outlined. Economic comparison with other alternatives for alleviation of water shortages such as water desalination was also made. Environmental evaluations consider potential disruption to nearby communities in the form of ice-making noise, icing and anticipated adversarial public perception of the concept. Other applications for winter-produced ice that may further improve the economic benefits of such an approach were also investigated.

Acknowledgement

I would like to thank my advisor Professor Robert Langer. Professor Langer's interest in solving practical engineering problems and applying science for the benefit of society has been a source of inspiration, making him my role model. I would also like to express gratitude to Professor Frank Perkins of the Department of Civil Engineering for his support, encouragement and the information he provided on the water shortage of Brockton, his hometown.

Other individuals who I wish to thank are Professor Kerry Emanuel of the MIT Department of Earth, Atmospheric and Planetary Sciences for his comments and discussions. Drs. Sam Colbert and Charles Ryerson of the Cold Region Research and Engineering Laboratory (CRREL) of the US Army Corps of Engineers offered to prepare a proposal for mutual R&D. Unfortunately this plan has not come through due to time constraints but it is hoped that future development of a prototype will be carried out with CRREL. Thanks also to Fergus Smith of Omichron Corporation for his enthusiasm and endless lecturing on snowmaking technology and ice and snow physics. Professor Baruch Fischhoff of the Department of Engineering and Public Policy at Carnegie-Mellon University has been kind and his encouragement and support are gratefully acknowledged.

Other people who I wish to thank are Professors Ali Argon, Patsy Sampson, Brenda Bemporad, Mark Ford and Connie Beal for their support and assistance.

1. Motivation

1.1 Introduction

The objectives of this thesis are to propose and study the feasibility of producing ice in the winter using snowmaking techniques in areas where the temperature is subfreezing for a significant portion of the winter. The ice produced by this process would be preserved and stockpiled. During the summer, melting ice would be used to supply water in areas experiencing seasonal shortage.

The northeast has, until recently, been blessed with adequate fresh water supplies from natural and man-made lakes, rivers and groundwater aquifers. However, the recent trend of population growth has put an increasing demand upon these drinking water resources. These factors combined with groundwater pollution have created a situation whereby supplies are dwindling; yet demand is growing. Surface and groundwater may be abundant during the fall, winter and spring, but that excess water is not retained and is ultimately lost to the ocean. Therefore, as in other areas of the country, non-traditional alternatives and solutions are being evaluated. There is an increasing realization that water reserves do not coincide with demand centers. Water reservoirs require large land areas and are often located in places where population is less dense and far from demand centers.

Massachusetts' environmental regulations restrict transfer of water among river basins. This limiting factor coupled with contamination of existing water supplies, and stricter drinking water standards, motivate the search for alternative supplies of water. The problem exists in most regions of the country with varying intensity. Eastern Massachusetts is no exception to this pattern [1].

In the Taunton River Basin of southeastern Massachusetts, the problem of supply, and more recently quality has been long standing. The major communities that are affected by the shortage are Brockton and Stoughton, located at the headwater of the river basin. In recent years many other communities, particularly in the northern portion of the basin, have had increasing water problems grow from infrequent incidents into major concerns. During drought years the Water Resources Commission has been forced to implement various water bans and emergencies. As a result, the economic growth of the region has been severely curtailed, either as a direct result of building moratoriums, or because of the water conservation requirements.

Several engineering and consulting firms have been developing various schemes to alleviate this water shortage problem. For example, Bluestone Energy Services, Inc., the developer of the Taunton River Basin Desalinization Project, has been pursuing and defining this project for the past several years [1]. Historically, desalinization technologies have been developed for applications in arid countries. Even in the case of reverse osmosis technology (RO), desalinization is more expensive than conventional water treatment methods. The cost of desalinization is significant considering energy, capital equipment and the need to dispose the unusable brine. One drawback is that desalinization plants should be located a short distance from the ocean, so this method is not applicable in inland areas.

The water shortage of Brockton, for example, amounts to three months of summer supply. The average daily consumption is 11 *million gallons* and is expected to increase to 15 *million gallons/day* within the next ten years. Therefore, additional storage capacity is required for about 1.35 *billion gallons*, which is equivalent to 5.1 *million* m^3 [2]. The case of Brockton is raised here as an example. Other communities in New England and other northern regions in the US have also experienced summer water shortages in recent years.

Southeastern Massachusetts is described as a "water rich-storage poor" area and it is clear that there is enough annual rainfall to supply the annual water demand. In the winter there is oversupply of water and reduced consumption. Although precipitation is relatively uniform throughout the year, transpiration and evaporation losses in the summer and the increase in consumption during the hot seasons are the main cause for a deficit of supply during the summer. The winter surplus of water cannot be stored due to the limited reservoir capacity. Therefore, a large amount of water flows to the ocean and is wasted.

1.2 Winter ice manufacture (WIM)

According to the concept proposed and described in this thesis, winter precipitation, which is currently wasted, will be pumped and sprayed into the air at times when the atmospheric

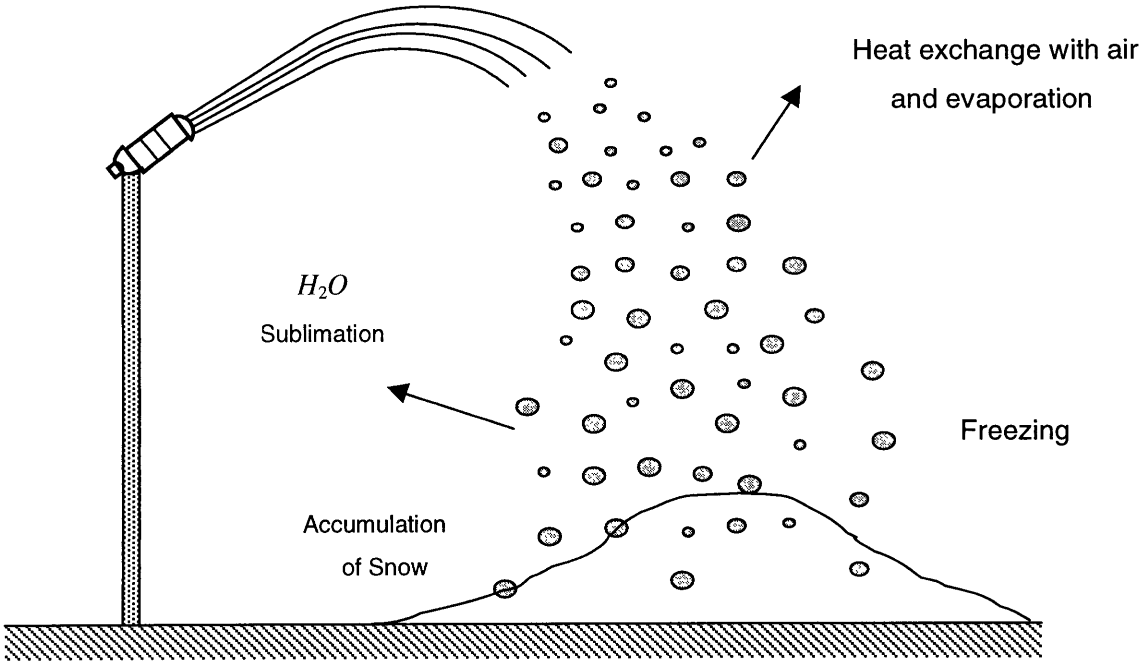

Figure 1.1: Schematics of snowmaking by atomization and projection.

temperature is subfreezing. The sprayed water will freeze when it comes in contact with the cold air as in the snowmaking process. The resulting ice will be stockpiled in the vicinity or on the banks of the existing water reservoirs. The operation will not require the construction of any permanent or dedicated infrastructure. The ice will melt gradually during summer and drain into the existing water reservoirs, alleviating summer water shortages. The system will use a modified version of snowmaking equipment to spray the water using high-rate high-head pumps. The features of the proposed system will be conceptually developed and analyzed in subsequent sections. The entire system can be made mobile, requiring neither dedicated equipment nor permanent construction. Such a flexible operational approach for solving water shortages will allow local variations in ice production from year to year. From an operational standpoint, the concept will not require any capital investment by municipalities. A company that owns the equipment and dispatches the system to various municipalities as needed may operate the mobile system. This mobile system approach will increase the utilization rate of capital equipment, especially the high-head water pumps. Equipment will be relocated during the winter to areas that have favorable weather conditions and the need for water storage.

Analysis of state-of-the-art snowmaking equipment leads to the conclusion that snowmaking equipment needs to be modified for this purpose. The focus of this thesis is the analysis of heat and mass transfer between the sprayed water and the atmosphere and the conceptual re-design of snowmaking apparatus. Other important aspects such as ice preservation, and nucleation of supercooled water are also addressed in this study. This concept can also be adopted, with some variations, for the manufacture and preservation of large amounts of snow for ski resorts to extend the skiing season.

1.3 The advantage of storing ice instead of water

In presenting this concept the following questions are addressed: Why should ice be stored instead of water? Why should one go to the trouble of manufacturing ice if the goal is to store water?

The answer lies in the physical properties of water versus solid ice. Water requires a container, which in this case requires permanent excavation, building of dikes, walls, etc. This, in turn, requires building a fixed storage capacity that cannot be extended easily. Solid ice, on the other hand, could be accumulated in large tall piles requiring no any permanent infrastructure or fixed storage capacity. Ice stockpiles sizes could be changed annually. Moreover, stockpiles can be accumulated to high altitude and large volume making a better economic use of scarce land in populated areas.

1.4 Additional potential applications for the winter ice

To improve economic returns, this study also explores the applications of ice for purposes other than water storage. Multiple applications may require the production of larger ice piles to create economies-of-scale. Alternatively, the ice, which ultimately supplies the water, will be used before and during melting for various cooling purposes extending the economic performance of the system.

Additional potential applications for ice include:

a. Providing chilled water for air-conditioning of commercial buildings.

b. Providing cooling capacity for industrial applications such as cheese making, brewing industries and cold storage warehouses.

c. Recreation.

Section 9 will review explore the feasibility of these additional applications.

2. History and review of snowmaking technologies

2.1 Introduction

There is agreement within the skiing industry that manufactured snow was produced in Canada during the mid to late 40's. During that period, Canadians were experimenting with de-icing equipment on airplanes. It was necessary to produce "field conditions" at the testing facilities to properly evaluate the effectiveness of the numerous de-icing methods being studied. As a result, various nozzles were fabricated in an effort to generate freezing rain, fog, and sleet [3].

The first attempt to manufacture commercial artificial snow was done at Mohawk Mt. Connecticut, winter 1949-50. Walter Schoenknecht, a ski resort owner, made a substantial investment in facilities, lift equipment, and a lodge in preparation for the coming ski season. However, snow failed to arrive by Christmas and the owner faced financial catastrophe. Mr. Schoenknecht who is regarded as the "father" of snowmaking, transported 700 *tons* of ice, then crushed and spread it over the slopes, thereby saving the Christmas ski season. This was, however, an expensive solution that could not be used on a regular basis [4].

During the same winter, of Mr. Schoenknecht's three friends from a business called Tey Manufacturing developed an external mixed water-air spray gun. The gun sprayed water on which expanding compressed air was impinged outside of the device. This method in which both water and air were ejected at a certain ratio, enabled them to produce 15 *inches* of snow per night. The process was patented and this basic principle is still being applied by most snow making technologies today [4]. The following winter two snowmaking facilities were installed one at Mohawk Mt. and the other at a ski resort in Pennsylvania. These systems used irrigation pipes and equipment to deliver compressed air and water from a centralized compressor and pump to the snow guns mounted on the ski slopes.

In December 1950 Larchmont Farms, an irrigation equipment supplier, approached Tey concerning their snowmaking patent, suggesting that an irrigation nozzle used to protect crops from frost by using steam and water, might be modified to make snow. These pieces of correspondence indicate that the idea of manufacturing artificial snow was conceived, as in the case of many inventions, by several inventors quite simultaneously. Larchmont began collaboration with Tey Manufacturing on the use of aluminum irrigation pipes and related valves and pumps for snowmaking. Eventually, Larchmont purchased the technology rights from Tey Manufacturing. The irrigation systems were used until 1964 when Ratnik Industries installed the first freeze proof system. For that, the pipes, which delivered the water, were buried deep in the ground on the ski slopes. This method which requires a substantial infrastructure is used today mainly in ski resorts in the US and adds much to the fixed capital cost of snowmaking [3].

Unfortunately, the system was plagued with many problems. Expanding air through a nozzle created unacceptable noise. Valves and hydrants were frequently frozen causing the need to thaw them with a torch. During the mid 50's in Midland, Michigan, A.W. Hanson was producing airless (no compressor required) snow with a used airplane engine, propeller and water ejector. In 1958, Hanson filed for the first patent on airless snowmaking [5]. Eventually, in 1968 Snow Machines, Inc. took out the license from Hanson and a radically new type of snow gun called the "airless" or fan gun was brought to the market. It used a fan powered by an electric motor to generate an air stream *in situ* instead of using a remote air compressor that required expensive piping and layout on difficult sloped terrain. The airless system has higher operational cost but high-pressure system that uses compressed air requires higher fixed capital cost. This basic airless design is used today mainly in Europe while a remote air compressor and piping are still used in the US and Canada.

Shortly after the release of the fan gun, another major airless snowmaker evolved. In 1969 Eustis and Wollin filed for a patent "Ice Nuclei Formation" [6]. This machine used an ice nucleus formation process and it incorporated a nucleator--a small air/water seeded gun mounted inside the barrel of a ducted fan to seed the bulk water drops which were introduced from the perimeter of the discharge end of the fan duct. In this method, very small drops, which are frozen immediately, were used to nucleate the larger drops, which constitute the bulk of the water supply. It used the fact that ice particles are the best freezing nuclei and can induce freezing of water at $0\ C$ (see section 5). The first machine was sold in 1970. Dewey Electronics bought out Wollin and Eustis and proceeded with mass manufacturing. After this dozens of different models emerged, but too numerous to enumerate. At the same time development in Austria built on the airless snow gun technology and it became the technical foundation for a substantial number of companies that manufacture snowmaking equipment in Europe.

2.2 Snowmaking parameters

The most important parameter in snowmaking is the water to snow conversion ratio. This is simply the fraction of the sprayed water that becomes snow, and is measured by a percentage termed the “ice fraction”. Ideally, all the sprayed water becomes snow (excluding unavoidable losses due to evaporation and sublimation). A realistic expectation, however, is having 70-90% ice fraction. The water that does not freeze returns to the watershed or leaches downhill forming ice.

The second parameter is snow quality. Artificial snow is not made of flakes, as natural snow but it resembles small ice particles. Some may become light aerated particle mass and other may be heavy chips, which look like granulated sugar. The measurement of snow quality is a subjective matter. Measuring snow density is probably the most accurate method for determining snow quality. The snow density used on ski slopes ranges from 250 to 450 Kg/m^3. Usually ski resorts use snow moving equipment to spread and aerate the produced snow when it is not manufactured in the right constituency and when production is done in piles and not spread evenly over the slopes [3].

2.3 State-of-the-art of snowmaking developments

It is interesting to note that for most Eastern and Midwestern ski resorts, snowmaking has become their largest single operational cost and most resorts rely on snowmaking to extend the ski season. Ski areas in the US spend about \$1,200/*acre-ft* to produce artificial snow. The main cost in snowmaking is the energy required for the compressed air and pumped water [3].

Snowmaking is in fact a misnomer as it involves the manufacture of ice globules, not snow flakes [7]. Methods used in snowmaking are varied, but the basic technique remains the same. Water is atomized and projected into a cold atmosphere where the drops are allowed to freeze as they fall to the ground. Factors affecting the production of snow are many and include:

- Water drop size
- ambient temperature

- relative humidity
- water temperature
- quantity and type of sediment in the water
- quantity and type of added nucleation agents
- flight time of the drops

The two basic methods used are known as low pressure (meaning fan) and high-pressure snowmaking (using compressed air). Low pressure relies on hydraulic atomization of the water through spray nozzles. The nozzles are located at the circumference of a large plenum complete with internal electrically driven fans. The fan produces a flow of air that carries the drops up into the atmosphere where the freezing process can begin [7]. Other low pressure systems utilize the centrifugal effect of fan blades sprayed with water. The low pressure system is the "airless" system described earlier.

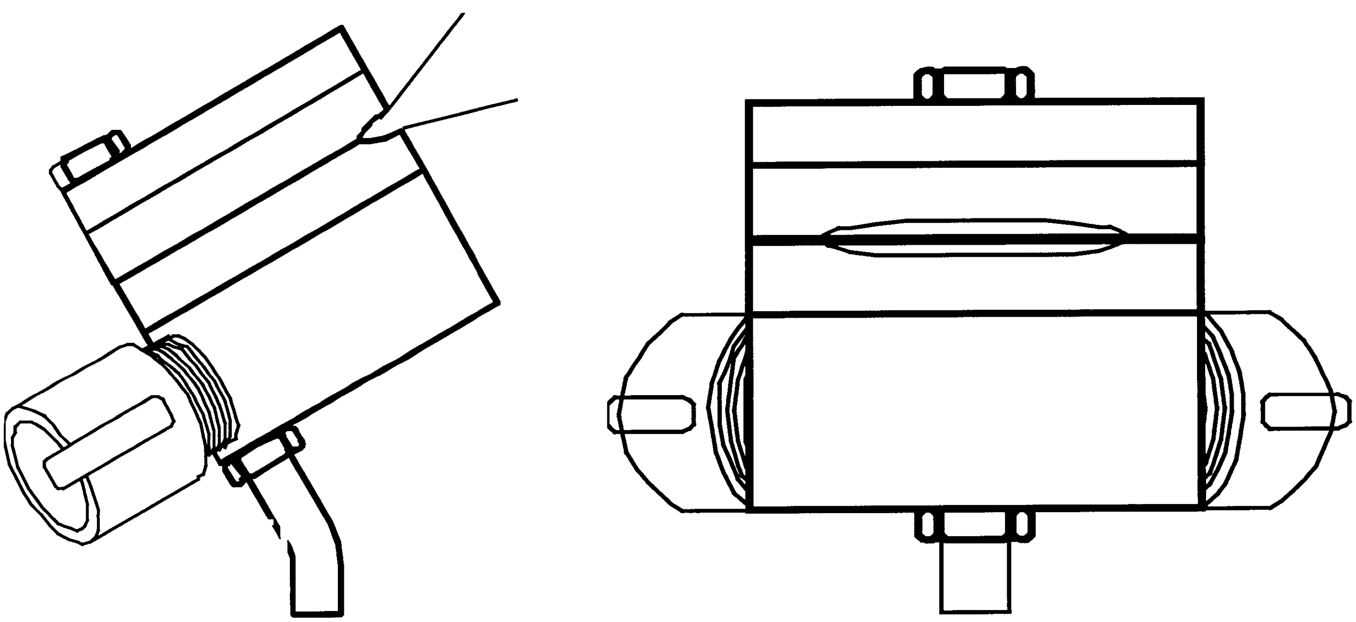

Figure 2.1: High pressure Whispergun™, a snowgun manufactured by Omichron Corporation.

High pressure snowmaking utilizes compressed air to atomize and project the water. Separate conduits bring compressed air and water to a nozzle that atomizes the water through high hydraulic pressure and/or expansion of the compressed air. The flow of the expanding air is through a choked converged nozzle; upon ejection it reaches sonic speed. The terms high-pressure and low-pressure refer to the air pressure. A high pressure system requires low hydraulic pressure (6-8 bar), whereas a low pressure system requires high hydraulic pressure (about 30 bar).

Leading developments toward less expensive snowmaking are the construction of automated systems utilizing process control and the use of bacterial nucleators.
The control systems are designed to optimize operation from an energy point of view considering ambient temperature and humidity. In some cases, the computerized system uses demand-side-management of electric power consumption. A second goal is to reduce the need for manual labor that is still used in the repeated adjustment of snow guns to various weather conditions. The problem with using a control system is that every ski area is different [8]. In addition to local weather variability, each ski resort has different conditions related to water quality and availability, and different electricity rates. Other important factors include amount and type of sediment in the water (which affects nucleation) and the topography of the ski slope. In spite of the efforts in optimizing the entire operation, sub-optimization is still predominant in this industry. Much work is still needed in understanding the basic principles of the process of snowmaking.

The development related to nucleation is a second factor in improving the snowmaking process [9]. Water can still be liquid at a temperature much less that $0\ C$; pure water can be cooled to $-40\ C$ and still remain in liquid phase. The supercooled water is in a state of nonequilibrium. To initiate the freezing, freezing nuclei must be introduced into the water promoting the freezing process (see discussion on nucleation in section 5). Nucleation can be induced by natural impurities, such as sediments in the water, or mechanical means such as using compressed air or adding material with specific crystalline properties, which resemble the crystalline properties of ice. Such material initiates the freezing process. Silver iodide is the traditional material, which is used for nucleation of supercooled clouds for weather modification and rain enhancement. However, such material is too expensive and unacceptable for use in snowmaking.

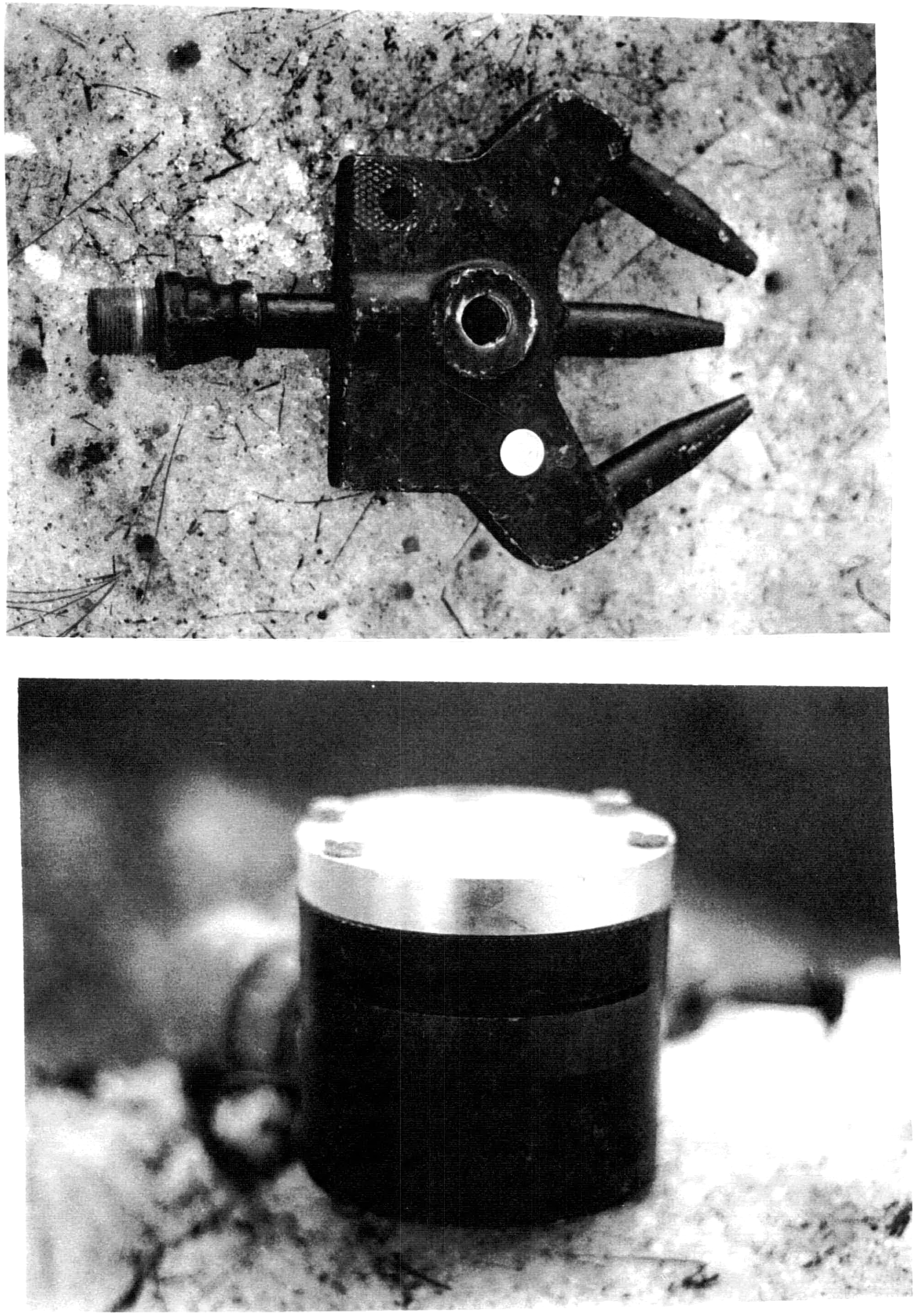

Figure 2.2: The upper photograph is of the first snowgun developed in the early 50's by Tey Manufacturing. In this gun water is ejected from the middle nozzle while two air streams impinge on the water jet externally. The lower photograph shows the Whispergun™, a modern high-pressure snowgun manufactured by Omichron Corporation, in which air and water are mixed internally.

During the past 20 years, a protein based on non-pathogenic bacteria has been developed as a snow inducer to initiate the freezing process [9]. The source of the protein is a bacterium called *Pseudomonas Syringae*. Steve Lindow of Berkeley who earlier conducted experiments at the University of Wisconsin investigating ways to protect plants from frost damage discovered the material [10]. The product called Snomax™, is grown and manufactured by Eastman Kodak in sterile fermenters. The final product is a freeze-dried pellet, inactivated by electron beam irradiation. York Snow, a division of York International, markets Snomax. The company claims that Snomax is able to elevate the freezing temperature to -2.8 to $-2.2\ C$. Concentrated Snomax slurry is injected into the snowmaking water at a prescribed rate of $1\ liter\ per\ 1000\ gallons$.

When a supercooled drop is nucleated after being ejected from the gun, a portion of the drop freezes and the released fusion heat elevates the temperature of the drop to $0\ C$. It remains so along the entire freezing process. Therefore, the temperature difference between the drop and the environment is maximum after nucleation. This results in high heat transfer between the drop and the environment after nucleation (see discussion in section 4). A higher rate of heat transfer reduces the flight time of the drop, in turn permitting the use of a larger drop diameter or spraying the water from lower heights. Using larger drops reduces the need for high pressure head through the atomizers and/or nozzles so the consumption of compressed air is reduced. This, in turn, lowers energy consumption. The use of nucleators that elevates the freezing temperature enables manufacturing of snow in marginal weather conditions such as slightly subfreezing temperatures (or even at ambient temperatures above $0\ C$ if the relative humidity is low). This makes it possible to manufacture snow early in the fall and late in the spring, thereby extending the ski season.

Because of public perception, it is unlikely that the use of Snomax, derived from bacteria, would be suitable for manufacture of ice destined for use as drinking water. In section 5 the author proposes to use small ice crystals to nucleate larger water drops in a method which resembles the system developed by Hanson in 1958 [5].

2.4 Other applications for snow making technologies

In the early 80's, Ted Taylor of Princeton University developed an ice pond created by snowmaking technology [11]. The preserved ice was intended to supply chilled water for commercial building air-conditioning systems, reducing electricity requirements. Other proposed applications were to provide cooling capacity for cheese making and brewing plants [12]. Another proposal by Taylor was to freeze seawater for the purpose of desalinization. His work was built on earlier work by Stinton [13]. Prototype facilities were tested in Greenport Long Island in 1985 but were abandoned due to the lack of support by local municipalities.

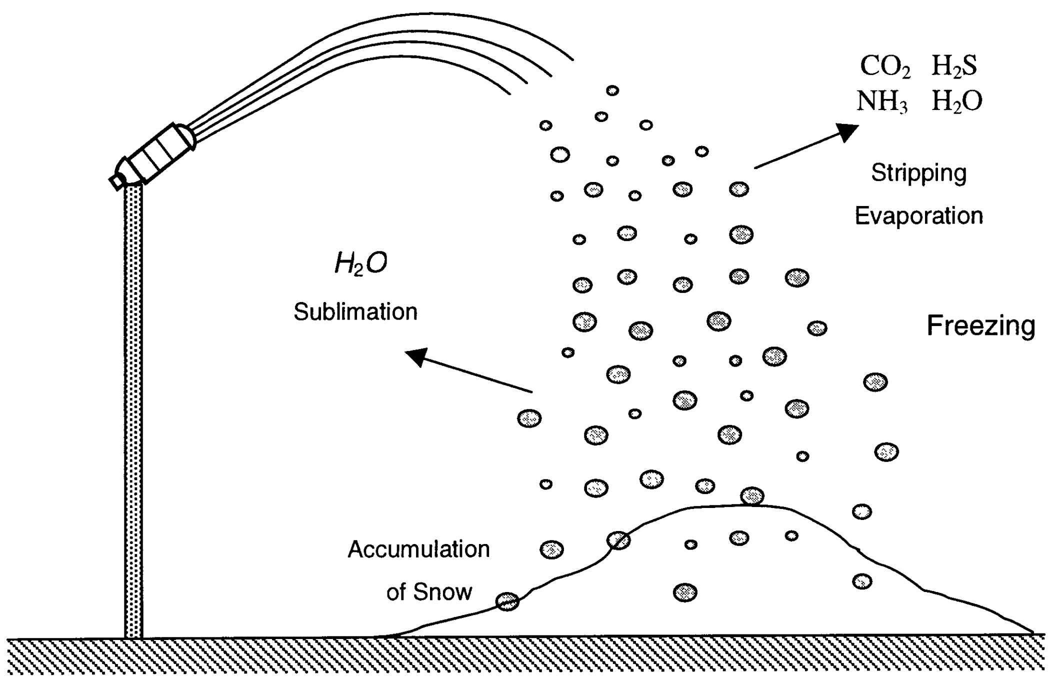

Figure 2.3: The Snowfluent™ process for wastewater treatment through atomizing freeze-crystallization [7].

Delta Engineering, a Canadian company, developed the Snowfluent™ process [7]. It is a wastewater treatment process specifically designed for cold climates. Snowfluent effectively treats wastewater by freezing it into small ice crystals using snowmaking equipment. The ice crystal structure rejects impurities, allowing separation of contaminants from the water. The process was developed with the cooperation of the Ontario Ministry of the Environment and Energy since 1980.

Ice made by flooding water and allowing it to freeze has been used for many years to construct bridges, roads and aircraft runways [14]. The military was a pioneer in ice construction in the early 1950's. The oil industry has used flood ice for offshore roads, deep water ice platforms and ice islands and protective barriers [7]. The methods for the production of ice from seawater might be improved by the principles of the winter ice manufacture process discussed in this thesis.

3. Hydrodynamics of single falling freezing water drop

3.1 Introduction

This section outlines the computation and analysis of the hydrodynamics of a single free falling water drop in still air. The analysis and computation assume a drop diameter in the range of $0.1\text{-}10\ mm$ falling at sea level, one atmosphere pressure under subfreezing atmospheric conditions. The air temperature is in the range of $0\ C$ to $-30\ C$. The effects of vertical temperature and density gradients in the atmosphere are negligible.

The analysis assumes a spherical drop that is ejected from an atomizer or nozzle located at a certain height above the ground. Knowing the terminal velocity of the drop enables the calculation of the Nusselt number, Nu and the convection heat transfer coefficient h_c, which in turn enables the calculation of the time, required causing the drop to freeze. The free-fall time and the terminal velocity enables determining the height from which the water drop should be ejected into the subfreezing atmosphere. These data, together with the pressure drop needed to atomize the water, will enable the assessment and optimization of the energy required for the manufacture of ice.

The free-falling water drop experiences the following stages:

a. Ejection from an atomizer or nozzle at negligible speed or at a speed U_0 and acceleration or deceleration to reach terminal velocity U_t.

b. Falling at terminal velocity while the drop supercools and its temperature is decreased until nucleation.

c. Upon nucleation, a portion of the drop freezes and the released latent heat causes a temperature elevation of the entire drop mass to $0\ C$.

d. Falling at terminal velocity until the entire drop mass freezes and impacts with the ground or accumulated ice below

One goal of this and the following sections is to analyze and calculate the speed of the drop at each stage and the time required for the heat transfer between the drop and the surrounding air to cause complete freezing. The calculation of the falling speed and the time required for freezing will enable the calculation of the necessary height from which the water drop should be sprayed to achieve complete freezing upon landing.

3.2 Terminal velocity of free falling spherical drop

The terminal velocity of a falling water drop has been analyzed in numerous publications concerning cloud and precipitation processes [15], [16], [17]. Most of these works have been done during the 1960's before the advent of high-speed computers. Earlier works made simplifications considering limited computing capabilities, which do not pose a problem today. In this section, it is assumed that the water drop is spherical and not deformed. In the following sub-section a deformed drop will be considered.

When the water drop achieves a terminal velocity the aerodynamic drag and the buoyancy forces are equal to the gravitational force:

$$\tfrac{1}{6}\cdot\pi\cdot d^3\cdot g\cdot(\rho_w-\rho_a)=C_D\cdot\tfrac{1}{2}\rho_a\cdot U_t^{\,2}\cdot\tfrac{\pi}{4}\cdot d^2 \tag{3.1}$$

where d is the drop diameter, ρ_a and ρ_w are the air and water densities, C_D is the drag coefficient, and g is the gravitational acceleration. Non-dimensional analysis of the problem shows that it can be described in terms of two dimensionless groups: the Reynolds number $R_e=\dfrac{U_t\cdot d}{\nu}$ (ν is the kinematic viscosity of air), and C_D, such that:

$$C_D=f(R_e) \tag{3.2}$$

C_D as a correlated function for various ranges of R_e is given in numerous works. However, in some, the function $C_D=f(R_e)$ is discontinuous or given for limited range of R_e [18] or its derivative is discontinuous [19]. The correlation which seems to be the best in matching (function and its derivative are continuous) the various R_e ranges is that of Cliff [20]:

$$C_D = \frac{24}{R_e}\left[1 + 0.1315 R_e^{(0.82-0.05w)}\right] \qquad 0.01 < R_e \le 20$$

$$C_D = \frac{24}{R_e}\left[1 + 0.1935 \cdot R_e^{0.6305}\right] \qquad 20 \le R_e \le 260$$

$$\log_{10} C_D = 1.6435 - 1.1242 \cdot w + 0.1558 \cdot w^2 \qquad 260 \le R_e \le 1500$$

$$\log_{10} C_d = 2.4571 + 2.5558 \cdot w - 0.9295 \cdot w^2 + 0.1049 \cdot w^3 \qquad 1.5 \cdot 10^3 \le R_e \le 1.2 \cdot 10^4 \tag{3.3}$$

while:

$$w = Log_{10} R_e \tag{3.4}$$

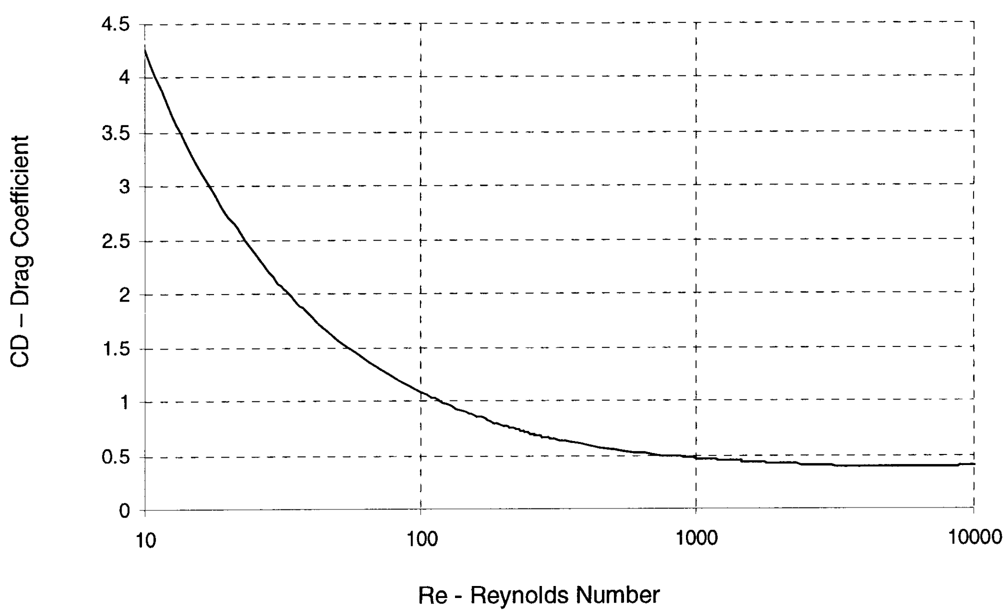

Fig 3.1: Drag coefficient vs. Reynolds Number for a rigid sphere, according to equation (3.3)

Equation (3.1) and the definition for R_e are rearranged to give:

$$C_D \cdot R_e^{\,2} = \frac{4}{3}\frac{d^3}{v^2}\frac{\Delta\rho}{\rho_a} g \tag{3.5}$$

$\Delta\rho = \rho_w - \rho_a \cong \rho_w$ and $C_D \cdot R_e^{\ 2}$ is referred to as either the Davies or the Best Number.

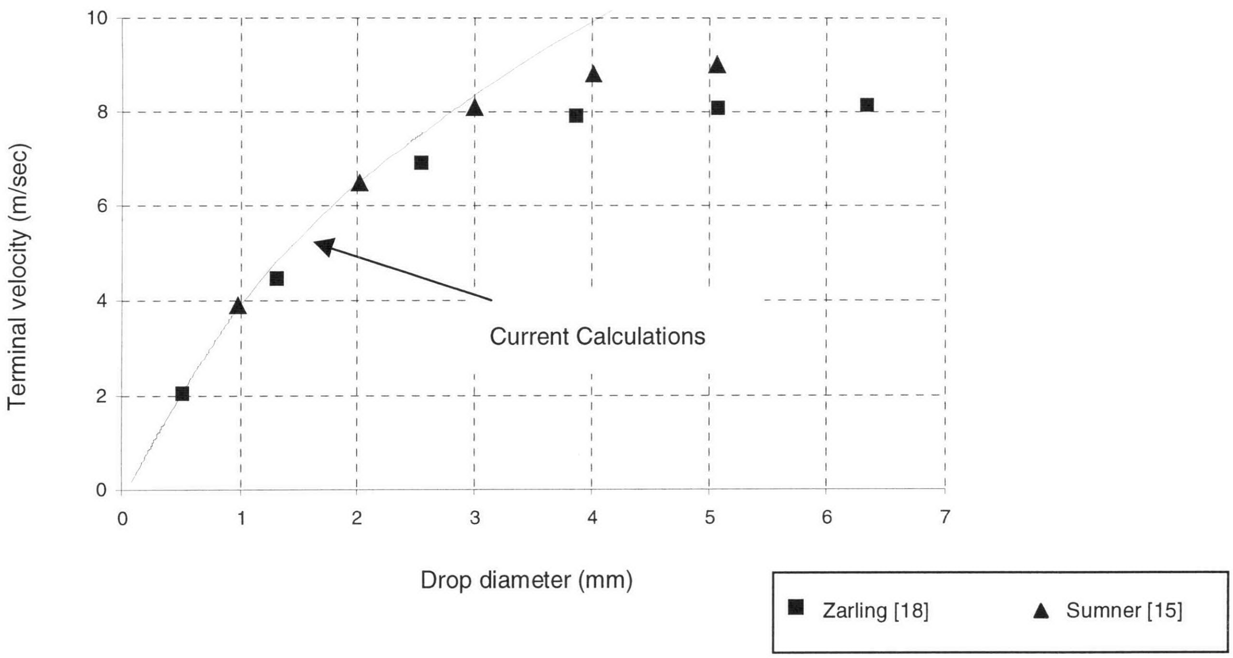

Figure 3.2: Terminal velocity of a spherical drop $P = 1\ bar,\ \ T = -10\ C$

The expressions for the drop diameter d and the terminal velocity U_t are extracted from (3.4):

$$d = \left[\frac{3}{4}\left(C_D \cdot R_e^{\ 2}\right)\frac{\nu^2 \cdot \rho_a}{g \cdot \Delta\rho}\right]^{\frac{1}{3}} \tag{3.6}$$

and

$$U_t = \frac{R_e \cdot \nu}{\left[\frac{3}{4}\left(C_d \cdot R_e^{\ 2}\right)\frac{\nu^2 \cdot \rho_a}{g \cdot \Delta\rho}\right]^{\frac{1}{3}}} \tag{3.7}$$

Equations (3.6) and (3.7) enable plotting the terminal velocity vs. drop diameter.

3.3 Variations in the terminal velocity of liquid and frozen drops

A falling liquid drop or ice drop experiences a slight reduction in diameter from evaporation and sublimation, respectively. Therefore, the drop terminal velocity is slightly reduced with time. At the time when a liquid drop freezes, it expands, its diameter increases and its density decreases. The effect of the increase in the diameter and the decrease in density is to increase the drag, leading to a lower terminal velocity. The effects of evaporation and sublimation will be explored in subsequent sections. The following analysis estimates the effect of freezing on spherical drop. It is assumed that the drop remains spherical when it freezes.

Upon freezing, the volume of a water drop increases by 8.696% and since the volume is proportional to the cube of the diameter, the expansion of the drop increases its diameter by 2.82%. Its density decreases by 8%. To determine the effect of the changes in diameter and density on the terminal velocity, equation (3.6) and the definition of R_e are used to obtain:

$$U_{t\, ice\, or\, water} \propto \frac{d^{1/2} \cdot \rho^{1/2}_{ice\ or\ water}}{C_D^{1/2}} \tag{3.8}$$

The effect of the increase in d is to increase the terminal velocity and the reduction in ρ is to decrease U_t. The combined effect changes slightly the Reynolds number R_e. Since C_D is a weakly decreasing function of R_e the change in the drag coefficient due to the change in R_e is negligible. Substituting the values for the changes in d and ρ due to the drop freezing, indicates that its velocity is reduced by approximately 2.5%. Since the drop freezes gradually and not at once, the 2.5% change in its velocity takes place during the entire freezing process. Therefore, this reduction in terminal velocity can be ignored in further calculations.

3.4 Acceleration of a spherical drop

A spherical drop may be ejected from a nozzle or an atomizer with no initial velocity or at initial velocity U_0. The drop will eventually reach its terminal velocity while under the influence of gravity and drag forces.

The governing motion equation is:

$$m_d \frac{dU}{dt} = m_d \cdot g \cdot (1 - \frac{\rho_a}{\rho_w}) - F_D \tag{3.9}$$

where m_d is the drop mass and the drag F_D is defined as:

$$F_D = \frac{1}{2} C_D \cdot \rho_a \cdot U^2 \cdot \frac{\pi}{4} d^2 \tag{3.10}$$

Combining (3.9) and (3.10) and using $\rho_a << \rho_w$ gives:

$$\frac{d^2 S}{dt^2} = \frac{dU}{dt} = g - \frac{3}{4} \cdot \frac{\rho_a}{\rho_w} \cdot \frac{C_D}{d} \cdot U^2 \tag{3.11}$$

where S denotes the falling distance. An exact analytical solution for (3.11) can be derived for small drops when $d \leq 10 \mu m$ and for $R_e << 1$. For these conditions $C_D = 24/R_e$ and Equation (3.11) becomes an ODE [21]. In the case when $d \geq 100 \mu m$ the expression for C_D is given by (3.3), so equation (3.11) becomes non-linear and a solution can be obtained only by numeric methods. Equation (3.11) can be re-written as a system of two first order equations:

$$\begin{bmatrix} U \\ S \end{bmatrix} = \begin{bmatrix} g - \frac{3}{4} \cdot \frac{\rho_a}{\rho_w} \cdot \frac{C_D}{d} \cdot U^2 \\ U \end{bmatrix} \tag{3.12}$$

Numerical solution of (3.12) gives the required time and the falling distance of a drop starting from rest to reach 99% of the terminal velocity. The time and the falling distance are given as a function of the drop diameter.

The same Matlab calculations used for plots 3.3, 3.4 and 3.5 below (where the drop starts from rest) can be applied for a small drop ejected from a snow gun driven by compressed air. Assuming that this drop acquires an initial velocity, which is comparable to the speed of the

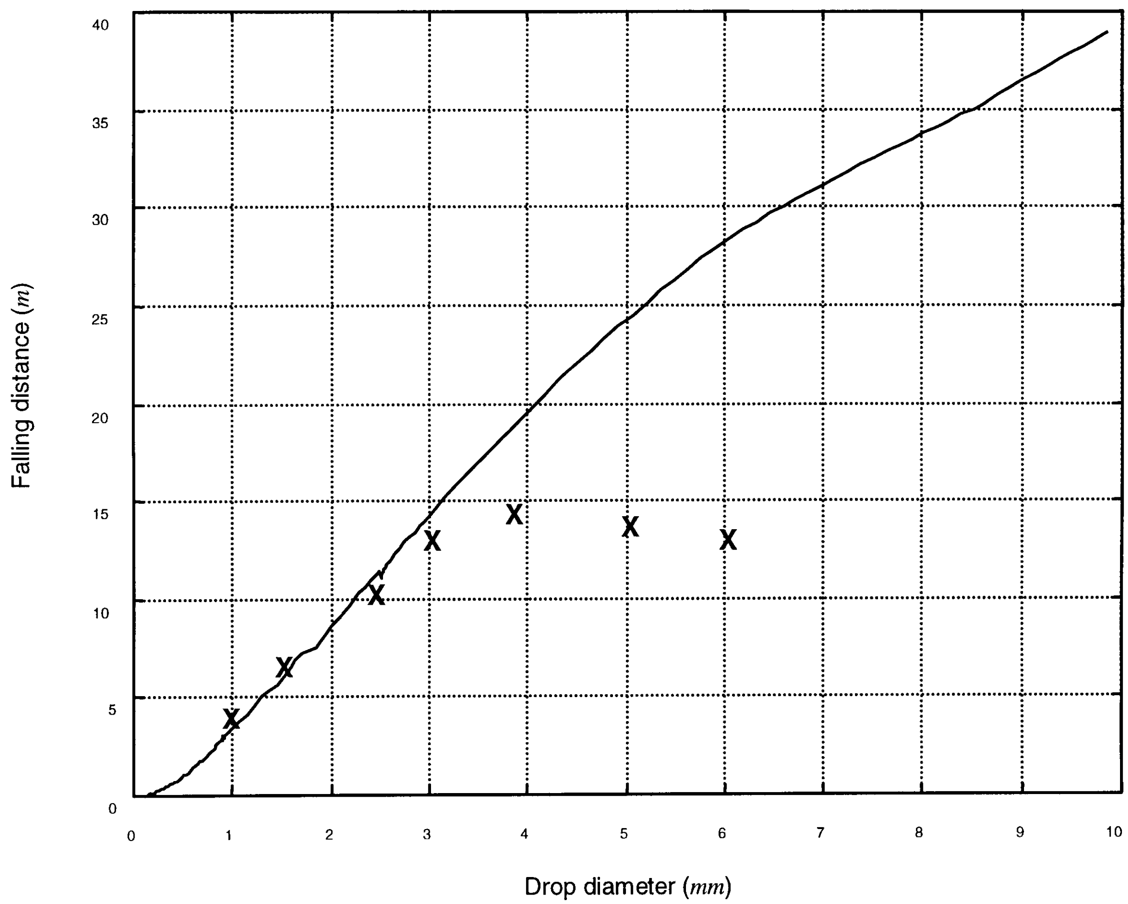

Figure 3.3: The fall distance for a drop to reach 99% of terminal velocity vs. drop diameter. —— current calculations, **X** are the results of experiments by Wang, [16].

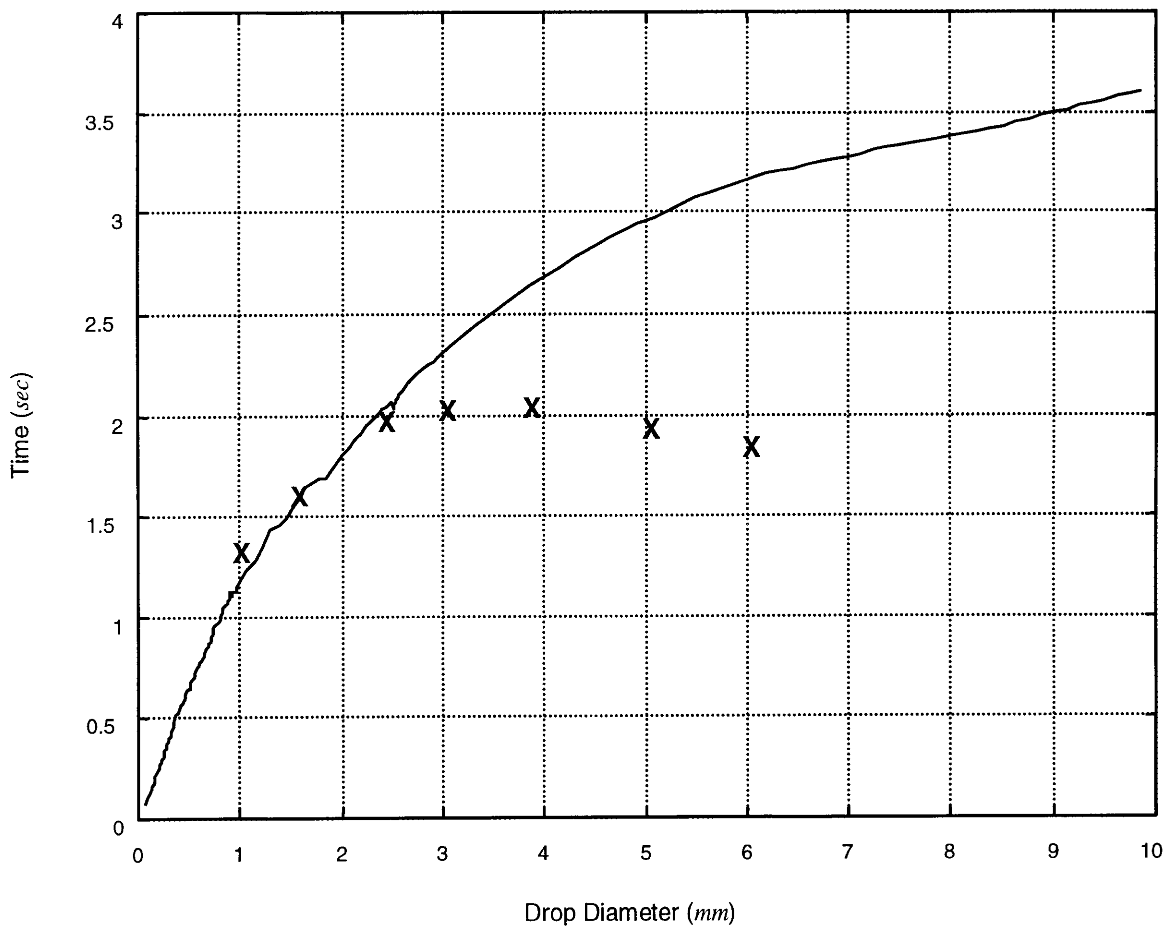

Figure 3.4: Time to reach 99% of terminal velocity vs. drop diameter. —— current calculations. **X** are the results of experiments by Wang, [16].

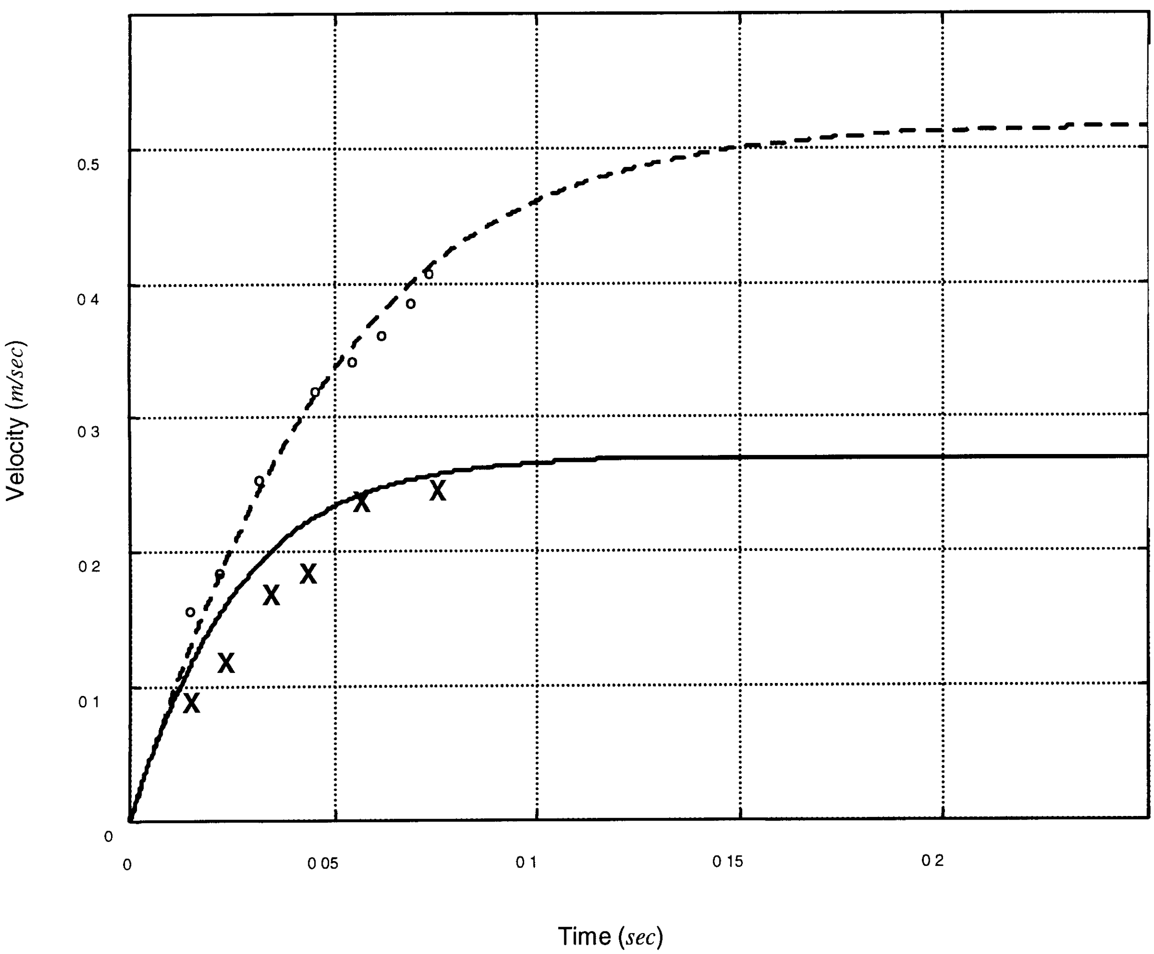

Figure 3.5: Falling velocity history of two drops. —— and - - - are for drop diameter 0.101 *mm* and 0.1573 *mm* respectively. **x** and **o** are experimental results obtained by Wang, [16]. However, the calculations are for ambient 1000 *mb* pressure and -10 *C* temperature while the experiments are for 828 *mb* and +20 *C* ambient conditions.

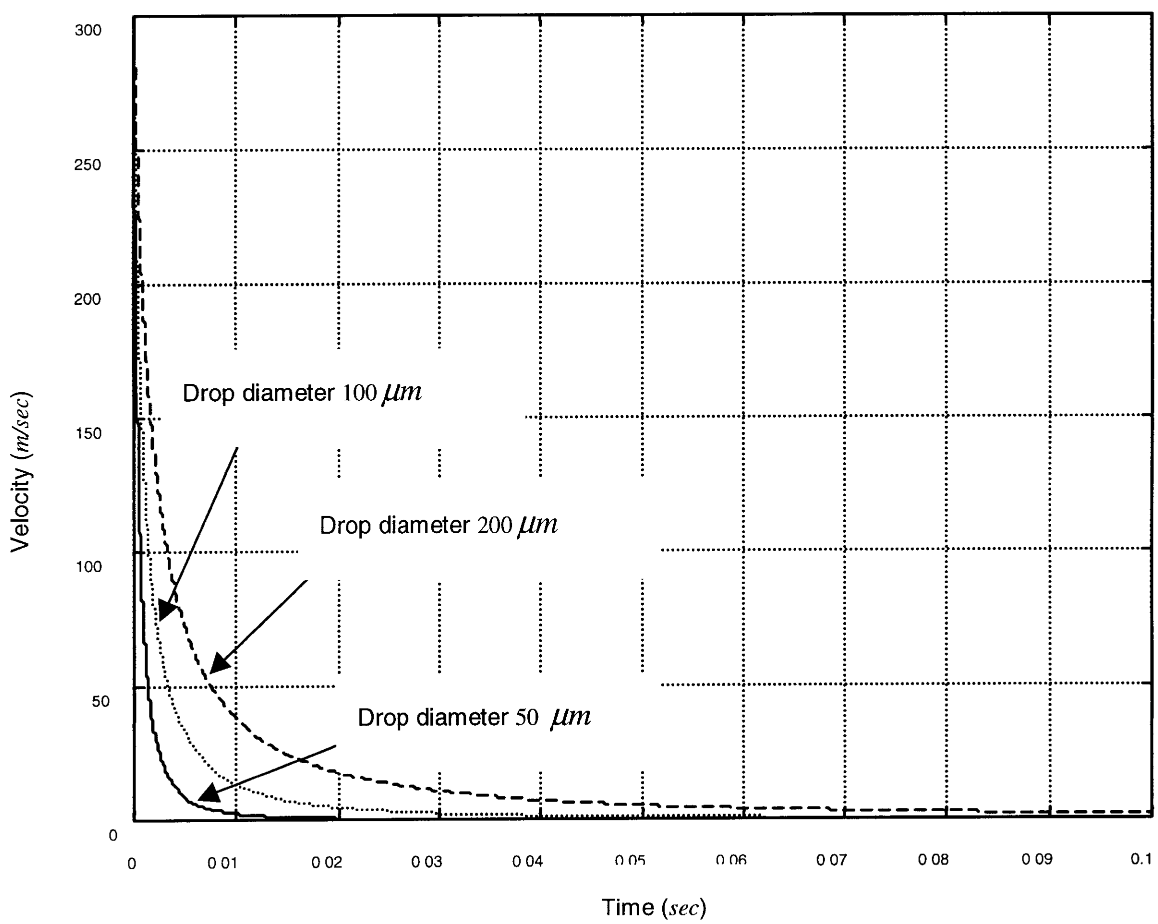

Figure 3.6: Calculated velocity history of water drops ejected from snowgun at 300 *m/sec* initial velocity. In less than 0.1 *sec* the drops reach zero velocity.

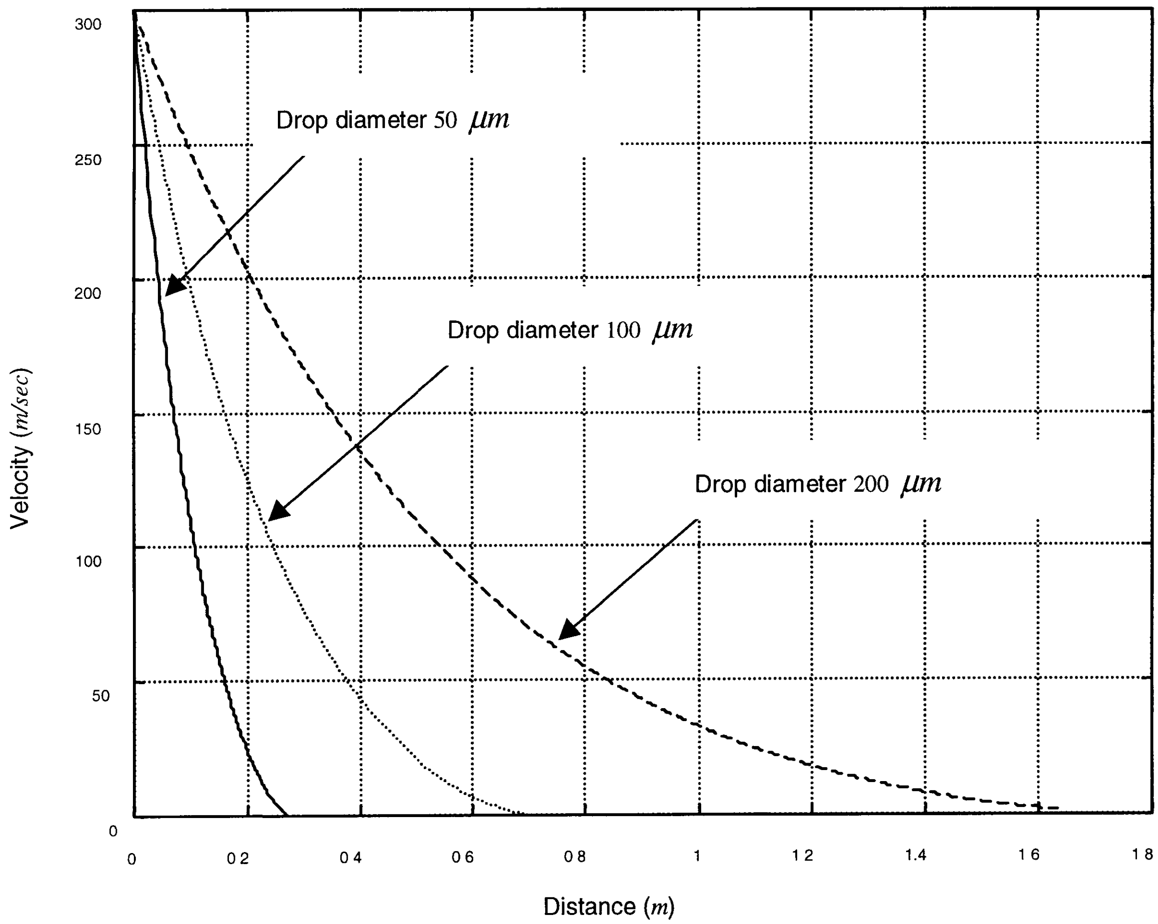

Figure 3.7: Calculated horizontal flight distance of water drops ejected from snowgun at 300 m/sec initial velocity. The flight distance is on the order of 1 *meter* for a typical drop size used in actual high pressure snowmaking.

discharged air in the choked flow. The velocity of the expanded air is roughly sonic. Since inertia of the small drop is also small, the drop velocity is comparable to that of the expanded air and could be estimated as $U_0 \cong 300\, m/\sec$. Figures 3.6 and 3.7 show the velocity and distance history for typical drop size used in snowmaking, which in these calculations is 50, 100 and 200 μm. Due to the small inertia of these drops, they reach near zero velocity is less than 0.1 *second* and the horizontal distance acquired by their tremendous initial velocity is on the order of 1 *meter*. The motion of the ejected drop, however, is due to the motion of the expanded air from the snow gun. This means that there is no relative velocity between the drop and the expanded air and also that heat transfer does not take place between the drop and the ambient air. The heat transfer is between the drop and the expanded air, which is cooled by the expansion. However, because there is no relative velocity between the drop and the expanded air, the convective heat transfer is not efficient.

The conclusion based on these arguments is that the high pressure air used in snowgun might be beneficial in atomizing the water into small drops, providing a trajectory to the drops and help in spreading the drops on the ski slopes. However, it does not promote heat transfer between the drop and the ambient air.

3.3 Terminal velocity of non-spherical drops

Free falling liquid and ice drops lose their spherical shape due to various reasons. A liquid drop maintains its spherical shape when its diameter is less than $300\mu m$ [21]. For a larger drop up to a diameter of 1 *mm* the drop is slightly deformed and resembles an oblate spheroid. For $d = 1\, mm$ the ratio of the major and minor axes is 0.98 and the oblate drop develops a flattened base. The flattening becomes pronounced when the diameter is 4 *mm* for which the ratio of the axes is 0.78 and a concave base depression begins to develop. With further increase in size, the concavity deepens until, at about $d = 10\, mm$ the drop becomes hydrodynamically unstable and breaks up, even in the absence of any turbulence in the air stream. Figures 3.3 and 3.4 show a substantial disparity between experimental and the calculated results for a drop diameter larger than 4 *mm*. For such a large drop, the oblate shape is substantial and a spherical model is not adequate.

A freezing drop of any size may completely lose its spherical shape, for some conditions, and a consistent analysis of its shape is impossible. When a liquid drop starts freezing, an

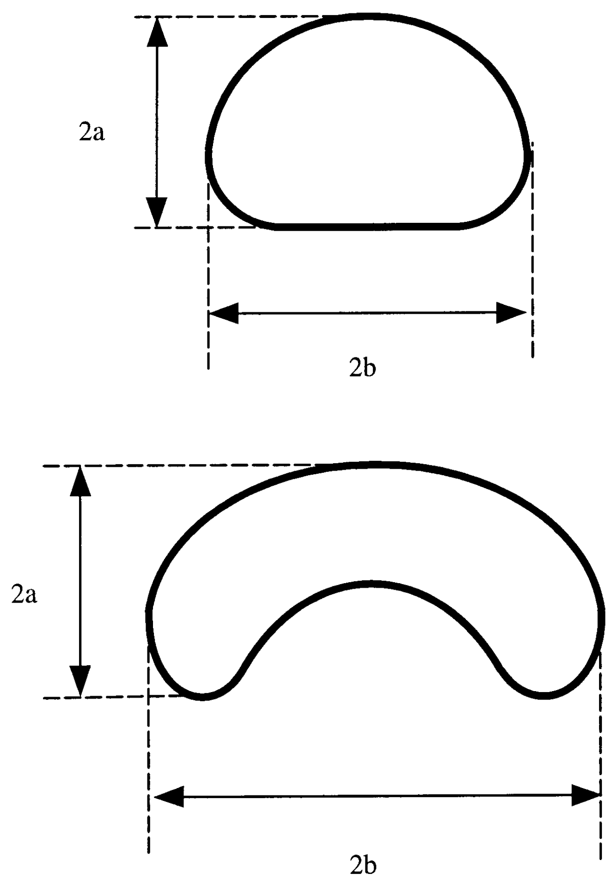

Figure 3.8: Oblate water drop at free fall. When the drop diameter is larger than 4 *mm* the lower face is flattened. When the drop is larger than 6 *mm*, a concave depression in the base is formed. The drop develops instabilities, which lead to breakup for a diameter of 10 *mm* [21].

ice shell is formed on the surface and its thickness grows with time. The shell thickness is uniform if the heat flux is uniform on the drop surface [22]. Due to ice volumetric expansion, the inner liquid is compressed to a pressure which could reach 70 *bar*. Eventually the shell shatters and the liquid is jetted in thin streams or filaments outside the drop core. Since the filament thickness is very small, the heat transfer is high and the stream freezes in the form of a needle, which is attached to the drop mass. This sudden change of its spherical shape, results in an abrupt change of velocity and the drop falls in an erratic trajectory instead of a straight-line [23]. Another reason for a variation from a spherical shape is that the nucleation is a statistical process and the nucleation point in the drop may happen anywhere in its volume and less likely in its center. Thus, the drop does not freeze concentrically and the drop may acquire any shape during freezing. The irregular shape of the freezing drop and its tumbling during free fall prevents the drop from reaching terminal velocity and the falling path may become spiral and erratic.

A precise analysis for the heat transfer of irregular shaped drops is beyond the scope of this thesis. The only way to estimate and calculate the heat transfer is to use a spherical model for both the liquid and the freezing drops.

4. Heat and mass transfer of a free falling drop

4.1 Introduction

The calculation of terminal velocity and the heat and mass transfer of the free falling drop are the central issues in the analysis of the concept of winter ice manufacture (WIM). Knowing the rate of heat transfer will enable the calculation of the needed flight time of the drop. This, together with the information on the terminal velocity will enable the calculation of the height from which water drops should be sprayed in order to achieve complete freezing upon landing. Knowing the height will enable the identification of the major parameters required for optimizing the operation. The main variables for economic assessment and optimization are: the pumping energy, which is dependent on the spraying height and the dimension of the structure needed to support pipes, hoses and spraying nozzles.

A free-falling drop experiences several different stages until it freezes completely. The first is ejection from a nozzle or an atomizer. The water is pumped from a water reservoir or a nearby river during subfreezing periods. At these times, the surface of the water reservoir is frozen or about to freeze and although the temperature of the water deep in the reservoir is $+4\ C$, the temperature just on the surface is $0\ C$ [24]. The water may be further cooled while flowing in a pipe leading to the spraying nozzles. It is imperative, however, that the water does not freeze in the pipes to prevent freezing and shut down of the entire system. Without loss of accuracy, it is estimated that the temperature of the water drop just upon ejection from the spraying nozzles is $0\ C$.

The drop accelerates until it reaches terminal velocity and during this time heat transfer to the environment supercools it. Upon nucleation, which might happen at certain subfreezing temperatures (see section 5), a portion of the drop freezes spontaneously and the latent heat released from the frozen mass elevates the entire mass temperature to $0\ C$. The convective heat transfer between the drop and the surrounding air is proportional to $\Delta T(t) = T_w(t) - T_a$, where $T_w(t)$ is the temperature of the supercooled water and T_a is that of the air. It is assumed that the temperature of the surrounding air T_a and the relative humidity ϕ are invariant to changes in altitude during the drop descent. Since the heat transfer is proportional to the temperature difference between the drop and the surrounding air, it is important that nucleation happens at the highest possible temperature. Otherwise, the water drop loses altitude without gaining significant cooling through heat transfer. After nucleation, heat is removed from the frozen ice shell to the environment by convection and sublimation while heat is removed from the liquid core to the outer ice shell by conduction until complete freezing.

Before nucleation when the entire drop is liquid, the shear stress on the surface of the drop induces circulation of the water inside the drop. This results in mixing and assures that the entire drop mass is isothermal, so the liquid drop can be treated as a lumped thermal mass [25].

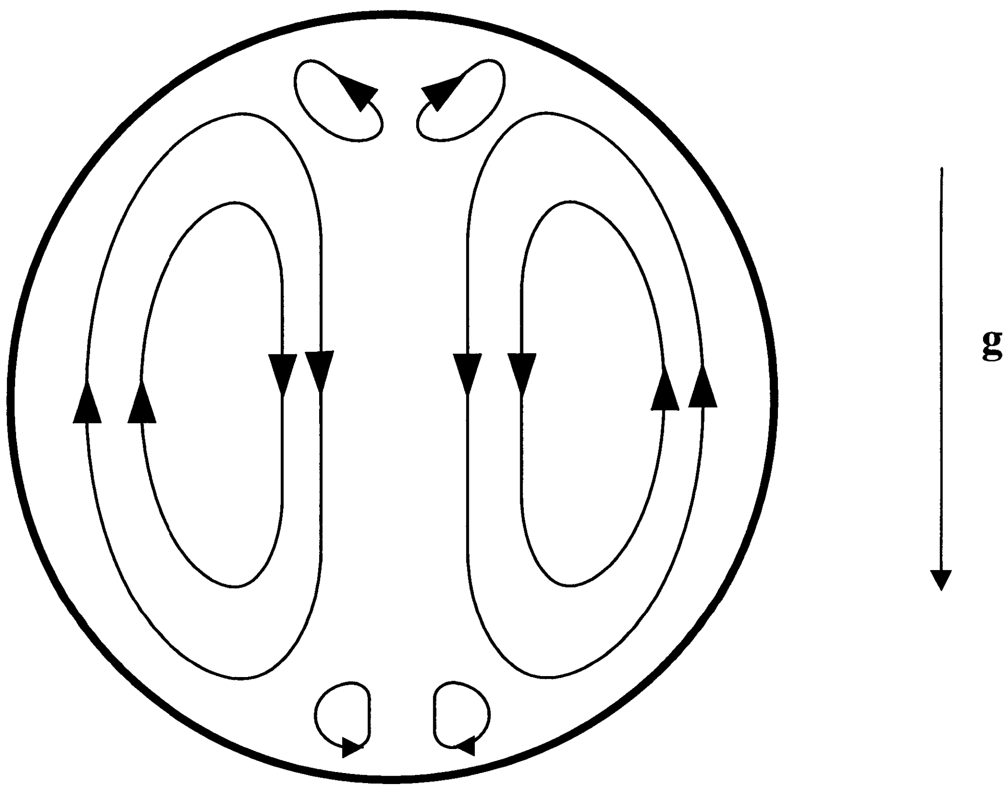

Figure 4.1: Internal circulation in a liquid drop falling through air. The shear stress on the drop surface induces internal circulation, which causes temperature uniformity throughout the entire drop mass [21].

The mass transfer due to evaporation from the liquid drop and the sublimation from the freezing drop is beneficial for the freezing process. The reason is that when a portion of the drop is evaporated, the latent heat is withdrawn from the rest of the drop mass which experiences freezing by release of fusion heat. The ratio between the heat of evaporation to heat of fusion of water is 7.495. Regardless of convective heat transfer, it means that for each unit mass of input liquid water $1/(7.495+1)=0.1177$ or 11.77% is evaporated while 88.23% ends as ice at $0\ C$. As for the surrounding air, it is beneficial that it be not only cold but also that its relative humidity be low.

4.2 Heat transfer of liquid and frozen drops--general considerations

The atmospheric science literature has numerous discussions and data on the heat transfer of cloud drops, and the formation of hail and snow [15], [21], [26]. However, the terminology used by atmospheric scientists is slightly different from that used by mechanical and chemical engineers. Therefore, although a reference will be made to atmospheric literature, another notation will be used here.

The heat transfer from a liquid drop is essentially different than the heat transfer from a freezing drop. A liquid drop changes its temperature with time during cooling, while sensible heat is removed, causing the drop to supercool. Evaporation occurs from the liquid phase. The rate of heat transfer is reduced with time as ΔT decreases and this is the reason that it is desirable that nucleation happens as soon as possible and at the highest temperature possible. Because of internal circulation, the drop can be treated as a lumped thermal mass and it is assumed that the drop starts its free fall at $0\ C$.

The heat transfer from a freezing drop withdraws latent heat from the mass, which is at $0\ C$ as long as the liquid and ice phases co-exist. Therefore, the rate of heat transfer is greater than that of a supercooled liquid drop. The saturation pressure of vapor over ice in subfreezing temperatures is smaller than the saturation pressure of vapor over supercooled liquid. Therefore, the rate of sublimation is expected to be smaller than the rate of evaporation for the same temperatures for liquid and ice [15], [26]. However, since sublimation from the ice drop happens only at $0\ C$, while evaporation from the drop can be at subfreezing temperature, the sublimation rate is higher than the evaporation rate. Moreover, the duration of sublimation is much longer than that of the evaporation, so the sublimation mass loss is higher than that due to evaporation.

The frozen drops, the final product of the WIM process resemble hail but this process is different from hail formation. Hail forms under special atmospheric circumstances. It is formed when the water vapor content in a cloud is less than what is needed for saturation and condensation but the temperature is such that the vapor pressure in the cloud is more than the saturation pressure over ice. Under these circumstances, an embryonic ice particle will attract water vapor which is deposited on the ice particle, while water vapor is formed by evaporating unsaturated liquid drops in a phenomenon called the Bergeson-Findeisen process, discovered by Bergerson in 1935 [15]. In order for the ice particle to grow, it should be caught in an upward air draft. The ice particle continues to grow until the draft cannot prevent the large particle from falling downward. The fallen particle may be caught again and again by upward drafts while its ice mass continues to grow due to further deposition of water vapor and accretion until its large mass forces it to fall and land on the ground as hail in spite of the updrafts. In fact, raindrops in northern latitudes are formed this way but the formed ice particles are melted in the lower atmosphere and reach the ground as liquid rain. It is clear from this description that there is no similarity between hail formation and the winter ice manufacture (WIM) process.

4.3 Heat transfer from a liquid drop

Literature concerning the heat transfer of drops in the snowmaking process does not exist except for two general papers written by Zarling 19 years ago [18] and by Chen et al 28 years ago [27]. The following analysis draws some data from Zarling and Chen but most of it starts from basic principles.

The governing differential equation for the heat transfer due to convection, evaporation and radiation from a falling, well-mixed liquid drop is:

$$\rho_w C_{pw} V_w \cdot \frac{dT_w}{dt} = -A \cdot \left[h_c (T_w - T_a) + h_d \cdot h_{fg} (\rho_{vw}(T_w) - \rho_{v\infty}(T_a)) + \sigma \cdot \varepsilon (T_w^4 - T_a^4) \right] \qquad (4.1)$$

Where: ρ_w, C_{pw}, V_w, A and T_w are the density, specific heat, volume, surface area and the temperature of the water drop, and

ρ_{vw} = saturation vapor density over the (liquid) drop surface

$\rho_{v\infty}$ = saturation vapor density in the ambient air

h_c = convective heat transfer coefficient

T_a = ambient temperature

h_d = convective mass transfer coefficient

h_{fg} = enthalpy of vaporization

σ = Stefan-Boltzmann constant

ε = emissivity of water.

The term on the LHS of equation (4.1) represents the time rate of change of the energy of the drop as it falls. In simplifying (4.1), it is assumed that the density, heat capacity and enthalpy of vaporization of water are invariant with temperature changes. As for the air, its density is assumed for further calculations as the density of air at $P = 1\ atm$ and $T_a = \text{-}10\ C$. As for radiation, according to an analysis and data on arctic cooling of the surface of a water pond, the air ambient temperature closely approximates the effective sky temperature [18]. The emissivity ε of water is estimated as 0.97-0.98 and that of ice as 0.97 [28].

The heat and mass transfer coefficients are correlated from experiments as [29]:

$$\overline{N_U} = \frac{h_c \cdot d}{k} = 2 + (0.4 \cdot R_e^{1/2} + 0.06 \cdot R_e^{2/3}) \cdot P_r^{1/3} \qquad (4.2)$$

$\overline{N_U}$ and P_r are the Nusselt and Prandtl numbers respectively. For air P_r=0.69. k is the conductivity of air.

There are two approaches for the calculation of the mass transfer coefficient. The first uses the Lewis Number L_e to relate the heat and mass transfer coefficients for water in air as [18]:

$$L_e = \frac{h_c}{\rho_a \cdot C_{P_{air}} \cdot h_d} \cong \left(\frac{\alpha}{D_{dif}} \right)^{2/3} \qquad (4.3)$$

Where α is the thermal diffusivity and D_{dif} is the mass diffusivity. For water-air, the ratio α / D_{dif} is approximately 0.85 [29] from which the value of h_d is easily calculated once h_c is known. The second approach is to calculate directly the mass transfer coefficient through the Nusselt number for mass transfer, or the Sherwood number, which is defined similarly as is $\overline{N}_U$:

$$\overline{S}h = \frac{h_d \cdot d}{D_{dif}} = 2 + (0.4 \cdot R_e^{1/2} + 0.06 \cdot R_e^{2/3}) \cdot S_c^{1/3} \qquad (4.4)$$

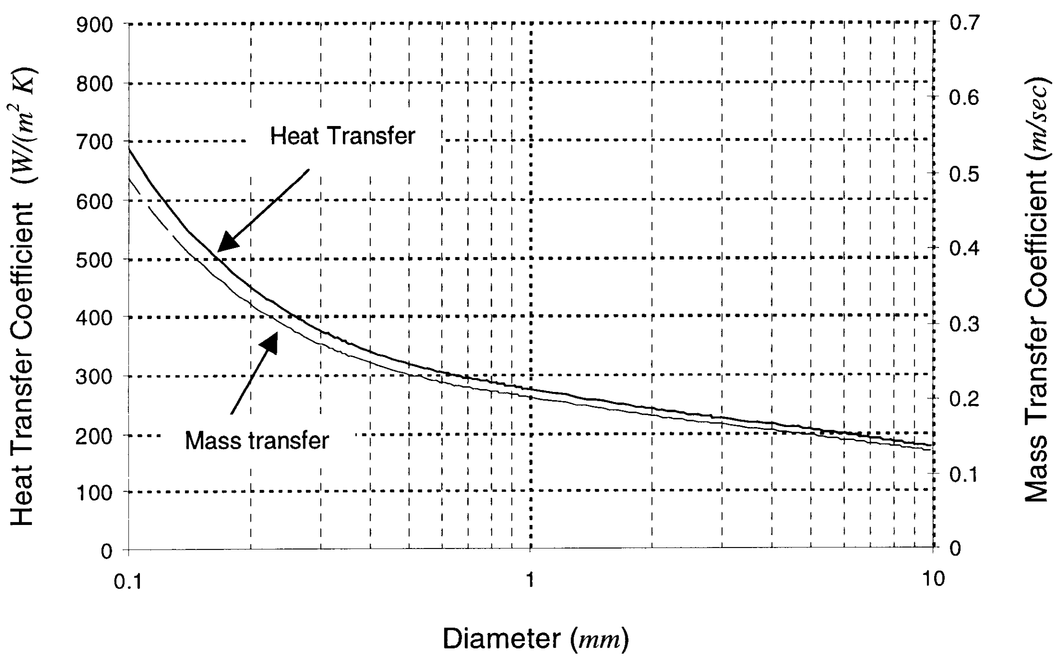

Figure 4.2: Heat and mass transfer coefficient vs. drop diameter.

$S_c = L_e \cdot P_r$ is the Schmidt number. For water-air $S_c \cong 0.62$ [29]. The error in calculating the mass transfer coefficient through equation 4.3 and 4.4 does not exceed 1.5%.

The expressions for the water vapor density needed for equation (4.1) are derived through the saturation pressure of water vapor over liquid and over ice as functions of the temperature. Ludlam gives a useful expression for the saturation vapor pressure over liquid and over ice [26]:

$$p_s = 100 \cdot \exp\left[1.8096 + \frac{a(T-273.16)}{(T-b)}\right] \tag{4.5}$$

p_s is the saturation vapor pressure in Pascals, T is the temperature in Kelvin and $a = 17.27,\quad b = 35.86$ over liquid and $a = 21.87,\quad b = 7.66$ over ice respectively.
The percentage error in the value of p_s is less than 1% above $-25\ C$ [26]. The saturation vapor density over the liquid or ice drop surface and in the ambient air is calculated using the equation of state for ideal gas:

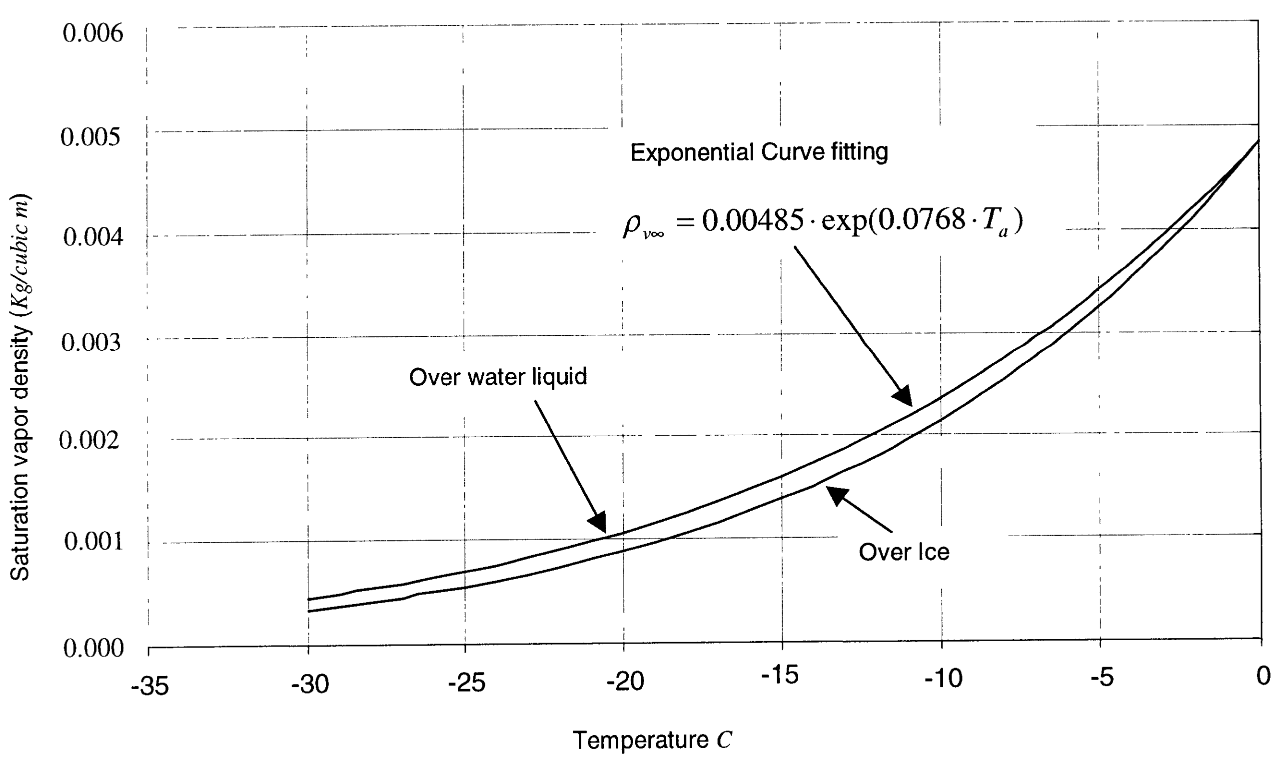

Figure 4.3: Saturation vapor density over liquid water and ice.

$$\rho_{v\ liquid\ or\ ice} = \frac{p_{s\ liquid\ or\ ice}}{R_{H_2O} \cdot T} \tag{4.6}$$

The temperature T in equation (4.6) is $0\ C$ in the case of ice since the cooling of the water drop ceases when the drop reaches complete freezing. In the case of liquid, T it is the supercool temperature. The vapor density in the ambient air is:

$$\rho_{v\infty} = \phi \cdot \frac{p_s(T_a)}{R_{H_2O} \cdot T_a} \tag{4.7}$$

Where $p_s(T_a)$ is the saturation vapor pressure in the ambient air, ϕ is the relative humidity and R_{H_2O} is the gas constant for water vapor. $R_{H_2O} = 461.5 \frac{J}{Kg \cdot K}$

4.4 Heat transfer of a freezing drop

From an energy expenditure point of view, it is important that the nucleation of the liquid drop takes place at the highest temperature possible. The reason is that when the drop is supercooled and its temperature is approaching the temperature of the ambient air, the heat transfer with the air is not efficient since ΔT is smaller. The result of an inefficient heat transfer process is the need to increase the falling time of the drop, which translates to a need to spray the water from a higher altitude. Also, if the nucleation temperature were lower than the wet bulb temperature of the ambient air, nucleation would not happen at all.

After the drop is nucleated, its temperature increases spontaneously to $0\ C$ and its temperature remains so until complete freezing [9]. If the drop nucleates at subfreezing temperature $-\delta T\ \ C$, the portion of the mass drop which freezes spontaneously releases fusion heat which elevates the temperature of the entire drop mass to $0\ C$. Therefore, just after nucleation the ratio of the frozen mass to the entire drop mass is:

$$\frac{\Delta m_{ice}}{m_{drop}} = \frac{C_{pw} \cdot \delta T}{h_{sf}} \tag{4.8}$$

while h_{sf} is the fusion heat. For water $\frac{C_{pw}}{h_{sf}} \cong \frac{1}{80} \quad K^{-1}$ so:

$$\frac{\Delta m_{ice}}{m_{drop}} \cong \frac{\delta T}{80} \tag{4.9}$$

The WIM process takes place near populated areas or large cities that are situated at the end of the watershed. Unlike ski resorts, which are located at the beginning of the watersheds, it is expected that the water used for WIM would have a large concentration of sediments, which may promote nucleation. Also, section 5 describes a method that nucleates water at $0\ C$. Therefore, it is assumed for further calculations that nucleation would happen at $0\ C$ to $-2\ C$ (wet bulb temperature). For a $-2\ C$ nucleation temperature, equation (4.9) shows that upon nucleation 2.5% of the drop mass freezes.

The following energy equation for the freezing process equates the heat of fusion that should be withdrawn from the drop to the heat transfer from the drop to the ambient atmosphere by convection, sublimation and radiation:

$$-m_{drop}(1-\frac{\delta T}{80})\cdot h_{sf} = -t_{freez}\cdot A\cdot\left[h_c(273-T_a)+h_d\cdot h_{fg}(\rho_{vi}(273K)-\phi\cdot\rho_{v\infty}(T_a))+\sigma\cdot\varepsilon_i(273^4-T_a^4)\right] \tag{4.10}$$

where t_{freez} is the time needed from nucleation until complete freezing, h_{sf} and h_{fg} are the fusion and evaporation heat, T_a is the ambient temperature in Kelvin, ρ_{vi} is the vapor saturation density over ice at $273\ K$, ϕ is the relative humidity and ε_i is the emissivity of ice. Equation (4.10) is not a differential equation since the freezing process is isothermal.

Equation (4.5) gives the saturation pressure of vapor over liquid and over ice. Although for a specific temperature the vapor pressure over ice is lower than that over liquid, it is important to note that the effect of sublimation in cooling the drop is stronger than that of evaporation. There are two reasons for this. The first is that the evaporation from the liquid drop is at a subfreezing temperature, while the sublimation from the ice is always at $0\ C$. The second is that the falling time of the supercooled liquid drop until nucleation is much shorter that the falling time of the drop from the time of nucleation until complete freezing.

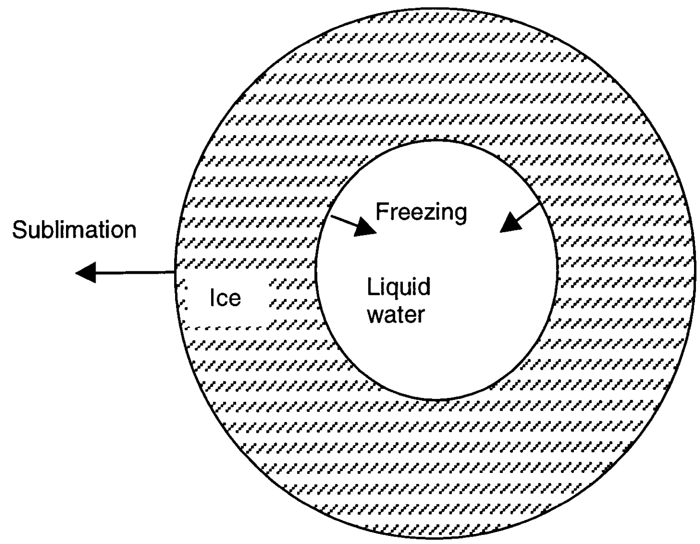

Figure 4.4: A spherical model of a freezing drop. Ice shell thickens with time by freezing the liquid core. The diffusion from the outer surface to the ambient air causes Sublimation cooling.

Although sublimation takes place from the frozen surface of the drop, the latent heat on the RHS of equation (4.10) is of evaporation and not sublimation. The reason is that the sublimated mass from the drop experiences first freezing, which releases latent heat of fusion and then sublimation that draws latent heat of sublimation. Therefore, the net heat withdrawn from the drop by the sublimated mass is the latent heat of sublimation minus the latent heat of fusion, equal to the latent heat of evaporation

The information obtained from equation (4.10) is t_{freez}, the time needed for free fall of the freezing drop. This data, combined with the terminal velocity of the drop gives the falling distance during freezing. To this, one needs to add the distance that the drop falls from spraying until nucleation. This procedure enables the calculation of the height from which the water drop should be sprayed.

A point of interest is the fraction of the drop mass α that sublimates in the freezing phase (when the drop is coated by ice shell so that only sublimation takes place). This information is extracted from equation (4.10):

$$\alpha = \frac{h_d \cdot [\rho_{vi}(273K) - \phi \cdot \rho_{v\infty}(T_a)] \cdot A \cdot t_{freez}}{m_{drop}} \tag{4.11}$$

A is the surface area of the drop. Using the expressions for the surface area and mass of the a spherical drop, equation (4.11) can be simplified to:

$$\alpha = \frac{6 \cdot h_d \cdot [\rho_{vi}(273K) - \phi \cdot \rho_{v\infty}(T_a)] \cdot t_{freez}}{\rho_w \cdot d} \tag{4.12}$$

Equations (4.11) and (4.12) assume constant surface area. In fact, during sublimation the surface area is reduced. The Maximum reduction in the surface area is *8%*, and it takes place when the freezing of the drop is done entirely by sublimation cooling without convection cooling. The maximum value of α is when the entire cooling provided to the freezing drop is by sublimation. For $h_{fg} = 2{,}501\ KJ/Kg$ and $h_{sf} = 333.6\ KJ/Kg$ the maximum value of α is 0.1177 and is found by solving:

$$(1 - \alpha_{\max}) \cdot h_{sf} = \alpha_{\max} \cdot h_{fg} \tag{4.13}$$

The plots below show the necessary spraying height vs. drop diameter for various temperature and humidity of the ambient air. For marginal subfreezing temperatures in the range of $0\ C$ to $-6\ C$ the results are strongly influenced by the relative humidity while for deep subfreezing temperature below $-10\ C$ the relative humidify does not matter. Also, the mass losses due to sublimation are larger for high ambient temperature since sublimation cooling is then substantial relative to the convective cooling. At lower temperatures the convective cooling increases so sublimation cooling decreases and mass losses due to sublimation decrease as well. For high ambient temperature the mass loss due to sublimation is 7-9% while it reduces to about 3.5 - 4.5% at $-20\ C$, depending on the relative humidity. Cooling due to radiation is insignificant and does not exceed more than 1% of the entire heat transfer for all meteorological conditions and drop diameter. For a spraying height, which does not exceed $200\ m$, the maximum drop diameter is about $2.5\ mm$, a size for which a spherical model is adequate as is shown in section 3.

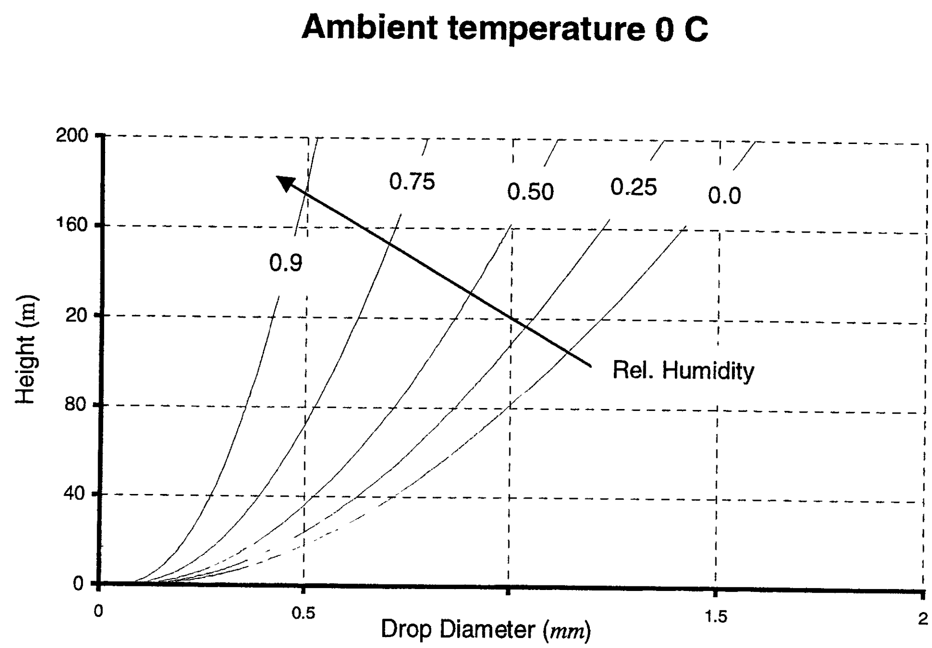

Figure 4.5: Spraying height vs. drop diameter to achieve complete freezing. Relative humidity range 0-90%.

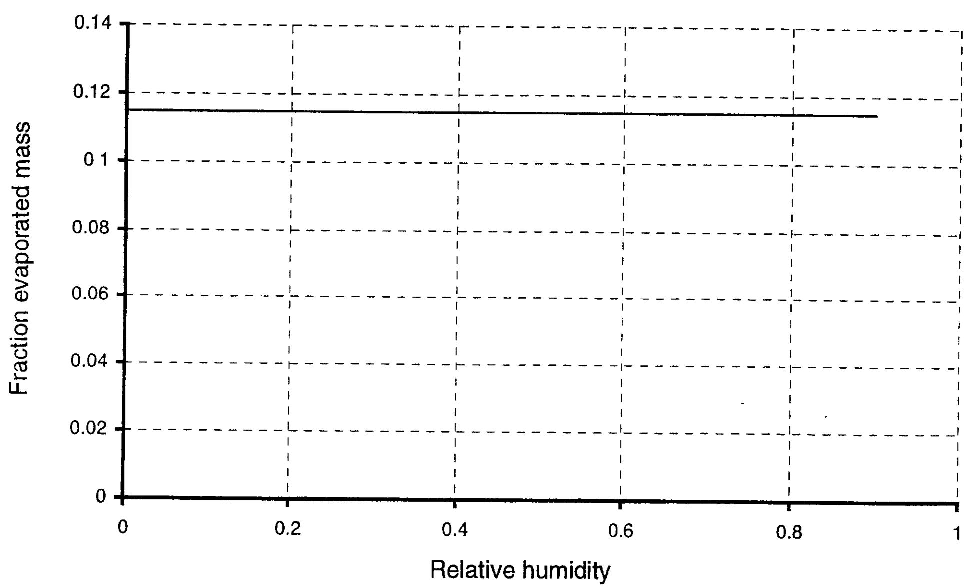

Figure 4.6: Ratio of evaporated mass to original drop mass

Ambient temperature -2 C

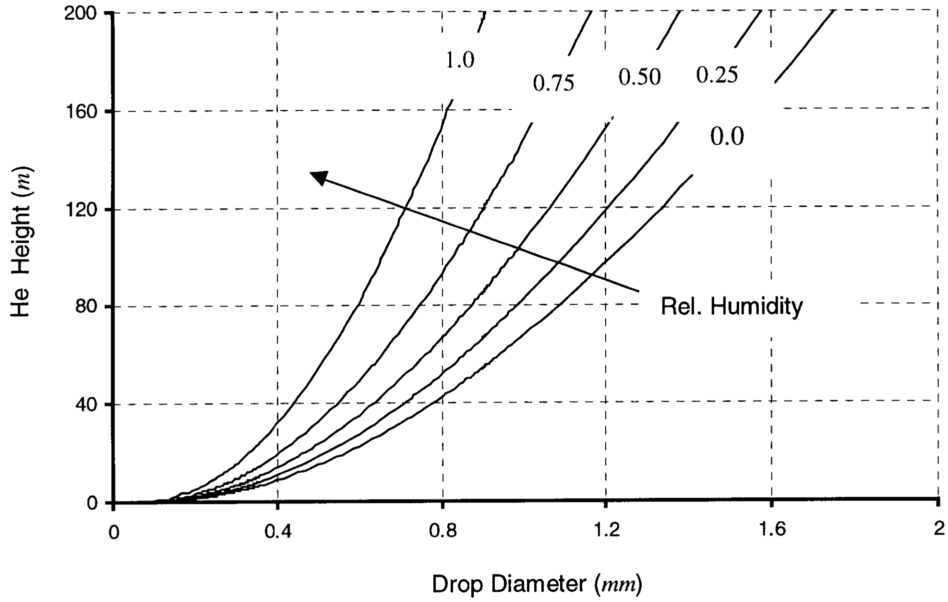

Figure 4.7: Spraying height vs. drop diameter to achieve complete freezing. Relative humidity range 0-100%.

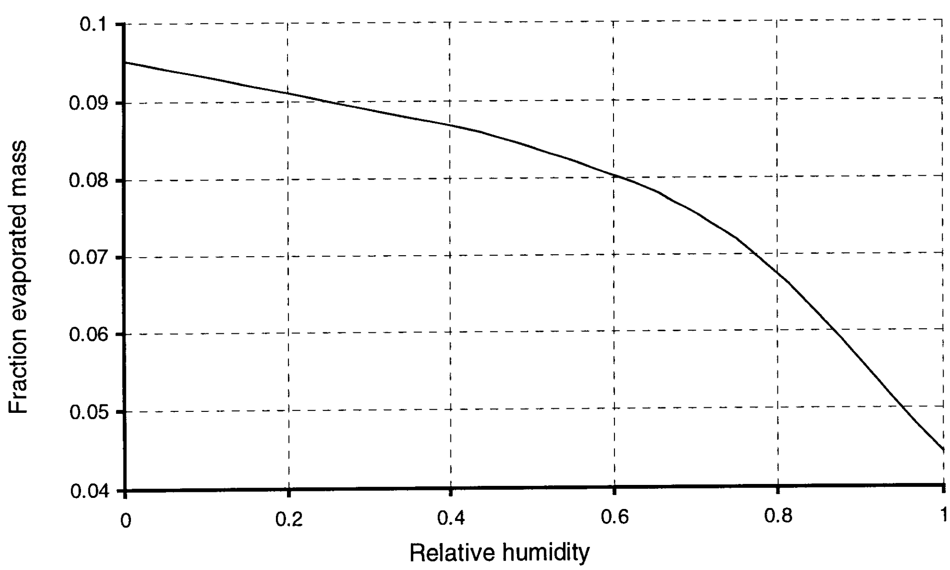

Figure 4.8: Ratio of evaporated mass to original drop mass

Ambient temperature -4 C

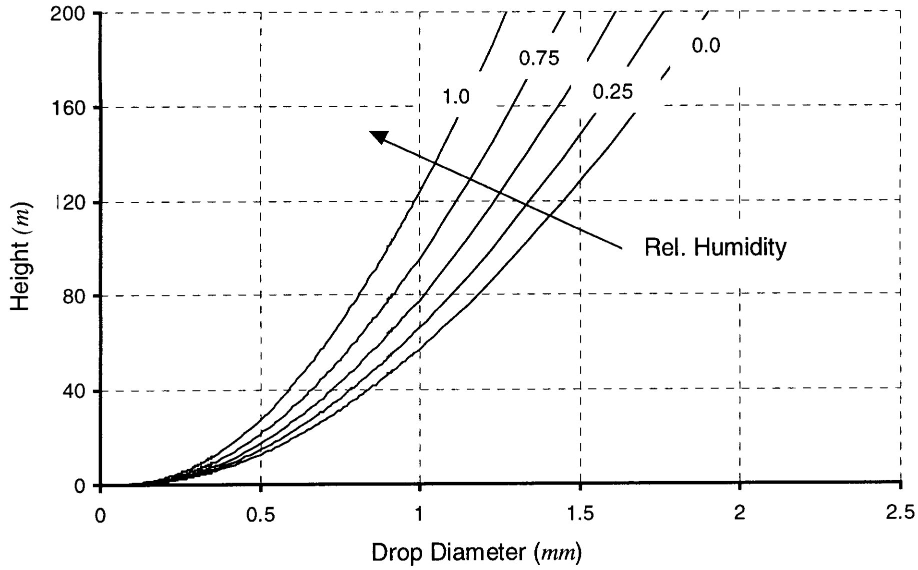

Figure 4 .9: Spraying height vs. drop diameter to achieve complete freezing.

Relative humidity range 0-100%.

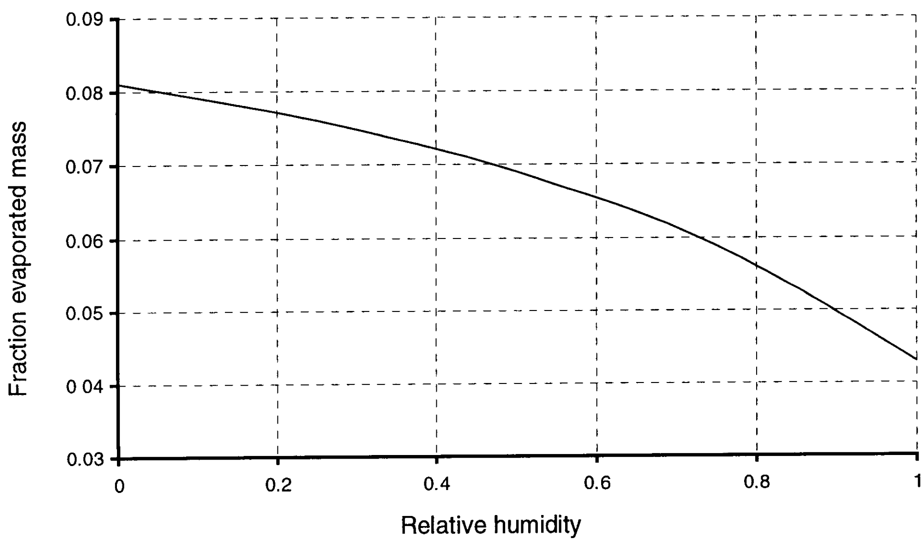

Figure 4.10: Ratio of evaporated mass to original drop mass

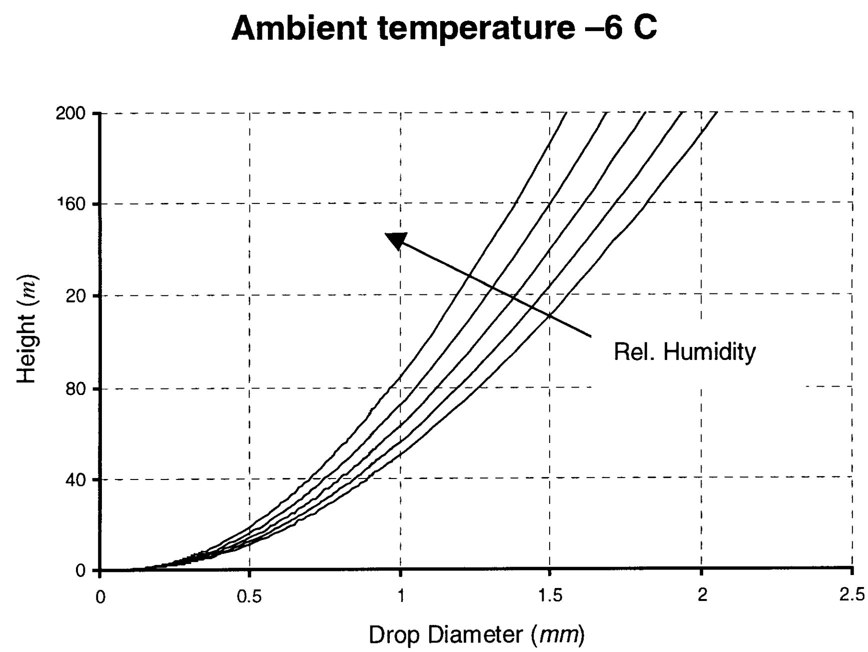

Figure 4.11: Spraying height vs. drop diameter to achieve complete freezing. Relative humidity range 0-100%.

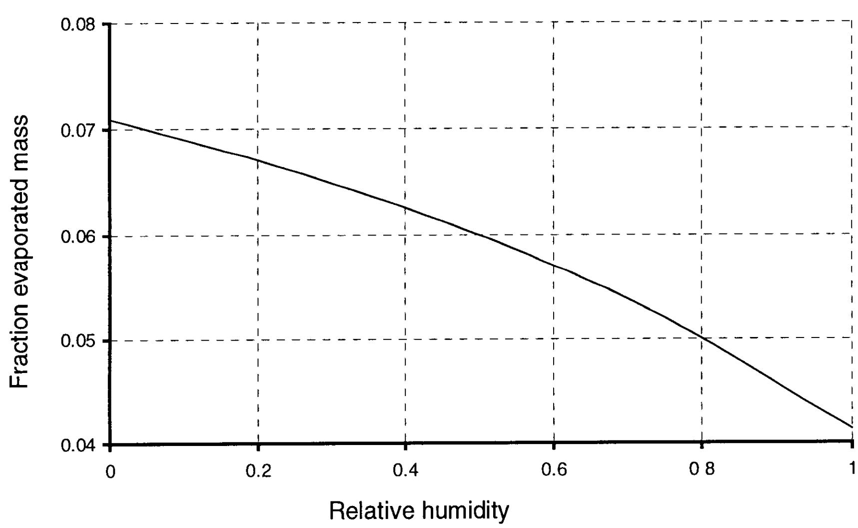

Figure 4.12: Ratio of evaporated mass to original drop mass

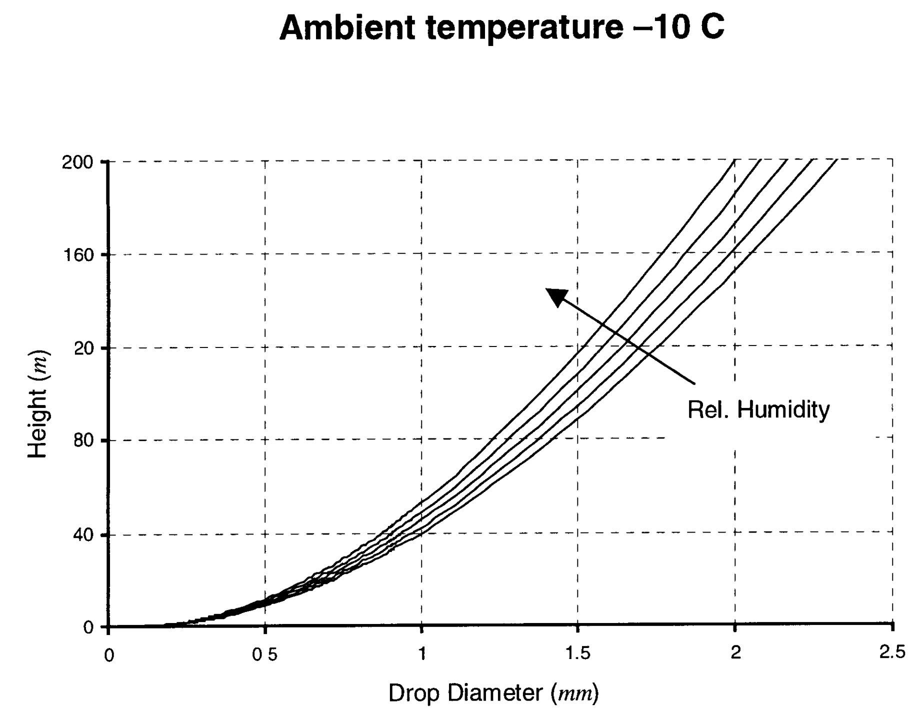

Figure 4.13: Spraying height vs. drop diameter to achieve complete freezing. Relative humidity range 0-100%.

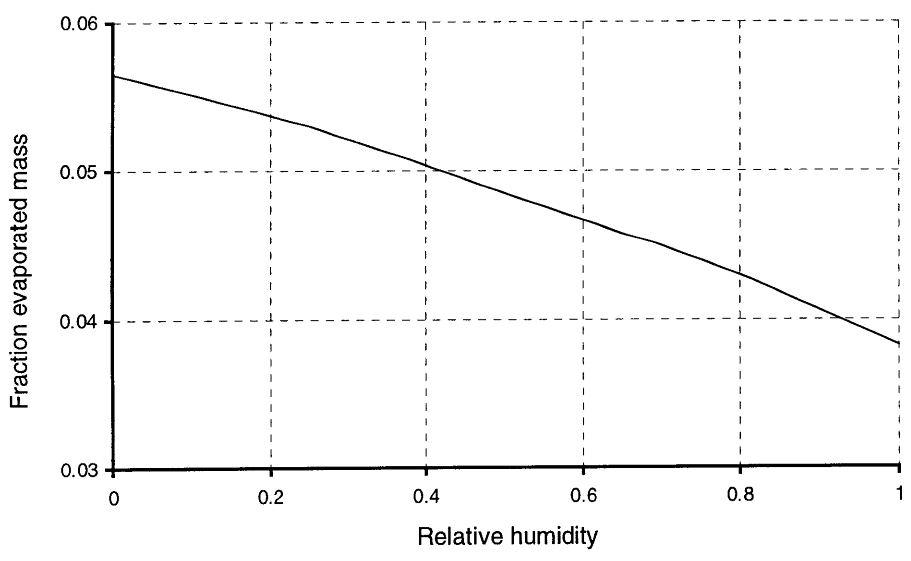

Figure 4.14: Ratio of evaporated mass to original drop mass

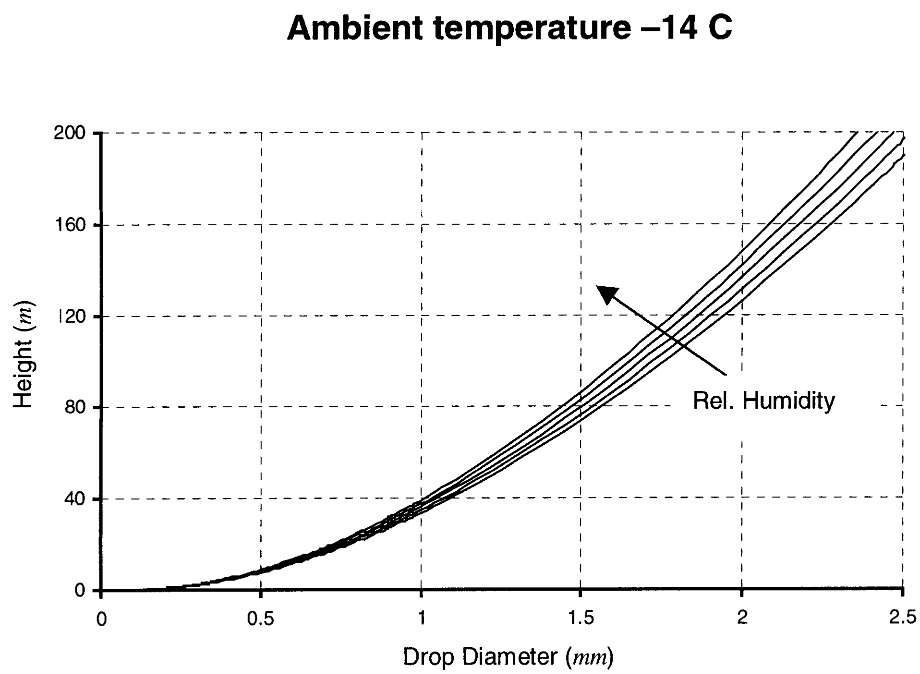

Figure 4.15: Spraying height vs. drop diameter to achieve complete freezing. Relative humidity range 0-100%.

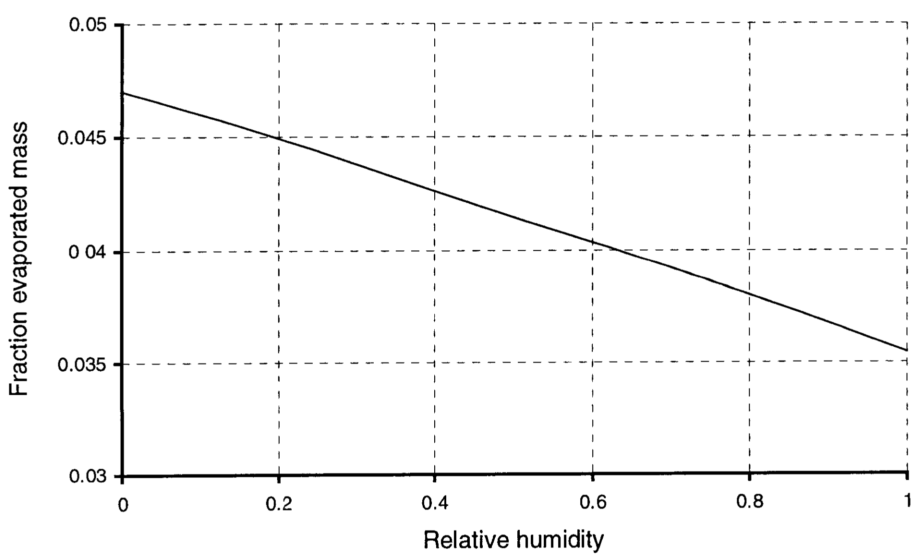

Figure 4.16: Ratio of evaporated mass to original drop mass

Ambient temperature –18 C

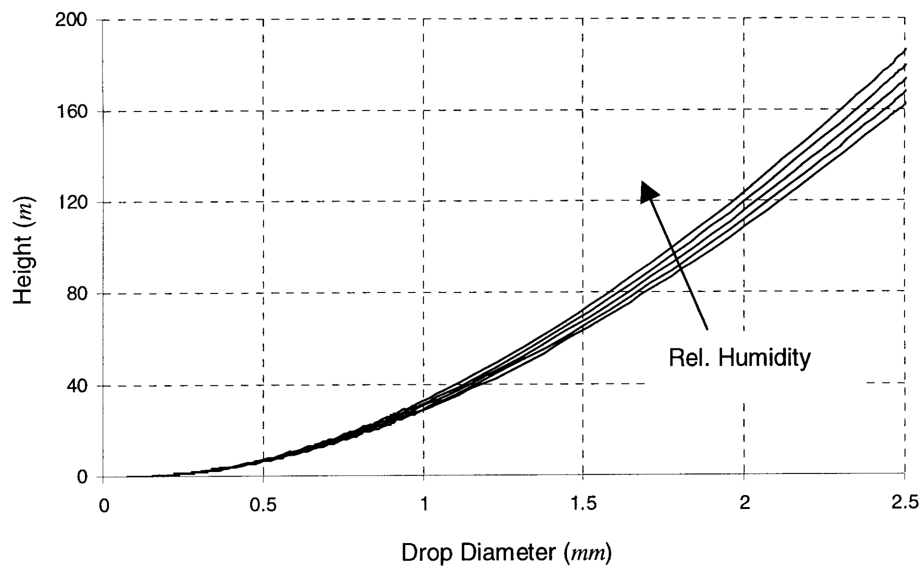

Figure 4.17: Spraying height vs. drop diameter to achieve complete freezing. Relative humidity range 0-100%.

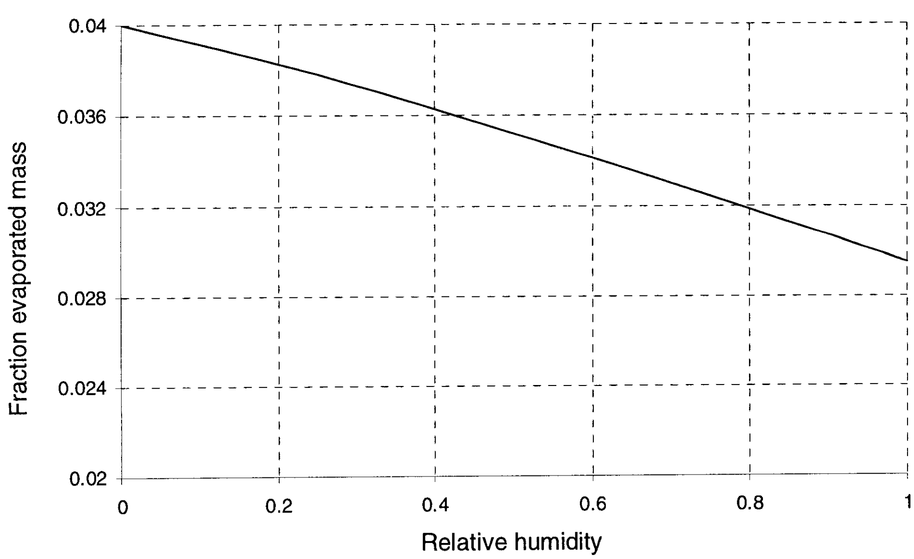

Figure 4.18: Ratio of evaporated mass to original drop mass

4.5 The Validity of modeling a freezing drop as a lumped thermal capacitance

Equation (4.10) treated the freezing drop as isothermal. For this assumption to be valid the resistance to thermal conduction within the ice solid should be much less than the resistance to convection on the surface of the drop. The Biot number quantifies this ration as [29]:

$$Bi = \frac{h_c \cdot Lc}{K_{ice}} \tag{4.14}$$

where $K_{ice} = 2.2\frac{W}{m \cdot C}$, h_c is the heat transfer coefficient and $L_c = \frac{d}{6}$ is the characteristic length for a sphere the diameter of which is d . For the thermal capacitance to be isothermal the Biot number should be smaller than 0.1.

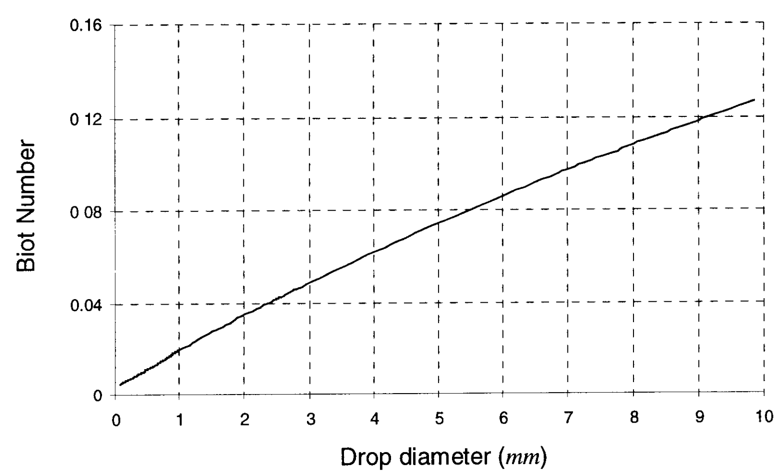

Figure 4.19: Biot # vs. ice drop diameter.

As shown is Figures 4.5 to 4.18 the WIM process will not use drops the diameter of which is larger than 3 *mm*. Therefore, the maximum Biot # is less than 0.1 so the drop can be assumed to be isothermal during its freezing.

5. Nucleation of liquid drops

5.1 Introduction

Nucleation of saturated or supersaturated water vapor to induce condensation and the nucleation of supercooled liquid water to induce freezing are central processes in the formation of clouds, precipitation and snow. Though many aerosol materials can induce condensation of vapor, few can produce freezing nucleation. The initiation of the ice phase in water drops is an important stage in the proposed winter ice manufacture (WIM) concept.

Although large quantities of water as in lakes and ponds do not supercool appreciably, cloud drops exist in the supercooled state down to temperatures as low as $-20\ C$ while drops of very pure water, a few microns in diameter may be supercooled to $-40\ C$ in the laboratory [30]. Such small supercooled drops can freeze spontaneously without any additives by homogenous nucleation. At higher sub-zero temperatures, the drops can freeze if contaminated with foreign particles known as ice- or freezing- nuclei in a process called heterogeneous nucleation [30].

When water is in the liquid state, the molecules are in continuous motion and the vibrational energy of this motion prevents the intermolecular crystalline structure from forming. Thus, to initiate the freezing process, a certain amount of free energy has to be removed from the water to retard the molecular motion. Upon release of free energy the molecules align in a stable hexagonal pattern—the basic crystalline structure of ice. Once a critical number of molecules are aligned, an ice nucleus will form, which in turn serves as a pattern for further crystallization. The freezing process is facilitated when the random molecules can attach to the surface of nucleators in the water [30].

Experiments addressing nucleation of supercooled water are difficult to reproduce, not only among different samples, but also within the same water sample. Results reported in the literature vary markedly and, consequently, no consistent relationships can be deduced [21], [30]. One reason is that the water samples used by different investigators have varied greatly in their origin and purity, indicating that sediment in the water may affect nucleation. The second reason is that the water drops in these experiments were contained in glass tubes or supported by metal surfaces so that freezing may have been initiated by a contact with surface boundaries. A third possibility is that one or more of the prior investigations neglected to vary the drops' volumes sufficiently; it is now known that the drop volume is a factor in initiating freezing [30].

Ice nuclei (IN) exhibit three basic modes of action. In the deposition mode, water is absorbed directly from the vapor phase to IN surface where, at low temperatures, the absorbed vapor is transformed into ice. In the second mode the IN initiates the ice phase from inside the supercooled water drop. Such a mode can be created, for example, by sediment that exists in the water prior to supercooling or by commercial additives (such as Snomax, see section 2) which is mixed with the water prior to snowmaking. This is called the freezing mode and the IN is called freezing nuclei. In the third mode, the IN initiates the ice phase at the moment of contact with a supercooled drop and this is known as the contact mode [21]. The seeding of supercooled clouds by silver iodide causes nucleation by the contact mode. Contact and freezing modes pertain to winter ice manufacture.

5.2 Ice nuclei (IN) materials

Early development of artificial ice nuclei involved the use of dry ice to seed clouds to induce precipitation [30]. Vonnegut discovered that there is similarity between the crystal structure of ice nuclei and that of ice and that ice nuclei materials are highly insoluble in water [30]. Vonnegut selected silver iodide by scanning a tabulation of crystalline substances for low solubility and crystal dimensions close to those of ice. Silver iodide is used in weather modification to seed supercooled clouds to induce and enhance precipitation.

Three different methods of nucleation are used in snowmaking. The first relies on natural nucleators, such as sediment in the water source. The second is a mechanical nucleator system, which uses compressed air in snow guns. The third is adding nucleators such as Snomax to the source water. The application of Snomax (a protein derived from a bacterium called *pseudomonas syringae*) as ice nuclei has been reviewed in section 2. York Snow, the vendor of Snomax, claims that it nucleates supercooled water at about –2.8 C to -2.2 C.

Houghton compiled a list of pure substances, minerals and organic materials, which are efficient as ice nuclei [30]. Ice is the best nuclei, inducing freezing at the highest temperature, $0\ C$. Among pure substances the best nuclei is silver iodide, which nucleates at $-4\ C$. The best mineral is vaterite, which nucleates at $-7\ C$. The best organic materials are testosterone and chloresterol, both of which induce nucleation at $-2\ C$. According to Houghton, pseudomonas syringae nucleates supercooled water at $-2.6\ C$.

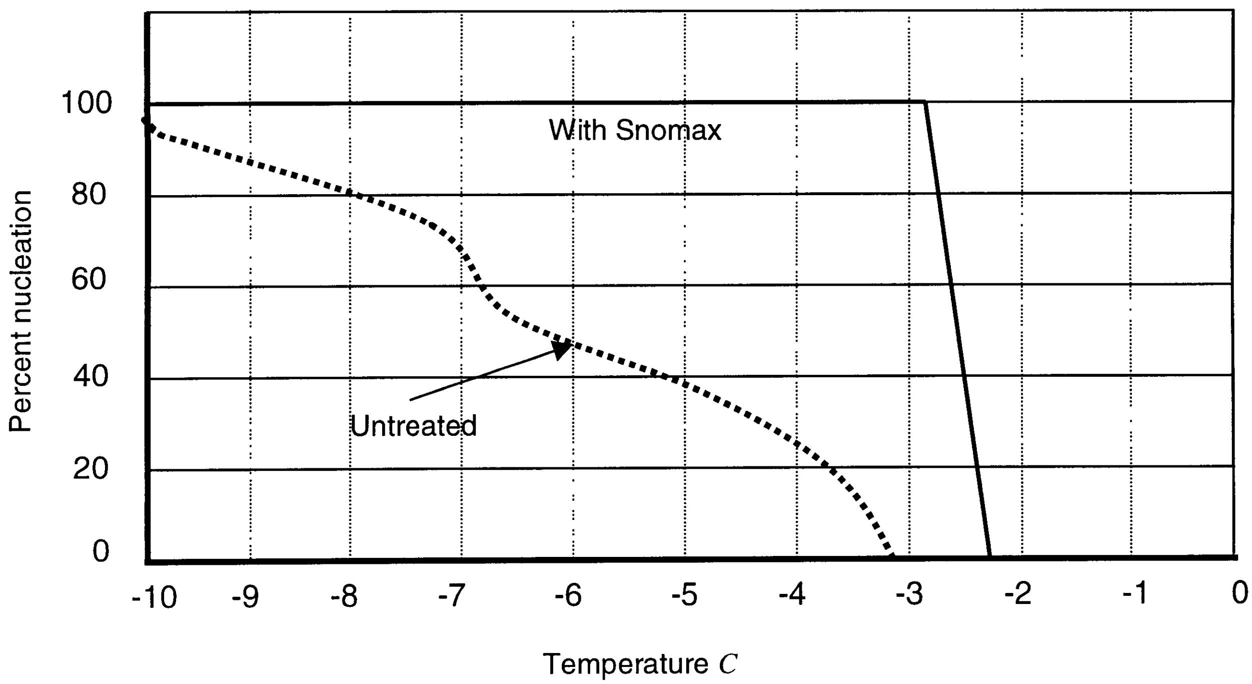

Figure 4.1: The performance of Snomax in nucleating sprayed water in snowmaking Process [31].

5.3 Ice nuclei for winter ice manufacture

The most important consideration in snowmaking and WIM is that the nucleation temperature must be higher than the wet bulb temperature of the ambient atmosphere. If the temperature of sprayed drops reach ambient air temperature without nucleation, there is no heat transfer between the drop and the air—freezing will not occur. Because it is intended that winter ice will also be manufactured at marginal subfreezing temperatures, it is imperative that the nucleation temperature be as high as possible. Snomax seems to be a good choice for snowmaking. However, public perception will likely discourage use of Snomax, which is derived from a bacterium, for winter ice since the melt-water will be used as drinking water. By contrast, from geographic point of view, populated regions experiencing summer water shortages (e.g., Southern Massachusetts) are at the ends of the watershed. Water from these areas has high concentrations of sediment, possibly amenable to nucleation.

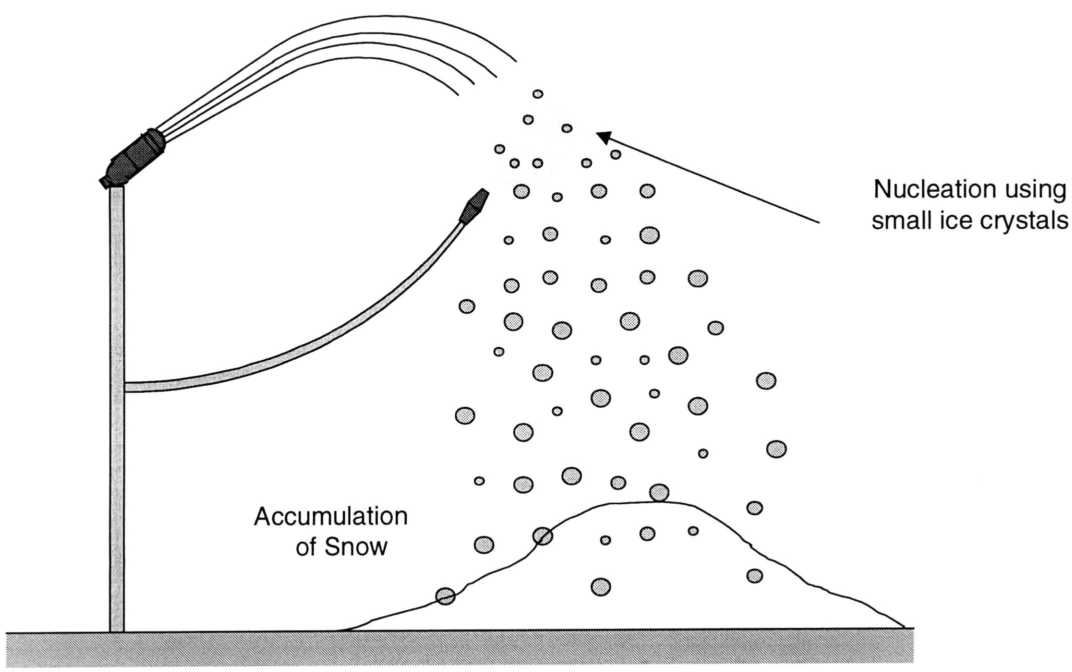

Figure 5.2: The proposed nucleation technique using high-pressure atomizers to spray small drops. These tiny drops freeze instantly and become ice crystals. The large water drops that constitute the main water mass collide with the small drops. In this proposed technique the nucleation happens at $0\ C$.

This thesis proposes to use small ice drops as ice nuclei in snowmaking and WIM. As stated earlier, ice is the best nucleation material inducing freezing at $0\ C$, the highest temperature of any IN. According to the proposed concept, the spraying nozzles are divided into two arrays. One array sprays the bulk quantity of water from high altitude in large drops. Below this array, a second array of atomizers spray smaller water drops which, if they do not nucleate spontaneously, will use commercial nucleation material in small quantities. The terminal velocity of the small frozen drops is low in comparison to the falling speed of the large drops. Thus, the large drops collide with the numerous small frozen drops so these tiny ice particles nucleate the larger supercooled drops. This method has been used effectively in the Hedco system described in section 2 and is the subject for a patent granted in 1961 [5]. Taylor has applied a similar method for nucleation in the development of his ice pond [12].

The small ice crystals that are intended to nucleate larger diameter drops can induce nucleation at $0\ C$. To be conservative and to assure that the larger colliding drops will nucleate and freeze it is assumed that the bulk supply of drops are supercooled to $-2\ C$. This assumption is used in the calculations for heat transfer in section 4. It is also imperative that the tiny ice particles serving as IN will not be too small so as to prevent their complete sublimation before having the opportunity to collide and nucleate the larger water drops.

Mr. Fergus Smith, president of Omichron Corporation, a company that manufactures snowmaking equipment has a unique explanation for the nucleation process in a high-pressure snowgun [32]. In this system, air and water are mixed internally and the high-pressure air atomizes the water and ejects the water drops into the atmosphere.

According to Smith's hypothesis, the compressed air is humid and its vapor condenses and freezes into small crystals upon expansion. The expansion of the air through the nozzle is choked and resulting in sonic speed. The compressed air passes through heat exchangers situated between the compressor and the snowgun. The stagnation temperature of air before expansion is assumed to be $0\ C$ or $273\ K$.

The ratio of the stagnation to the static temperatures of compressible isentropic flow is:

$$\frac{T_0}{T} = 1 + \left(\frac{\gamma - 1}{2}\right) M^2 \tag{5.1}$$

Where T_0 and T are the stagnation and static temperatures respectively, $\gamma = 1.4$ is the ratio of the constant pressure heat capacity to constant volume heat capacity for air and $M = 1$ is the Mach number for the choked flow. Eq. (4.1) gives $\frac{T_0}{T} \cong 1.2$ or

$T = \frac{273}{1.2} = 228\ K$ or $T \cong -45\ C$. For such subfreezing temperature the vapor in the expanded air experiences homogenous nucleation, and it freezes and forms tiny water crystals. Upon ejection from the gun these tiny crystals nucleate the large water drops which constitute the bulk of the water supply. This hypothesis may explain why there are instances where high-pressure snow guns are successful in manufacturing snow without the need for added nucleation agent such as Snomax.

6. Heat and mass transfer of a system of water drops

6.1 Introduction

The hydrodynamics and heat and mass transfer analyses in sections 3 and 4 considered a single drop. This idealization is appropriate when the drops are sparse in space, do not interact with each other, remain intact and do not appreciably change the temperature and humidity of the ambient air due to the release of fusion heat and evaporation.

The microphysics of a system of multiple drops is covered in numerous investigations related to cloud formation and precipitation [15], [21], [30]. However, the small size of cloud drops and their volumetric concentration do not resemble those of the sprayed drops in the proposed winter ice manufacture (WIM) process. In the WIM, the size of the drops is 1-3 orders of magnitude larger than the size of cloud drops. The volumetric concentration of the drops in the WIM's air space will be calculated in subsequent sections.

In general, drops of various sizes have different terminal velocities. Their relative velocities may cause collisions. Even when a drop falls in the path of a similar size drop, the trailing drop experiences a reduced drag from the wake of the leading one. This causes the speed of the trailing drop to be higher than the leading one, causing a collision and possible coalescence [21]. The most important effect of multiple drops, however, is to increase the temperature and humidity of the ambient air due to the release of fusion heat and evaporation. If the temperature of the ambient air increases, it would lead to a reduction in the efficiency of the freezing process even if the temperature of the undisturbed air were subfreezing. The following analysis establishes approximate quantitative relationships between the mass rate of the sprayed water, area of the site where ice manufacture takes place, drops size, the height from which water is sprayed and the meteorological conditions such as temperature, humidity and wind speed.

6.2 The effect of heat and mass transfer on the ambient air

In one of only two papers ever published on the analysis of snowmaking process, Chen and Kevorkian describe a snowmaking experiment [27]. Although the undisturbed ambient temperature was subfreezing before the experiment, the release of fusion heat and evaporation from the sprayed water elevated the temperature of the ambient air. In their experiment, there was no wind to replenish the snowmaking area with fresh, cold and dry air, so the snowmaking process was halted. Natural convection is not enough to aid the replenishment with cold and dry air. It is clear that for the WIM there must be windy conditions.

Figure 6.1 depicts a control volume (CV), the height of which is H into which water drops at $0\ C$ enter from the top and frozen drops at $0\ C$ exit from the bottom. Atmospheric air at temperature T_a, density ρ_a, and vapor concentration ρ_v enters the CV from the left at the prevailing wind speed and warmer and more humid air at $T_a + \Delta T_a$ and $\rho_v + \Delta\rho_v$ leaves the CV at the same speed. Attenuation of the wind speed due to drag caused by the water drops is considered negligible. The wind speed is U_a. The dimension of the horizontal cross section of the CV is $a \; x \; b$ meters and its vertical cross section facing the

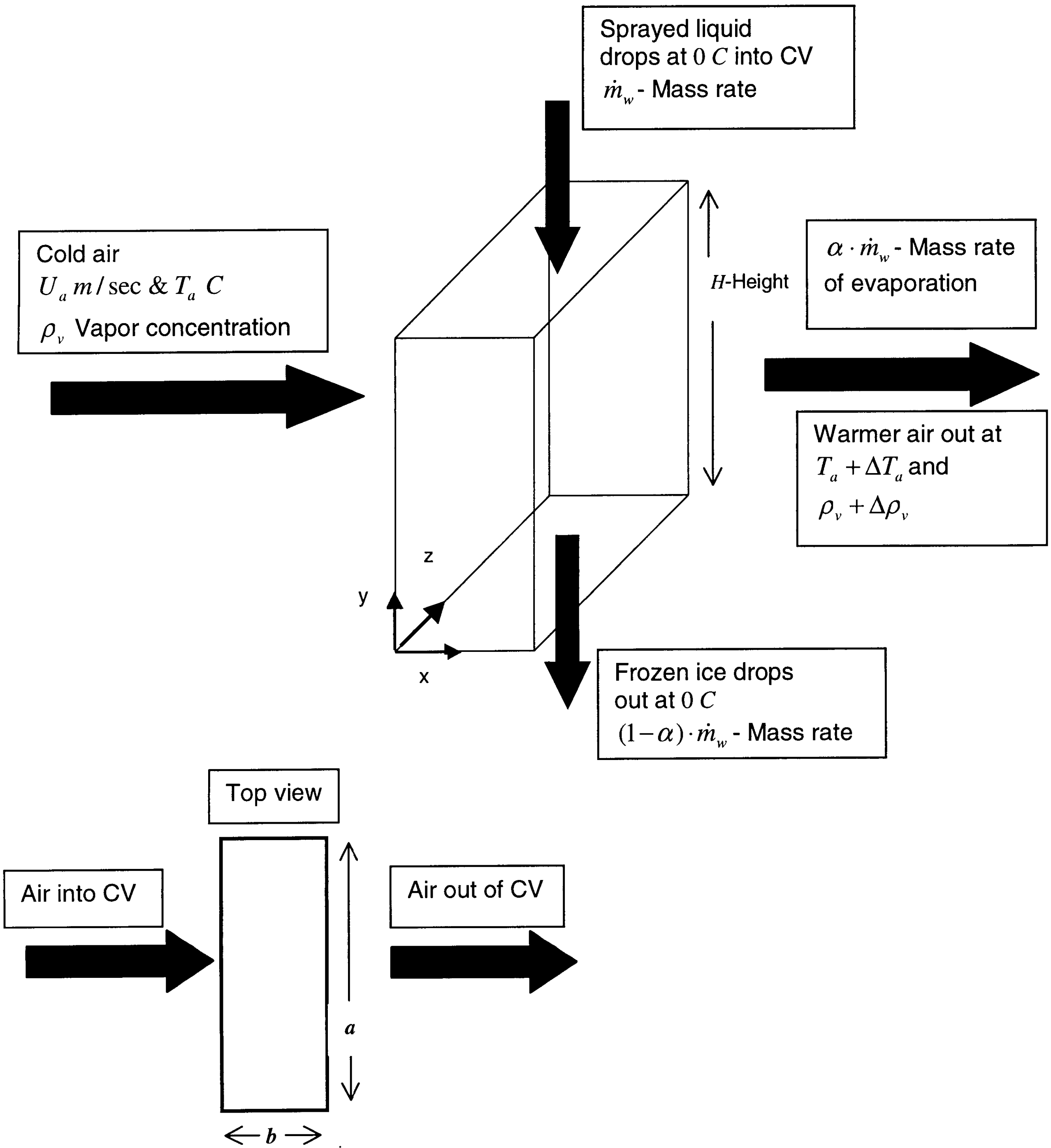

Figure 6.1: Control volume for winter ice manufacture

wind is $a \times H$. H is the height from which water is sprayed into the CV. It is assumed that the drops' trajectory is vertical although in practice the water drops would descend at an inclined angle due to the drag caused by the wind.

The increase in air temperature ΔT_a and vapor concentration $\Delta \rho_v$ is caused by the release of fusion heat and evaporation from the freezing water drops. The following analysis quantifies the bounds for the mass rate of the water as a function of the relevant variables.

6.3 Production rate of ice

The energy conservation for the CV gives that the total cooling provided by air passing through the CV and by the evaporating mass is equal to the fusion heat of the produced ice:

$$\rho_a \cdot U_a \cdot C_{pa} \cdot a \cdot H \cdot \Delta T_a + \alpha \cdot \dot{m}_w \cdot h_{fg} = (1-\alpha) \cdot \dot{m}_w \cdot h_{sf} \qquad (6.1)$$

where C_{pa} is the heat capacity of the air, α is the portion of mass that evaporates, $\dot{m}_w$ is the mass rate of sprayed water and h_{fg} and h_{sf} are the latent heat of evaporation and fusion respectively.

Mass conservation for the CV gives:

$$\alpha \cdot \dot{m}_w = \Delta \rho_v \cdot a \cdot H \cdot U_a \qquad (6.2)$$

Substituting (6.2) into (6.1);

$$\Delta\rho_v \cdot a \cdot H \cdot U_a \cdot h_{fg} + \rho_a \cdot U_a \cdot C_{pa} \cdot a \cdot H \cdot \Delta T = (1-\alpha) \cdot \dot{m}_w \cdot h_{sf} \tag{6.3}$$

Multiplying and dividing the first term on the LHS of (6.3) by $[\rho_{vi}(0\,C) - \phi \cdot \rho_{v\infty}(T_a)]$ and multiplying and dividing the second term on the LHS by $-T_a$ give:

$$\frac{\Delta\rho_v}{[\rho_{vi}(0\,C) - \phi \cdot \rho_{v\infty}(T_a)]} \cdot [\rho_{vi}(0\,C) - \phi \cdot \rho_{v\infty}(T_a)] \cdot a \cdot H \cdot U_a \cdot h_{fg} + \\ + \rho_a \cdot U_a \cdot C_{pa} \cdot a \cdot H \cdot \frac{\Delta T_a}{-T_a} \cdot (-T_a) = (1-\alpha) \cdot \dot{m}_w \cdot h_{sf} \tag{6.4}$$

In order to prevent the air passing through the CV from warming-up appreciably and becoming more humid, it is necessary to limit the ratios $\frac{\Delta\rho_v}{[\rho_{vi}(0\,C) - \phi \cdot \rho_{v\infty}(T_a)]}$ and $\frac{\Delta T_a}{-T_a}$ to β while $\beta \le 1$. Rearranging equation (6.4):

$$\frac{\dot{m}_w}{a \cdot b} = \frac{1}{b} \cdot \frac{\beta \cdot H \cdot U_a}{(1-\alpha) \cdot h_{sf}} \cdot \left\{ [\rho_{vi}(0\,C) - \phi \cdot \rho_{v\infty}(T_a)] \cdot h_{fg} + \rho_a \cdot C_{pa} \cdot (-T_a) \right\} \tag{6.5}$$

$a \cdot b$ is the horizontal cross section area of the CV. The exponential curve fitting for the saturation vapor density $\rho_{v\infty}(T_a)$ of the ambient air is shown in Figure 4.3 section 4 as:

$$\rho_{v\infty}(T_a) = 0.00485 \cdot e^{0.0768\,T_a} \tag{6.6}$$

and

$$\dot{m}_{ice} = (1-\alpha)\cdot \dot{m}_w \tag{6.7}$$

and the density of vapor over ice at 0 C:

$$\rho_{vi}(0\ C) = 0.00485 \quad {Kg}/{m^3}$$

The results are:

$$\frac{\dot{m}_w}{a\cdot b} = \frac{1}{b}\cdot\frac{\beta\cdot H\cdot U_a}{(1-\alpha)\cdot h_{sf}}\cdot\left\{\left[0.00485 - \phi\cdot 0.00485\cdot e^{0.0768\cdot T_a}\right]\cdot h_{fg} + \rho_a\cdot C_{pa}\cdot(-T_a)\right\} \tag{6.8}$$

and

$$\frac{\dot{m}_{ice}}{a\cdot b} = \frac{1}{b}\cdot\frac{\beta\cdot H\cdot U_a}{(1-\alpha)^2\cdot h_{sf}}\cdot\left\{\left[0.00485 - \phi\cdot 0.00485\cdot e^{0.0768\,T_a}\right]\cdot h_{fg} + \rho_a\cdot C_{pa}\cdot(-T_a)\right\} \tag{6.9}$$

While T_a is in Celsius.

To find the rate of the increase in the height $h(t)$ of the manufactured ice:

$$\frac{\dot{m}_{ice}}{a\cdot b} = \rho_{ice}\cdot\frac{dh(t)}{dt} \tag{6.10}$$

ρ_{ice} is not the density of the frozen drop but the density of the accumulated ice pile. In section 7 it is shown that $\rho_{ice} \cong 500\,{Kg}/{m^3}$.

Substituting into (6.9):

(6.11)

$$\frac{dh(t)}{dt}=\frac{1}{b}\cdot\frac{\beta\cdot H\cdot U_a}{\rho_{ice}(1-\alpha)^2\cdot h_{sf}}\cdot\left\{\left[0.00485-\phi\cdot 0.00485\cdot e^{0.0768\cdot T_a}\right]\cdot h_{fg}+\rho_a\cdot C_{pa}\cdot(-T_a)\right\}$$

The solution for equation (6.11):

$$h(t)=t\cdot\frac{1}{b}\cdot\frac{\beta\cdot H\cdot U_a}{\rho_{ice}\cdot(1-\alpha)^2\cdot h_{sf}}\cdot\left\{\left[0.00485-\phi\cdot 0.00485\cdot e^{0.0768\cdot T_a}\right]\cdot h_{fg}+\rho_a\cdot C_{pa}\cdot(-T_a)\right\}$$

(6.12)

where the atmospheric conditions U_a, T_a and ϕ are invariant with time. t is the duration of the operation.

Equation (6.11) is valid if H is constant, but invalid if the spraying nozzles are fixed in space since when $h(t)$ grows, so the falling distance of the drops becomes shorter. For equation (6.11) to be valid, the spraying nozzles should be continuously elevated at the same rate that the ice pile grows below. When the spraying nozzles are fixed in space H is replaced by $H-h(t)$ and equation (6.11) becomes:

(6.13)

$$\frac{dh(t)}{dt}=\frac{1}{b}\cdot\frac{\beta\cdot(H-h(t))\cdot U_a}{\rho_{ice}(1-\alpha)^2\cdot h_{sf}}\cdot\left\{\left[0.00485-\phi\cdot 0.00485\cdot e^{0.0768\cdot T_a}\right]\cdot h_{fg}+\rho_a\cdot C_{pa}\cdot(-T_a)\right\}$$

The solution for (6.12) gives:

$$h(t) = H \cdot [1 - \exp(\gamma \cdot t)] \tag{6.14}$$

while:

(6.15)

$$\gamma = \frac{\beta \cdot U_a}{b \cdot \rho_{ice} \cdot (1-\alpha)^2 \cdot h_{sf}} \cdot \left\{ \left[0.00485 - \phi \cdot 0.00485 \cdot e^{0.0768 T_a} \right] \cdot h_{fg} + \rho_a \cdot C_{pa} \cdot (-T_a) \right\}$$

In the analysis above, the meteorological conditions T_a, U_a, and ϕ are invariant with time.

6.4 Discussion and comments on ice mass production rate

Equations (6.8) and (6.9) show that the mass rate of ice production is linearly proportional to the spraying height H and the wind velocity U_a. Furthermore, the production mass rate per spraying unit area is inversely proportional to the length of the control volume in a direction parallel to the wind denoted as b. The dry-bulb temperature of the ambient air affects both the evaporation and convective cooling. Equation (6.9) shows that ice can be manufactured at zero degree C or slightly above $0\ C$ if the ambient air is dry.

When the value of the factor β is 1.0 the mass rate of ice production is maximized according to equations (6.8)-(6.15). In this case the air passing the control volume will exit from the control volume at $0\ C$ and *100%* humidity and the air will give up the maximum amount of cooling. However, in portions of the control volume, which are close to the exit from the CV, the heat transfer rate would be lower and become zero

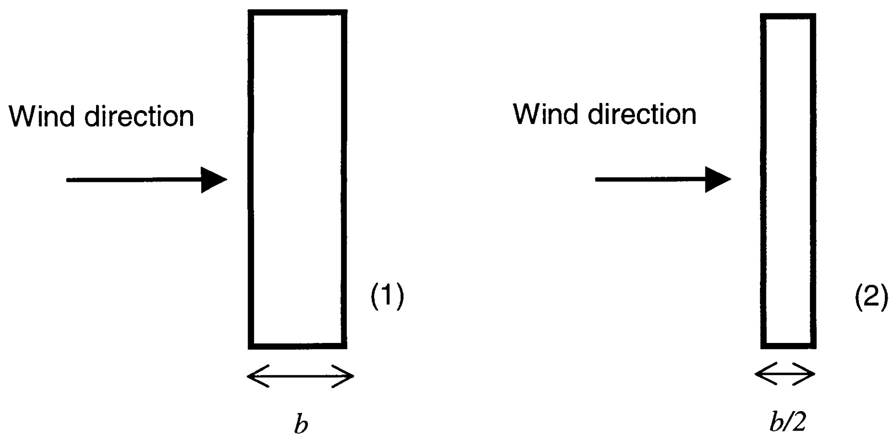

Figure 6.2: The area represented by rectangle (2) is half the area of (1). These rectangles represent the spraying area for winter ice manufacture. Equation (6.9) indicates that the total amount of ice manufactured in both sites is identical, while all other variables such as weather conditions and spraying height are identical.

At the exit from the CV. It also means that the spraying nozzles should be arranged to eject smaller drops along the x direction of the spraying area, see Figure 6.1. If $\beta = 1$ The size of the sprayed drops at x=b should be impractical and infinitely small. Therefore, the value of β should be smaller than 1. Determining the value of β is a matter of judgement that will be based on trail and error and operational experience. For now the value of β is determined conservatively as 0.5.

Figure 6.3 shows the mass rate of ice production/hour as a function of the temperature, relative humidity and for wind speed of $1\ m/\sec$. Since the rate of production is linearly

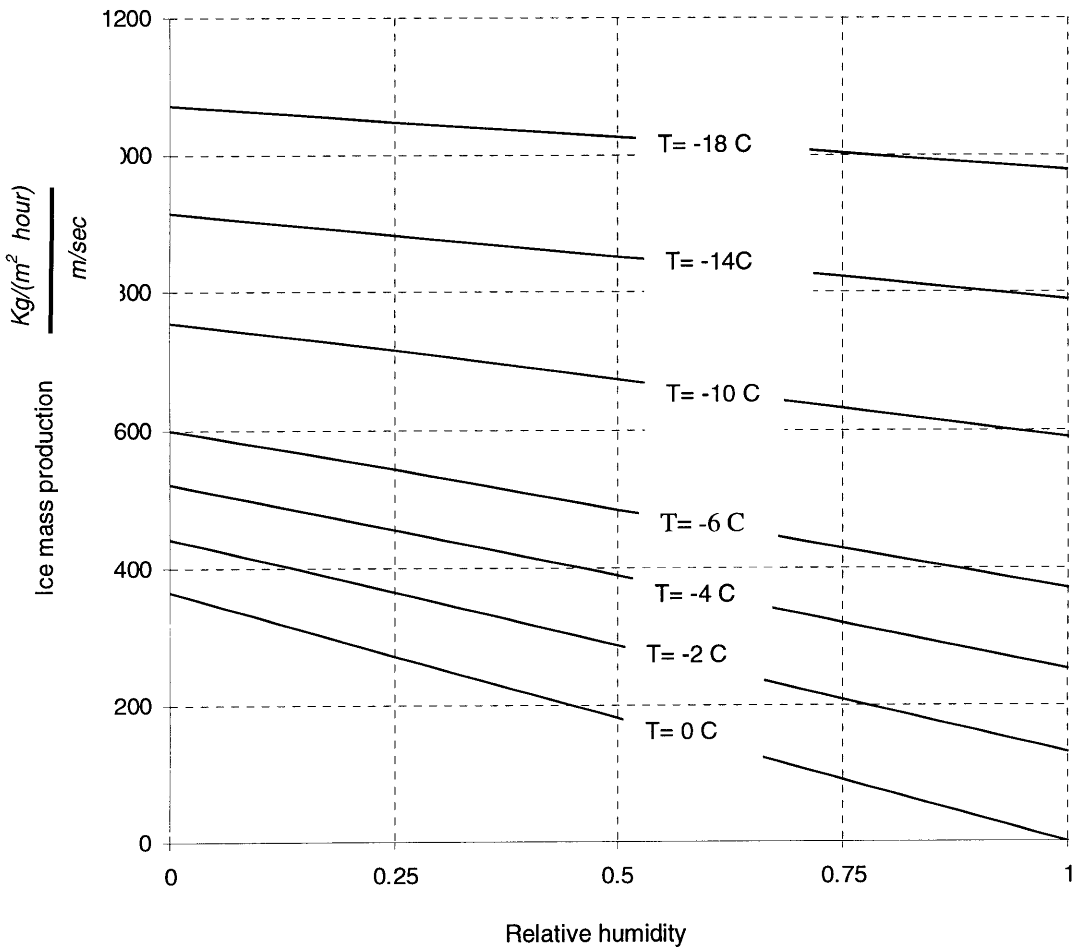

Figure 6.3: Ice mass production rate vs. relative humidity for various subfreezing ambient temperatures. The ice mass production rate is per hour and per spraying unit area and also per wind speed of $1\ {}^{m}/_{\sec}$. The spraying height H is $100\ meters$ and the width of the spraying area b is $20\ meters$. Since ice mass rate is proportional to wind speed, the value of mass rate should be multiplied by the prevailing wind speed in ${}^{m}/_{\sec}$.

proportional to the wind speed as shown in equation (6.12), this figure enables the forecast of production rate for any weather conditions.

Figure (6.3) enables the calculations of the ice production rate as a function of atmospheric conditions. In plotting Figure (6.3) equation (6.12) were used while H=100 *meters*, b=20 meters and $\beta = 0.5$.

<u>Example</u>: WIM operation takes place for 15 *hours* when the ambient conditions are:

$U_a = 3.5\, {}^{m}\!/_{\sec}$, $T_a = -2\ C$, $\phi = 0.5$

Using Figure 6.3, determine the mass of ice produced per spraying unit area.

<u>Solution:</u> Using Figure 6.2, for the given T_a and ϕ the mass produced per hour per m^2 per wind speed of $1\, {}^{m}\!/_{\sec}$ is 250 *Kg*. For wind speed of $3.5\, {}^{m}\!/_{\sec}$ and 15 *hour* operation duration:

$$\frac{m_{total}}{Area} = 250 \cdot 3.5 \cdot 15 = 13{,}125\ {}^{Kg}\!/_{m^2}$$

Because the density of accumulated ice is about 500 Kg/m^3, the height of the accumulated ice is about 26 *m*. For the given spraying height, ambient temperature and humidity, Figure 4.7 shows that the required drop diameter for is 1 *mm* on the left side of the control volume. Further to right within the control volume where the temperature and humidity of the ambient air increase the drop diameter of the sprayed water should be smaller.

Considering the mass rate per unit area, the terminal velocity, the spraying height and 1 *mm* drop diameter in the example above, the density of water in the air is 0.052 Kg/m^3. For 1 *mm* diameter drop, the air below the spraying nozzles contains about 10^5 $drops/m^3$. The average distance between the drops is approximate 2 *cm*.

6.5 Production rate of and accumulation of ice

The analysis above assumed an unrealistic situation where the accumulated ice is a rectangular prism the dimensions of which are $a \times b \times h(t)$. This could be the case if the manufacture ice is piled into a pit with vertical wall. In reality, the manufactured ice will be developed into trapezium prism since the ice will avalanche and create two inclined surfaces that are sloped at 35^0 from the horizontal, see Figure 6.4 and discussion in section 7.2.

Figure 6.2 depicts a 2-D trapezium prism for the accumulated ice. In reality, the avalanched ice will be spread to create a 3-D pyramid. However, if the length of spraying area perpendicular to the wind direction (denoted as a) is much longer than b, the ice volume can be modeled as a 2-D trapezium prism. Referring to Figure 6.2, the ice mass at any particular time t is:

$$m(t)_{ice} = \rho_{ice} \cdot a\left[\frac{h^2(t)}{\tan\gamma} + b \cdot h(t)\right] \qquad (6.16)$$

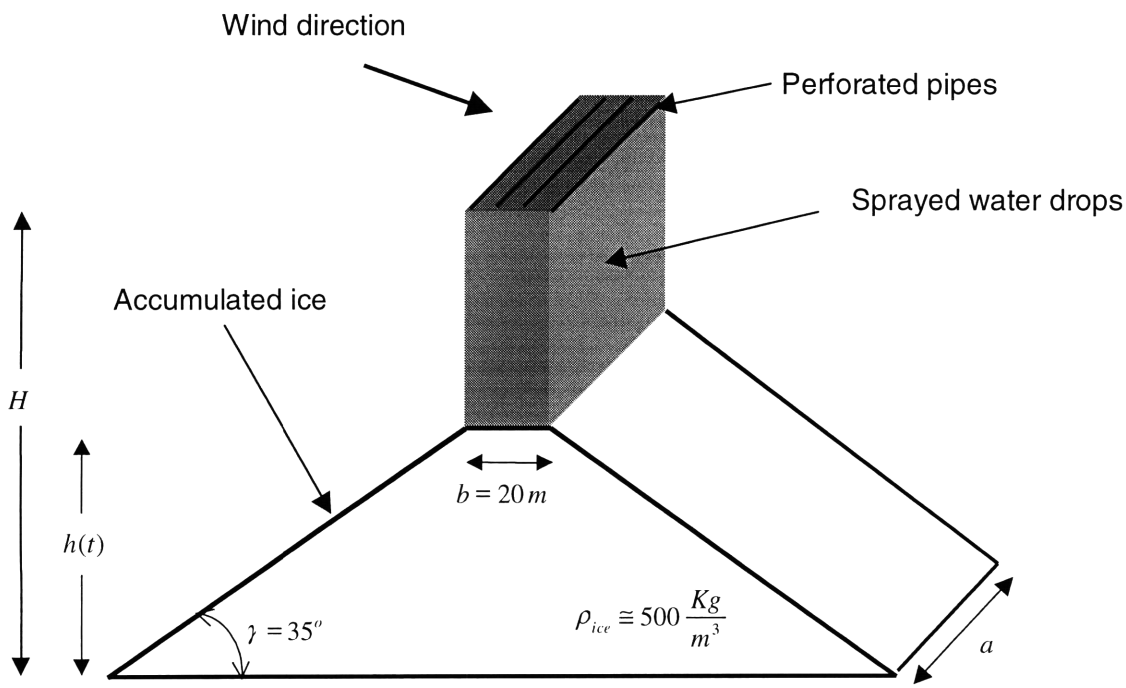

Figure 6.4: 2-D model for the shape and height of the accumulated ice volume as a Function of time.

Differentiating and dividing by the spraying area $a \cdot b$:

$$\frac{\dot{m}(t)}{a \cdot b} = \frac{\rho_{ice}}{b}\left[\frac{2h(t) \cdot \dot{h}(t)}{\tan \gamma} + b \cdot \dot{h}(t)\right] \qquad (6.17)$$

This rate of ice accumulation is equal to the rate of ice production given in equation (6.9). However, the height H in equation 6.9 should be replaced by the actual falling distance of the water drop, which is $H-h(t)$, see Figure 6.4. Combining equation (6.9) and (6.17) gives:

(6.18)

$$\frac{\rho_{ice}}{b}\left[\frac{2h\cdot\dot{h}}{\tan\gamma}+b\cdot\dot{h}\right]=\frac{(H-h)}{b}\left[\frac{\beta\cdot U_a}{(1-\alpha)^2\cdot h_{sf}}\right]\cdot\left\{(0.00485-\phi\cdot 0.00485\cdot e^{0.0768\cdot T_a})\cdot h_{fg}+\rho_a\cdot C_{pa}\cdot(-T_a)\right\}$$

Equation (6.18) can be re-arranged to give:

(6.19)

$$\frac{\frac{2}{\tan\gamma}h(t)\cdot\dot{h}(t)+b\cdot\dot{h}(t)}{H-h(t)}=\frac{\beta\cdot U_a}{\rho_{ice}\cdot(1-\alpha)^2\cdot h_{sf}}\cdot\left\{(0.00485-\phi\cdot 0.00485\cdot e^{0.0768\,T_a})\cdot h_{fg}+\rho_a\cdot C_{pa}\cdot(-T_a)\right\}$$

The last equation can be further re-arranged to give:

$$\left(\frac{A\cdot h(t)+B}{E\cdot H-E\cdot h(t)}\right)\cdot dh(t)=dt \qquad (6.20)$$

Where:

$A=\frac{2}{\tan\gamma}=\frac{2}{\tan 35^o}$ (See section 7.2)

$B=b=20\ meters$

$$D = \frac{H \cdot \beta \cdot U_a}{\rho_{ice} \cdot (1-\alpha)^2 \cdot h_{sf}} \cdot \left\{ (0.00485 - \phi \cdot 0.00485 \cdot e^{0.0768\,T_a}) \cdot h_{fg} + \rho_a \cdot C_{pa} \cdot (-T_a) \right\}$$

and

$$E = \frac{\beta \cdot U_a}{\rho_{ice} \cdot (1-\alpha)^2 \cdot h_{sf}} \cdot \left\{ (0.00485 - \phi \cdot 0.00485 \cdot e^{0.0768\,T_a}) \cdot h_{fg} + \rho_a \cdot C_{pa} \cdot (-T_a) \right\}$$

Integrating equation (6.20):

$$t = \left(\frac{A \cdot h(t) + B}{E \cdot H - E \cdot h(t)} \right) \cdot \int_0^{h(t)} dh(t) \tag{6.21}$$

The result is:

$$t = \frac{1}{E^2} \cdot \left[(E \cdot B + D \cdot A) \cdot \ln(D) - A \cdot h(t) \cdot E - (B \cdot E + D \cdot A) \cdot \ln(D - E \cdot h(t)) \right] \tag{6.22}$$

The expression given in equation (6.22) is plotted in Figures 6.5, 6.6, and 6.7. The Figures are for marginal subfreezing temperatures –2 *C*, -3 *C*, -4 *C* and – 5 *C*. All the plots are for 50% relative humidity and 3 *m/sec* wind speed. The spraying height is 50, 100 and 200 *meters*. The plots show how many hours of operation are required at the prescribed atmospheric conditions and spraying height to achieve a certain stockpile height, the shape of which is depicted in Figure 6.4 and 7.2.

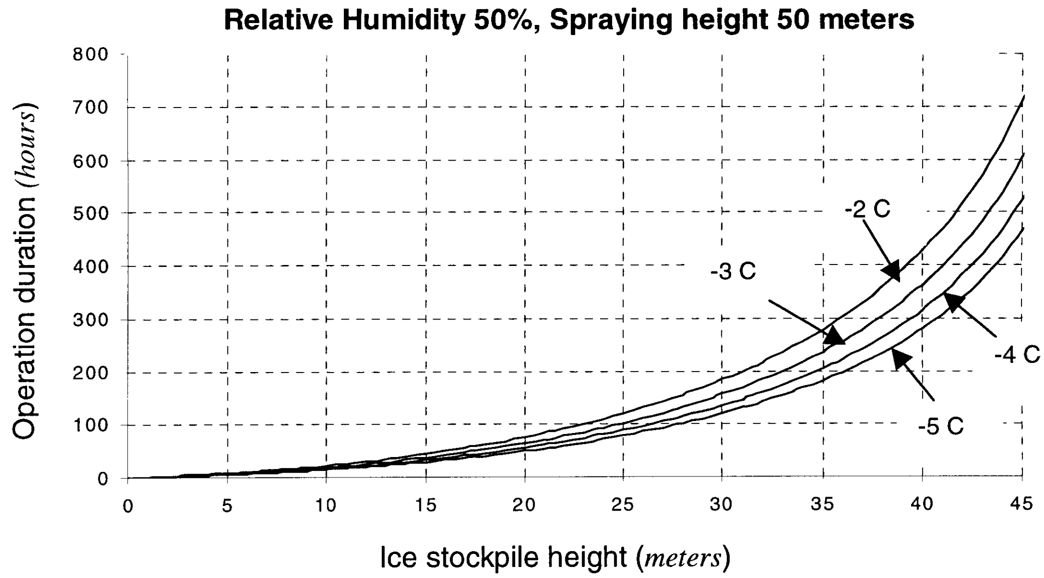

Figure 6.3: Height of ice stockpile vs. total operation hours for marginal subfreezing weather conditions. Spraying height is 50 *meters*. Wind speed is 3 *m/sec*. Width of spraying area 20 *meters*.

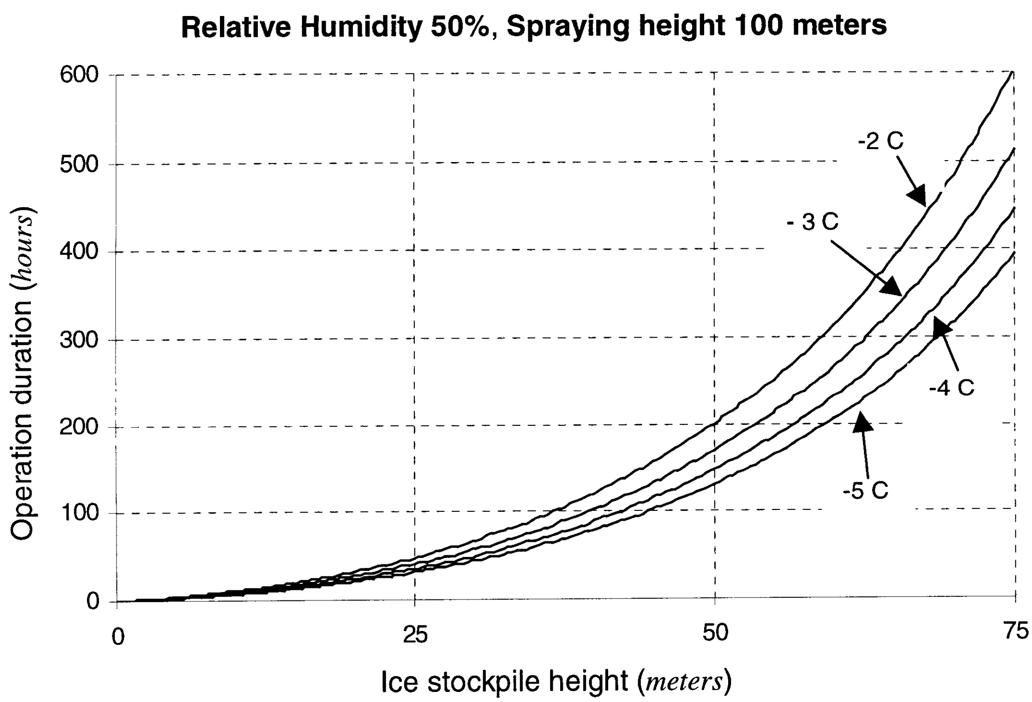

Figure 6.4: Height of ice stockpile vs. total operation hours for marginal subfreezing weather conditions. Spraying height is 100 *meters*. Wind speed is 3 *m/sec*. Width of spraying area 20 *meters*.

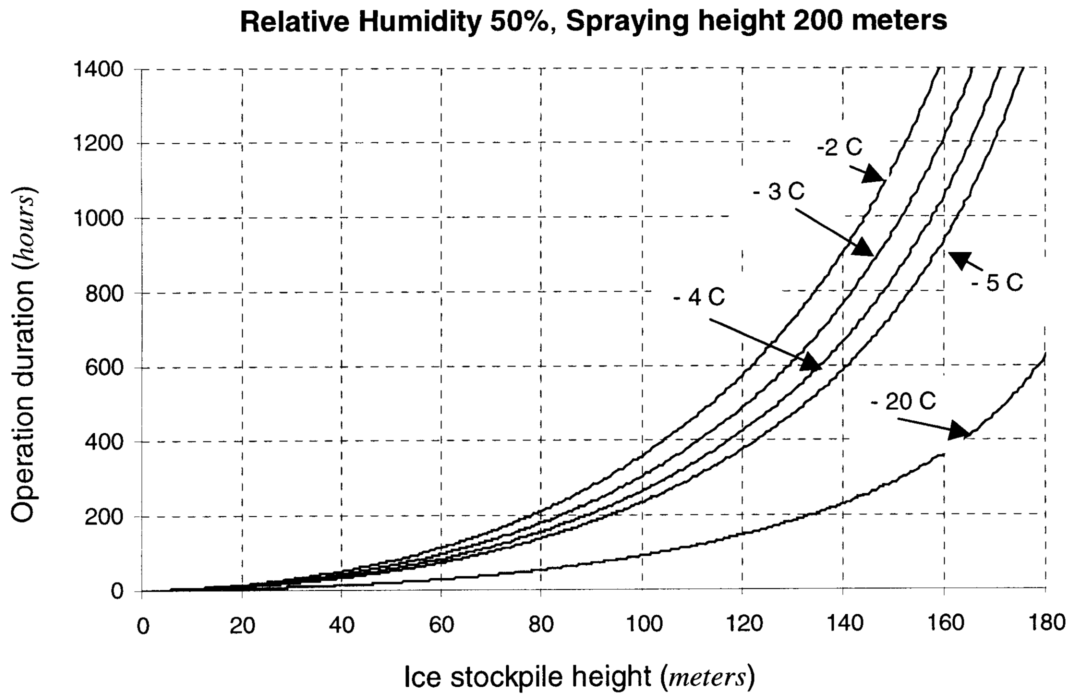

Figure 6.5: Height of ice stockpile vs. total operation hours for marginal subfreezing weather conditions. Spraying height is 200 *meters*. Wind speed is 3 *m/sec*. Width of spraying area 20 *meters*.

6.6 Conclusions

The analysis above is based on an approximate model. For example, the results obtained for the total mass of ice as a function of weather conditions are based on the assumptions that the weather patterns are uniform along the entire subfreezing period. In fact, temperature, wind speed and humidity of the ambient air fluctuate and are never constant. Furthermore, the geometric description for the shape of the accumulated ice is an idealization since in reality the changing wind speed will tend to spread the ice and form a pile shape different than the one depicted in Figures 6.4 and 7.2.

Another uncertainty is related to the settling angle of the surfaces of the ice stockpile relative to the horizontal. In the analysis above, this angle was assumed to be 35^0 [40]. This angle may be so in the case of accumulated fresh snow and it is likely that it will be larger in the case of manufactured ice since the adhesion force between the ice spheres are expected to be stronger. The stockpiles of the manufactured ice may resemble snow after being plowed, removed and piled by municipalities. These solid piles seemed to be able to sustain higher slope angles than the sloping angle of soft fresh snow.

The conclusions from the calculations and analyses above is that the falling distance of the sprayed water drop is continuously changing and the temperature and the relative humidity within the control volume is different in space and time. Considering the results obtained in section 4, it means the size of the sprayed drops should also be changed continuously with time and different drop sizes should be used along the x axis of the spraying control volume due the changes of temperature and relative humidity. In practice it is impossible to design spraying systems to accommodate such requirements. The spraying systems may form a few different drop sizes to accommodate the most prevailing ambient air conditions. Further analysis of these issues should consider the economics of the entire operation and the pricing of the spraying systems.

7. Preservation of ice

7.1 Introduction

Preservation of winter-manufactured ice is technically challenging and requires environmental sensitivity and public acceptance. The ice stockpile will be preserved in relatively populated areas, and public reaction to different aspects of the concept is yet unknown.

The motivation for the development of the WIM concept is the scarcity of land in densely populated areas, which makes it difficult to extend the local water reservoirs. For example, the average depth of the water reservoir of Brockton is 1-2 *meters*. Assuming also that the ice stockpile height is 50 -100 *meters*, the water storage per unit land area will be increased by at least an order of magnitude. Another important benefit for having large volume ice stockpiles is that the amount of (premature) thawing is roughly proportional to the surface of the ice. Therefore, in large and bulky stockpiles, the ratio of surface to volume is small making the preservation of ice more efficient.

Many Factors lead to undesirable thawing, including ambient temperature and humidity, wind velocity, solar radiation and precipitation. High summer temperatures in Southeastern Massachusetts combined with spring and summer precipitation motivates development of an inexpensive cover to control thaw rates. In addition, manufactured ice cannot be stored in the water reservoir, since the heat transfer between the ice and water is much larger than that between ice and air. Piling ice in the reservoir could collapse the ice pile's base, thereby causing large portions of the ice to crumble into the water. Therefore, the only alternative is to stockpile the ice on the reservoir's bank, allowing the summertime meltwater to return to the reservoir, thereby replenishing it.

7.2 Earlier methods for preserving ice and snow

The basic idea of using natural winter ice for summer cooling goes back to antiquity, when ice collected from natural water bodies was stored under insulating blankets of organic refuse, such as sawdust or crop residues and used for cool storage of food in summer. During the 19th and early 20th centuries before refrigeration technologies were developed, ice was harvested in the winter from rivers and ponds in New England. The ice was coated with sawdust or coal ash and was preserved for the summer in icehouses. This method was used extensively and at that time ice was even exported overseas. Currently, snow produced for ski resorts is not preserved since most ski resorts are not operational in the summer. However, in some resorts, large piles of artificial snow 20-50 *ft* high are produced toward the end of the winter and the snow is spread on the slopes during the spring to extend the skiing season.

During the late 70's and early 80's Ted Taylor of Princeton University developed the concept of the ice pond [12]. Snow machines and spraying nozzles produced the ice, which was housed in a 120-by-160 *ft* plastic-lined pit 20 *ft* deep and covered by a 30 *ft* tall dome. The chilled water from the ice pond was intended to cool a 130,000 *square ft* office building. A thin, multilayered fabric skin covered the dome. It was composed of an insulated layer and a waterproof layer on the outside, a layer of 9 *inch* thick fiberglass

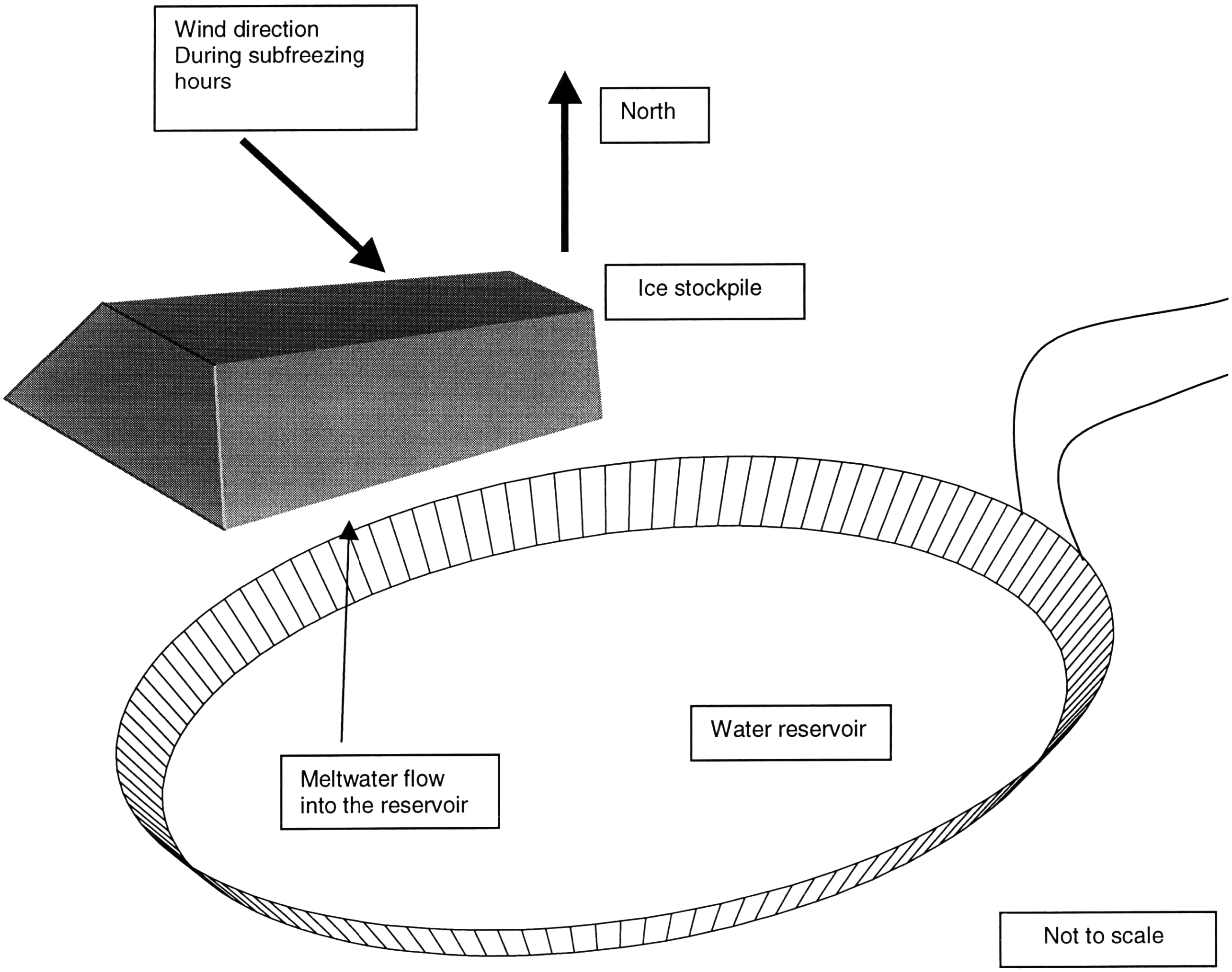

Figure 7.1: Schematic diagram of the ice stockpile in relation to the water reservoir. During subfreezing winter periods the prevailing wind direction in Massachusetts is northwest [33]. The analysis of section 6 shows that the width of the ice stockpile parallel to the wind direction should be as small as possible for a given base area. Thus, the longer dimension of the stockpile base should be positioned northeast-southwest.

under it, and a waterproof skin on the inside to keep water vapor out of the insulation. In 1979, 2,500 *tons* of ice was manufactured and a portion of this amount was preserved up to 15 *months* [12].

During the 90's interesting ice pond and snow projects were developed in Japan and China [34]. In 1995 a group of Japanese and Chinese engineers conducted low temperature storage experiments of food and vegetables with snow throughout the year in an abandoned road tunnel in Toyama, Japan [35]. The road tunnel located in a mountainous district and was 4 m wide, 4.7 m high, 240 m long and 800 m above sea level was separated into 6 rooms by plastic curtains. The snow was covered with aluminum foil-coated sheets. Natural snow was used and the experiments were repeated in Jiyayin Town near the Russian Territories. This area is very cold in the winter. The water that was gradually poured in a hole in the ground 3.5 m deep, froze without the need for the technique of snowmaking.

Kobiyama et al [36] proposed and tested a new snow air-conditioning system in which hot air is cooled directly on the surface of holes bored through a snow pile. He made experiments on direct heat transfer between snow and air. A snow box about 1 m^3 was covered with foam plastic insulation with a thickness of 10 cm. The experiments were made on the direct heat transfer between snow and air. The relationship between Nusselt number, Reynolds number and the geometry of the holes was deduced. Okajima et al [37] developed cold storage by natural ice. Cold air from an ice room was supplied to food storage rooms from spring to autumn.

During the 70's there was an interest in iceberg utilization as a source for fresh water and feasibility studies were conducted. The target areas included Saudi Arabia and Southern California. There was a concern about microclimate change in places where the iceberg would be utilized and it was agreed that even heavily insulated icebergs would cause more condensation of vapor from the air than they would give off in evaporation [38]. Kollmeyer [39] investigated in detail the melting of an iceberg and estimated that the heat transfer by radiation is about 1/500 of that by conduction and convection. However, it was anticipated that most of the premature melting would occur during towing of the iceberg from the poles. The most significant melting during this transport would occur in the submerged portion of the iceberg due to ablation by the flowing seawater.

The developments described above use ice and snow in small quantities for relatively high-value purposes, which are not comparable to the goal of WIM. The preservation of ice for refrigeration can afford expensive storage relative to the preservation of ice that is intended to be used as potable water. After all, it is expected that the winter ice will ultimately melt in summer although at a controlled rate to supply meltwater when needed.

7.3 Ice stockpiling for Northeast of the United States

WIM system will not require a dedicated infrastructure, so no fixed structures will be used. In this context, the entire system will be mobile, conducive to relocating any equipment annually when needed. Another factor, in which the system differs from the ice pond concept, is that the winter ice stockpile is not placed in a pit, so there is a need to cover its sides as well as its top. The cover would also prevent contamination by airborne pollution particles, which tend to adhere to ice and snow, enhancing thawing. The cover should also reflect radiation.

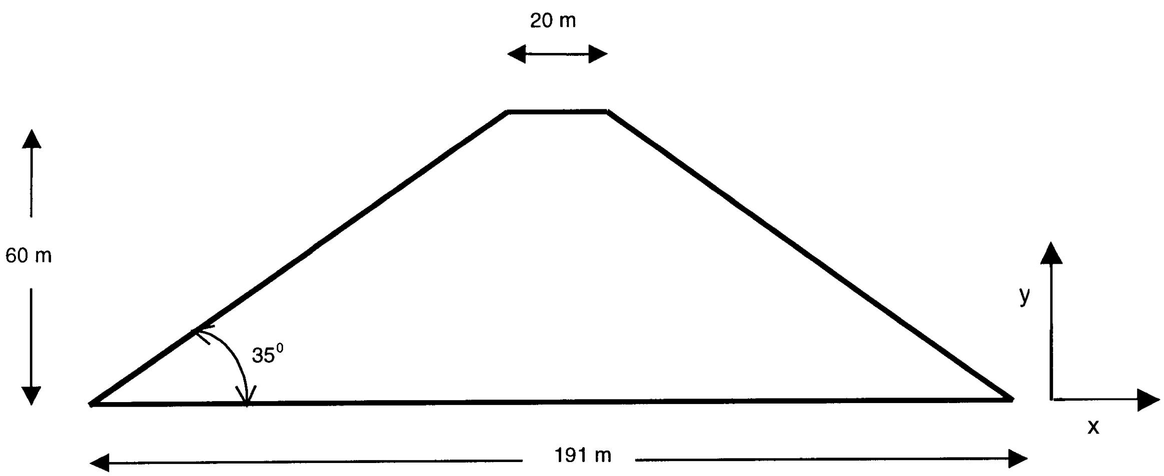

Fig. 7.2: Cross section of accumulated porous ice stockpile at the end of the winter subfreezing period. The natural slope angle of the ice from the horizontal is expected to be about 35^0 [40].

The frozen ice drops are made of glaze ice, the density of which is about 0.9 *gram/cc*. The drops are spherical. Consequently during accumulation, the ice mass becomes porous and its density can be calculated in the following way: The volume of a sphere of diameter d is $\frac{\pi \cdot d^3}{6}$ and it occupies a cube the volume of which is d^3. Therefore the density of the ice is $\frac{0.9 \cdot \pi}{6} \cong 0.47\ gr/cc$.

Adhesion forces between ice spheres can be substantial, especially if the stockpile is impregnated with flushing water during the manufacturing process. Upon freezing, the water contributes to the adhesion of the ice spheres. Later in the winter, the stockpile's lower layers will be substantially compacted from the resulting hydrostatic pressure. It is expected that the stockpile sides will be naturally sloped at a maximum of 35 *degrees* from the horizontal [40]. Calculations of the rate of the accumulated ice stockpile in conjunction with the rate of ice manufacturing were described in detail in section 6.5.

7.4 Cover design

The insulating cover for the ice stockpile should prevent erosion of the ice by wind and rain and protect it from particulate pollution that tends to adhere to ice and snow. The cover should have appropriate albedo to reflect sun radiation and should insulate the ice from conduction and convection of heat from the ambient air. It should also be durable for annual reuse.

Solid foam insulation is not appropriate for WIM. As stated earlier, the entire WIM system is intended to be mobile. Because of the large surface area of the cover, solid foam insulation would require an unacceptable total volume for the cover, which would make it difficult or impossible to relocate. Instead, it is proposed that a cover be made of two mylar or polyester sheets, which are fused to form a quilt [41]. Trial and error would determine the size of the fused sections of the quilt. An air compressor will continuously supply air at a pressure slightly above atmospheric pressure to keep the quilt inflated. The distance between the two inflated separated sheets may be 5-10 *cm*. The upper sheet would be made of aluminized mylar to reflect solar radiation. The reasons for this design are the following: The first is cost, since the effective insulation medium is air. The second is the low volume of the cover system when it is not inflated. This will

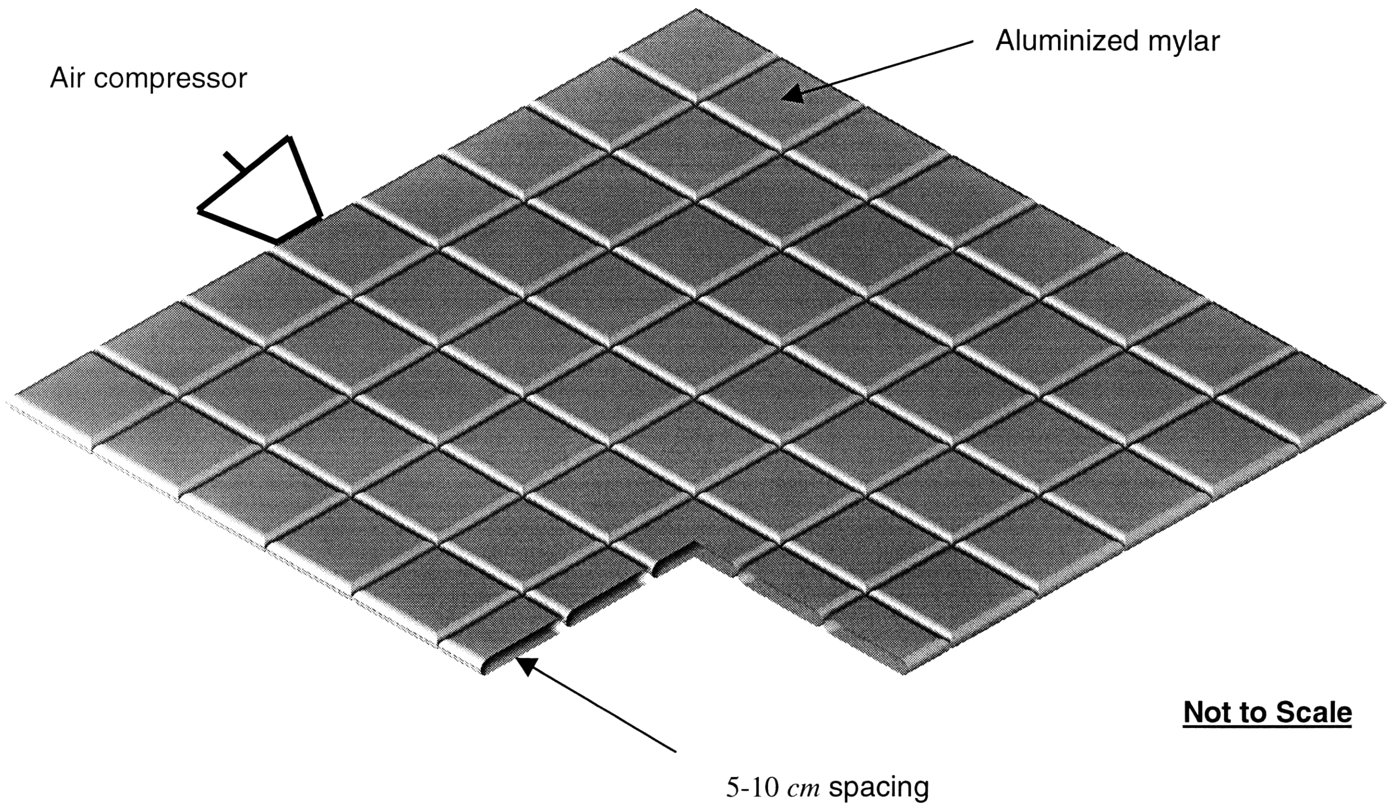

Figure 7.3: The concept of insulating inflated quilt. The quilt is divided into sections and is kept inflated by an air compressor that is operating continuously.

enable folding the two sheet cover and easy relocation with the entire WIM system. The third reason is the potential insulation capability of the trapped air in the quilt. If the quilt's section size is chosen appropriately, the trapped air in the quilt is nearly motionless and the only significant mode of heat transfer through the quilt is by conduction. This is due to the fact that air in the quilt is stable since the cold side is down and the warm surface of the quilt is up, preventing natural convection from occurring.

To protect the quilt from being blown by the wind, it is proposed that the quilt will be attached to the ice by spikes 2-3 *meter* long. The spikes could be made of stainless rods shaped with barbs to secure the cover to the ice.

7.5 Insulation capability of the ice cover

The calculation of the insulation capability of the cover and the melting rate of the ice follow that of Freitag and McFadden [42]. The assumptions made are the following:

a. The ice surface is horizontal. It can be assumed as semi-infinite medium.

b. The air trapped in the quilt segments is motionless.

c. All the meltwater is removed from the surface of the ice by leaching into the porous ice and/or by flowing off the ice surface. Therefore, the meltwater does not add thermal resistance for the heat transfer from the environment to the ice surface.

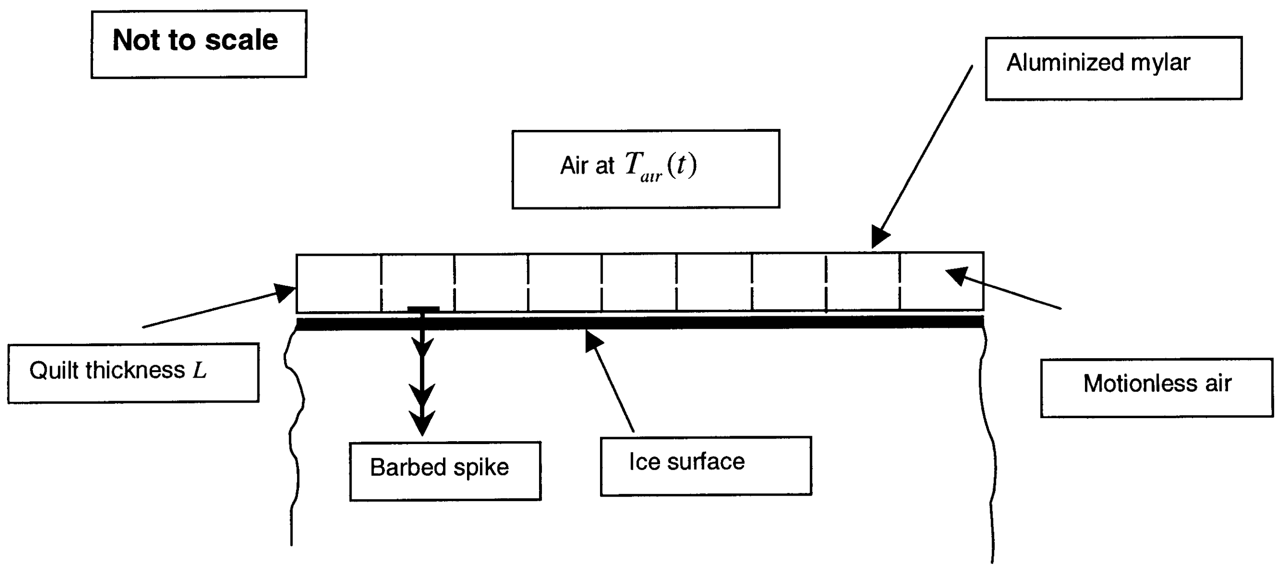

Figure 7.4: Insulation cover for the ice stockpile

The convection heat transfer coefficient between the ambient air and the upper layer of the quilt is h. The overall thermal resistance is:

$$R = \frac{1}{h} + \frac{L}{k_{air}} \tag{7.1}$$

L is the quilt thickness. The thermal resistance of the mylar sheet is negligible due to its small thickness. The total quantity of heat per unit area that will flow in a time increment dt from the air to the ice is equal to the heat of fusion of a unit area of ice multiplied by a melted incremental ice thickness dX and density ρ_{ice}:

$$Q = \frac{T_{air}(t) - T_{ice}}{R} \cdot dt = \rho_{ice} \cdot h_{sf} \cdot dX \tag{7.2}$$

$T_{ice} = 0\,C$, Re-arranging (5.2) and integrating:

$$X(t) = \frac{1}{\rho_{ice} \cdot h_{sf} \cdot R} \int_0^t T_{air}(t) \cdot dt \qquad (7.3)$$

When the problem relates to freezing of ice (on rivers and ponds) the integral $\int_0^t T_{air}(t) \cdot dt$ is defined as the "freezing index" [42]. In the case of WIM, this integral can be easily calculated from the meteorological data of the monthly average temperature at the WIM operational site.

In calculating the amount of undesirable ice melting, a value for the convection heat transfer coefficient for various weather conditions should be estimated. The suggested values for h with the following considerations for wind are [42]:

Condition	Heat transfer coefficient $\frac{W}{m^2\,C}$
Still air conditions	10
Typical for Midwestern United States	20-25
Windy conditions	30

The thickness of the air layer in the quilt is assumed to be $5\ cm$.

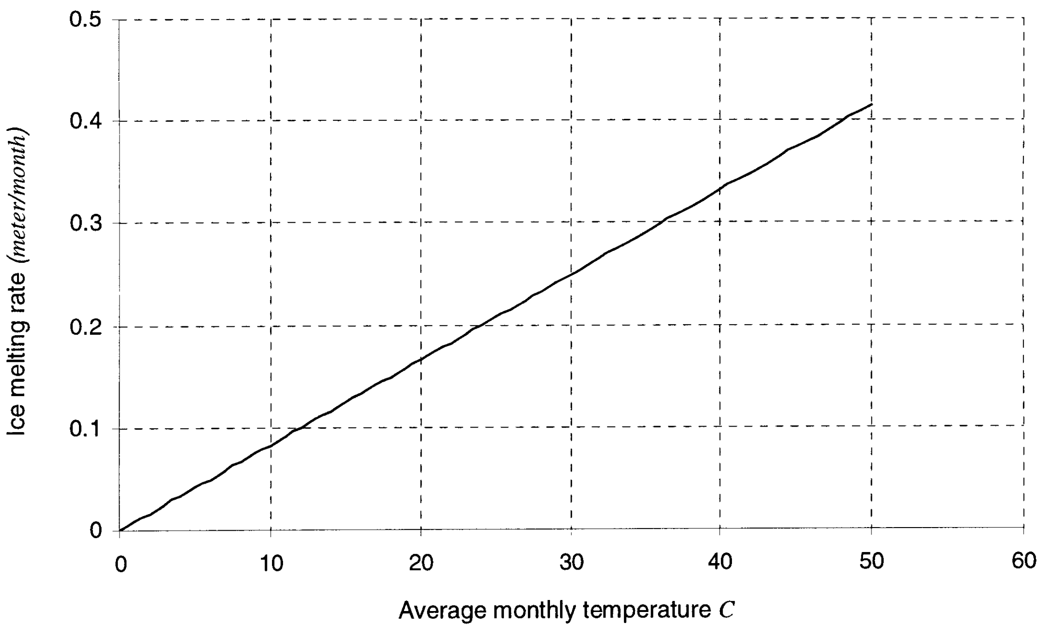

Figure 7.5: The upper bound of the ice melting rate in meters per month vs. the average monthly temperature. The quilt covers the ice and the air inside the quilt is motionless.

7.6 Conclusions

The approximate calculations above show that the melting rate of ice would be about 0.2-0.4 *meter/month*. Referring to Figure 7.2, this monthly melting rate represents roughly 1% of the entire ice volume.

The insulation capability of the quilt is excellent if indeed the air in it is motionless. It is difficult to estimate at this stage the necessary dimension of the quilt segments since it is anticipated that the quilt upper sheet would flutter in the wind and this may cause some motion of the air, which would lead to heat convection. Therefore, the final quilt configuration is left for experimental investigation.

The goal of WIM is to eventually result in the melting of the ice and supply drinking water. There is no need, therefore, to keep the ice stockpile covered continuously. In spring time, when natural snow melts up in the watersheds and water is plentiful, the ice stockpile would be kept covered, while in the summer when water is in short supply there may be times when an accelerated melting rate would be desireable.

Removing the cover completely in the summer will cause evaporation losses. To prevent evaporation and sublimation it is suggested that the insulation cover be maintained all the time. This will also prevent contamination of the frozen ice by airborne pollution. However, when melting is required, the introduction of compressed air into the quilt would be ceased to cause its deflation. The insulation capability of the sheets without the trapped air is poor and they will not retard heat transfer and melting significantly. If the natural melting rate of ice is not sufficient, an earth mover may be applied to flatten portions of the ice stockpile to accelerate its melting rate.

8. Hardware and operation of the winter ice manufacture system

8.1 Introduction

This section outlines the anticipated hardware for and the mode of operation of the winter ice manufacture (WIM) system. The description of equipment is general and further details will be developed for site-specific implementation projects. The storage capacity of the system is assumed to be 1 *million* m^3 of water, equivalent to 2 *million* m^3 of ice, the density of which is 500 Kg/m^3.

8.2 Spraying nozzles and pumps

The WIM system will use relatively large water drops, the diameter of which is in the range of 1 *mm*. Therefore, there will not be need for expensive atomizers such as those used in snowmaking. The pressure head to generate such drops is low and could reach 2-3 *bars*. On the other hand, the nozzles will be mounted on a structure, the height of which will be in the range of 100 *meters*. Pumping the water to such altitude will create the need for additional 10 *bars*. In considering the pressure drop due to friction in the pipes leading to the nozzles, it is anticipated that the overall pressure provided by the pumps is 15-20 *bars*. Therefore, the energy needed to elevate and spray 1 m^3 of water is:

$$E \cong 20\, bar \cdot 100{,}000 \frac{N/m^2}{bar} \cdot 1\, m^3 = 2 \cdot 10^6\ Joul = 0.56\ killowatt\ hour$$

Thus, the energy needed for a million gallons of water is approximately 2,120 *kWh*.

Assuming that a community in New England requires the storage of a million m^3 of water and that the ice will be manufactured over 500 subfreezing hours, the total energy required for pumping is $0.56 \cdot 10^6$ *kWh*. This energy is consumed over 500 subfreezing hours. If the pump efficiency is 75%, the total power required for the operation is about 1.5 *Megawatt*. The flow rate of the pumps is 2,000 m^3*/hour* or 0.53 *million gallon/hour*.

Summary: Flow and spray equipment capacity and power for the storage of one million m^3 of water.

Total ice weight:	1 *million tons*
Total ice volume:	2 *million* m^3
Operation duration:	500 *hours*
Pump and nozzle flow rate:	2,000 m^3*/hour*
Pump power:	1.5 *Megawatt*
Pump pressure head:	~20 *bar*
Nozzle pressure drop:	~3 *bar*

The water pump represents the major cost of capital equipment. To improve the utilization rate of the pump, one proposes that it would be mounted on flatbed trailer(s) and be relocated when necessary. It is also possible that the pump may be rotated between various operational sites in the winter. Such rotation would increase its utilization rate and make a better use of it since the pump is the major capital equipment of the entire system. It is expected that the local municipality, in other words, the customer for the ice storage operation will be able to provide a portion or all of the needed pumping capacity.

The calculations in section 6 and the plots in Figures 6.3, 6.4 and 6.5 assumed constant weather conditions, which is unrealistic scenario. However, the calculations assumed marginal subfreezing conditions so the ice mass rate given by these calculations is the lower bound. If the spraying nozzles are fixed in space the falling distance of the drops becomes smaller with time. Theoretically there is a need for spraying nozzles that form variable drop sizes and this variation should be done continuously during the operation. Obviously, this required performance from the spraying nozzles is unrealistic. It would require choosing a nozzle that can deliver a few drop sizes. Adjusting such nozzle for a specific WIM project is left for further development.

8.3 Structure

The most challenging task is the design and construction of the supportive structure for the nozzles, and pipes leading to the nozzles. Considering Figure 7.2 which represents the cross section of the ice pile, and that the total ice volume is 2 $million\ m^3$, the necessary length of the structure perpendicular to the wind direction is 315 *meters*. The length parallel to the wind direction is denoted as b and is 20 *meters*.

However, the calculations above assumed that the ice stockpile is a perfect 2-D cylinder. In reality, the ice stockpile will naturally be sloped at $35°$ from the horizontal [40] in the y-z plane as well as the x-y plane (see Figures 6.1 and 7.2). Therefore, for the dimension given in Figure 7.2 the structure length could be assumed to be about 400 *meters*. The complete structure dimensions are; 100 *meters* high, 20 *meters* wide and 400 *meters* long. The structure will support a piping system that delivers 2000 $m^3/hour$. It is anticipated that the load is mainly the weight of the structure itself, while the weight of the flowing water might be negligible in comparison to that of the structure. The structure will be modular making it possible to assemble and disassemble as well as to relocate it to various sites from year to year.

8.4 Electric substation

The electric substation provides 1.5 *Megawatts* for the pumps. Because demand for electricity peaks in New England in the summer, there are no difficulties in obtaining this level of power in the winter. It is anticipated that the local municipality, its water department and the local power utility will provide the substation, power and technical support.

8.5 Insulating cover

The insulating cover is described in some detail in section 7. The total area required is about 17 *acres*. When the cover is deflated, its volume is drastically reduced. Assuming a distance between the cover sheets of 3 *mm* when the cover is deflated, the total volume of the cover is about 200 m^3. Such a cover could be relocated from site to site by 4-5 trucks. The cover may be comprised of 10-20 sections, which are put together when necessary. Placing the cover over the ice and re-folding it presents a task that requires substantial labor for a short duration.

8.6 Miscellaneous

Weather sensors that measure temperature, humidity and wind speed will facilitate the WIM operation. Such information and also weather forecasts are critical for successful operation.

As outlined in section 5, nucleating the sprayed water with ice crystals will require the formation of very small drops using a small amount of water that is atomized by compressed air. The atomizers may be mounted under the spraying nozzles so the large falling water drops will collide with the numerous but tiny crystals, see Figure 5.2. Such a system will require a low flow secondary piping system that delivers both water and compressed air. It will also require an air compressor. Detailed design of such a system may become site - specific to accommodate different qualities of water due to sedimentation, see section 5.

One hazardous factor is the potential icing and accretion of the support structure. In general, ice accretions are formed when supercooled water drops hit a cold object and freeze on contact. Thus, the formation of ice usually grows into the wind [43]. If the ambient temperature is just below freezing, water drops hitting a cold object will not freeze on contact but rather will be blown to the leeward side and freeze in the shape of icicles. This process results in high density clear ice accretions [43]. It can cause the collapse of TV and radio towers and power transmission poles [44]. This hazard motivated the design of structures that takes into account the weight of the attached ice. Therefore, the weight of these tower structures approximately doubled and became more expensive.

Removing ice from tall structures could be achieved by using a concrete vibrator, which has been used in Finland for such purpose. The vibrator is attached directly to the structure or to its guy lines. The frequency of the vibration is 20-30 Hz and the ice loosened after a few minutes [44]. This method does not require much energy and is likely to be effective in removing ice from the WIM structure that is supported by guy lines.

9. Environmental, economic, and public acceptance assessment

9.1 Introduction

The development of water resources requires the conception, planning, design, construction, and operation of facilities to control and utilize water. Water resource problems are the concern of hydrologists, economists, politicians, geologists, electrical and mechanical engineers, biologists and chemists. Each water development project encounters unique, site-specific physical conditions; hence, standard design, which leads to a simple, handbook solution, is impossible. The specific conditions of each project must be met through integrated application of basic principles of many disciplines.

The field of water-resources engineering involves the assessment of available water sources and demand, water quality, hydraulic structures of the watershed and area served, economics, social aspects and planning. Most water projects are planned and financed by some government units such as a municipal authority, a federal irrigation unit or a public utility. Many such projects involve controversial political issues, debated at length by people whose understanding of the basic engineering aspects of the problem is limited. It is the responsibility of an engineer who has the necessary facts to take a firm position in the public interest if the final decision is not to be made on political and emotional grounds.

Planning is an important step in the development of water resource projects. The planning of a project generally involves public recognition of the need for additional water supply [45]. This is followed by the conception of alternative technically feasible solutions, which would satisfy the need. The alternative proposals are subjected to an economic study that analyzes its benefit and cost and thus determines their economic feasibility. Financial feasibility for being able to pay for the project and political practicality based on real or unfounded public perception enter the picture and play an important role in the choice of an alternative.

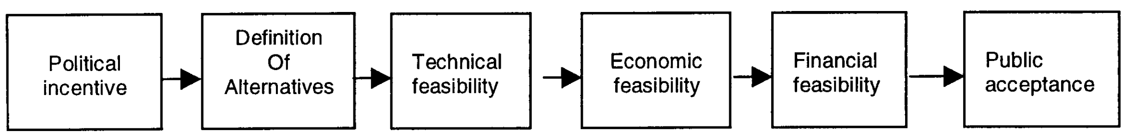

Fig. 9.1: Steps in the planning of water resources project [45].

The environmental, economic and public acceptance assessments of the proposed winter ice manufacture (WIM) would be interwoven in each other and cannot be separated. Public acceptance of new technologies is not an easy task to forecast. History of public opposition to technological advances such as high voltage power transmission, nuclear power generation, and recently to biotechnology food production testifies to the unpredictability of public perception and acceptance of new technologies. Another problem is the "not in my backyard" syndrome, in which a community or segment thereof fails to accept the local building of a public enterprise such as, for example, a landfill or highway—even when their development is intended to benefit that community.

9.2 Potential environmental impacts of WIM

Snowmaking takes place in remote ski resorts far from population centers, so it is difficult to compare or predict the rare instances of public opposition to snowmaking and the public reaction to the proposed WIM. Snowmaking equipment is noisy due to the expansion of high-pressure air. In addition, the drift of small supercooled drops due to the wind produces an artificial cloud over the ski slopes. The major complaint about snowmaking, however, is that snowmaking requires large amounts of water in relatively high altitude, at the beginning of the watershed where water resources are limited [46]. Such a complaint is not an issue for the WIM operation.

One possible concern is drifting of small supercooled water drops that freeze upon hitting a cold surface, icing nearby roads, structures, trees, and power transmission lines. Drifting drops do not constitute a loss of water since their volume is small in comparison to the larger drops that constitute the major supply of water. Iced roads may become dangerous to traffic; iced trees and power towers may collapse. For example, cooling towers of power plants in the Midwest cause evaporation, which in winter cold days condenses and supercools, drifting to a distance up to a mile, causing icing in the power plant neighborhood.

In anticipation of this problem, it is recognized that the prevailing wind direction in New England when the temperature is subfreezing is from the northwest [33]. Therefore, when ice would be manufactured in New England, the WIM system could be positioned on the northwest bank of the existing water reservoir, as shown in Figure 7.1. This will guarantee that all or most of the drifted of supercooled drops would land in the reservoir, causing no harm.

The WIM system is not expected to be as noisy as high-pressure snowmaking equipment since it operates without the need for compressed air. However, the water pumps might create noise, especially if powered by diesel as opposed to and not by electrical power.

Another concern is the potential formation of fog either during the manufacture of ice or storage. One expects fog will be created during manufacturing, but its extent is unknown at this stage and this should be left for an investigation during pilot testing. During storage it is not expected that fog will be created since the ice will be covered. As mentioned in section 7.2, even for an exposed iceberg brought to a warm location, more condensation than evaporation is expected in summer time [39].

Additional concern is aesthetics. For example, some real estate is highly valued because of its proximity to the placid view of a body of water. It is expected that residents would object to the view of a large tall ice mound, especially if it covered by a shiny metallic surface. On the other hand, it is entirely possible that the view of a large ice mountain in the summer would become an attraction. If the ice would be used to supply chilled water to distant commercial buildings, the neighboring residents can be provided free-of-charge installations to supply them with chilled water for their air-conditioning needs, calming their opposition. In the worst case, properties nearby would be declared public, expropriated by "eminent domain" as in the case of public projects like the construction of highways. In many cases, the area around a water reservoir is kept rural to preserve the quality of the water. This fact minimizes residential buildings in the operational area.

A potential benefit that may result from the WIM operation is higher water quality. This is due to the fact that the water used for ice manufacture is plentiful in the winter so that sediment concentration is relatively low at that time. Therefore, it is anticipated that the quality the meltwater would be better than that of the water, which is supplied in the summer from dwindling water reservoirs containing higher sediment concentration. If the meltwater flows at low rate into the reservoir, it is not expected that the quality of the water that is ultimately distributed and supplied to customers would be different than the quality of the water already in the reservoir. By contrast, if future developments will enable the distribution of the meltwater directly to customers without first flowing and mixing with the water in the reservoir, then its quality would be unusually high.

Another unknown impact is the possible effect on wildlife, such as birds, frogs, etc. If the ice pile is kept covered this might be less of an issue. From a public perception point of view even a minor microclimate change may result in opposition and lawsuits.

Large ice piles visible in the summer may attract children or adventurers who may wish to ski or test it for recreational purposes. It is not known what would be the constituency of the ice in the summer. It is possible that in some cases the outer shell would be frozen solid while below there will be a mixture of water and ice. Children who may choose to walk on the ice may be drowned or be buried in an avalanche. These safety issues should be addressed during the development of a prototype and testing.

9.3 Public perception and Acceptance

The WIM concept has inherent problems; it will be implemented on the one hand to make a better use of scarce land in populated areas. On the other hand, operating it near populated areas may cause real or imagined disruption and public opposition.

Public perception of new technologies and their risk is the topic for extensive research done by experts from various disciplines [47], [48]. Some new technologies are portrayed in the media and perceived by the public as dangerous, damaging to the environment, or as a means to benefit someone else. As the US society becomes increasingly litigious, new technologies and their implementation has been the subject of numerous lawsuits that intend to prevent implementation.

To overcome this problem, it may be necessary to demonstrate the WIM system on a small scale and to test it initially at remote sites distant from population centers. It will also be necessary to communicate to the community the economic consequences of water shortages, which in some places result in stagnated economic development and/or inconvenient water shortage rations.

The WIM system is mobile and its implementation does not require a long term infrastructure or financial commitment from the community. Therefore, it is possible to classify some WIM projects as an experimental pilot study and based on the initial public reaction, to decide whether to continue operation the following season or make revisions. These revisions could be: a scaled-down operation, a change of operational site, or complete termination. Such flexibility is not available when conventional water projects are planned and implemented.

The objection to the WIM operation could come from a narrow portion of the community that resides near the operational site and this objection may not be based on perception, but on real inconvenience. Declaring the area by "eminent domain" could be expensive or politically unacceptable. In such cases, there will not be a choice but to address these inconveniences by design and site changes.

9.4 Water economics - water is not a commodity

Classic economics defines a commodity as a product that does not posses "differentiation" and obeys the "law of one international price". The meaning of this law is that a commodity is priced uniformly in the international market, excluding transportation cost. If a price disparity for a commodity exists, it is always temporary since an arbitrage trading opportunity is created that motivates traders to "buy low, sell high" leading ultimately to a price parity. Indeed, the price for commodities such as oil, grain or steel have an international uniform price. However, water cannot be traded between continents, or within a country, nor can be stored over more than a season or two.

Another feature of a water supply project is that it requires a substantial sunk cost in development and also economy-of-scale. The operational cost of a water project and distribution is relatively low while most of the cost is related to the initial construction. The economy-of-scale requirements make water projects the subject of government regulations and usually a water utility is a government or municipal monopoly. Thus, its distribution and marketing are not subjected to free market competition. Water prices are fixed by regulations and usually the pricing is highly inelastic. This means that an increase in price of water does not affect appreciably its demand. In many cases the price for water is subsidized, especially when used in industry on agriculture. Water for residential consumption, on the other hand is priced intentionally high in attempt to curtail consumption.

As described in previous sections, the WIM concept may become a step in introducing an element of free market into the water supply industry (although it is suitable for limited geographical regions). The WIM system requires minimal infrastructure and does not require large sunk cost. Instead it requires higher operational cost mainly in the form of planning, labor and electricity. Since the WIM system is mobile, a for-profit company that would relocate it on an annual basis can best operate it. Municipalities need not provide up-front capital investment, rather pay only for the manufactured and stored ice. In other instances, the WIM concept that can be installed at a short notice may also be used by municipalities as a short term solution during the construction of a conventional water project that requires a substantial infrastructure and long building duration.

9.5 Applications for ice

Large masses of ice available in the summer may have economic applications higher in value than using it just as a means to store water. Additional applications for ice may require the production of larger quantities of ice than just for water storage, creating economy-of-scale in production. Alternatively, the ice mass that later supply meltwater may provide cooling for a variety of applications before it melts.

The motivation for the development of the ice pond concept by Ted Taylor, York Snow and lately by a score of Japanese engineers is to provide summer cooling capacity for various applications [12], [9], [31], [34]. Such a goal also motivated research and development programs in the early 80's at MIT, aimed at winter production of ice for summer cooling of buildings [49], [50].

The WIM operation may be used to provide chilled water for air-conditioning of large commercial buildings. This possibility is economically promising for the WIM concept since the WIM operation would be carried out in proximity to population centers. The manufactured ice could also be used to store foodstuff, reducing the need for refrigeration power [34], [51]. One pilot study of Taylor was performed in up state New York, providing cooling capacity for a cheese making plant [12]. Cheese making requires a continuous supply of cooling capacity since processing is done at about $7\,C$. Cooling is also required for brewing, ice cream and diary food processing.

Perhaps the most high-value application for the ice would be recreational activities such as indoor or outdoor summer skiing. This possibility may contradict the motivation for using the ice as a mean for water supply since recreational activities may cause contamination of the meltwater. Nevertheless, this possibility should be further explored since commercial summer ski resorts may become a recreational trend and provide a substantial economic return.

9.6 Comparing WIM with water desalinization

As outlined in section 1.1, Bluestone Energy Services, Inc. is studying the feasibility of building a water desalinization plant to provide water to Brockton and a score of communities in Massachusetts [1]. There are a variety of water desalinization processes in the market; the one under consideration by Bluestone is reverse osmosis (RO). Desalinization requires a substantial energy input and capital equipment. Although the process seems to be environmentally friendly, desalinization requires disposing large quantities of accumulated brine. The brine is usually disposed back to the sea and care is taken not to cause large concentrations of it in specific spots, but rather to dispose it over large sea areas to prevent harm to marine life [52].

The following Table includes estimates for the energy requirement for a few water desalinization processes:

Desalinization Process	**Energy Requirements/1000 gallons of Water**
Reverse Osmosis	~12 kWh
Vapor Compression*	24-26 kWh
Multi Effect Distillation	11 kWh + 40 $tons$ of steam

* For a large unit with a capacity of at least 1.5 million gallons/day

Table 9.1: Energy requirements for desalinization processes [53].

In Section 8.1 it has been shown that the upper bound for the consumption of electricity used in the WIM process is $2.1 kWh/1000\ gallons$ of water. Comparing this with RO, the most efficient desalinization process, the WIM process requires less energy by a factor of approximately 5.7. In other words, the energy required for the winter ice manufacture process is less than 18% of what is required for the most efficient water desalinization process.

A complete economic comparison requires the information on the capital equipment investment for the WIM and RO processes. Such information is not readily available for an RO process since each RO plant has site-specific economics, and a generic RO process is not available. As for the WIM process, it is clear that capital investment requirements are minimal. Moreover, all equipment for the WIM process are recoverable and can be relocated and reused as needed. Once the WIM process is developed, it is likely that it is more economical than any desalinization process. Likewise, the pump that represents the main capital equipment for the WIM process can serve more than one WIM site during the same winter as described in section 8.2. In some cases, the municipality where the WIM operates may provide pumping capacity.

9.7 Cost and pricing of water & potential WIM in Brockton, Massachusetts

Table 9.2 below presents an itemization of fixed and variable costs of water supply in Brockton, Massachusetts. To summarize its content, the cost, which does not include debt to supply a thousand gallons of water, is 87.7 *cents*, of which 12.4 *cents* are variable cost. The total annual consumption of water is about 4 *billion gallons* or 11 *million gallons per day*. The consumption is expected to increase to 15 *million gallons per day*. The city charges customers $2.41 *per* 1000 *gallons* [2].

The city requires three months of additional supply in the summer so the WIM operation should provide annually 1.35 *billion gallons* of meltwater, which is equivalent to 5.11 *million* m^3 of water. The ice density is half that of water, so the total volume of the required ice pile is slightly greater than 10 *million* m^3.

The variable cost in Table 9.2 plus the energy cost for pumping water for the WIM operation will be the total variable cost of the meltwater provided by the WIM. As summarized in section 8.1, the energy requirement for 1000 *gallons* of water is less than

Fixed cost 1998	Raw cost		
1. Contractor	$2,500,000		
2. Filter	150,000		
3. Debt	1,034,645		
4. EPA	165,000		
5. Other	200,000		
6. Total not including debt	3,015,000	Cost per million gallon	$754
7. Total including debt	$4,049,645	Cost per million gallon	$1,012

Variable cost	Per million gallon		
Treating chemicals	$65.66	Total cost not including debt:	
Power	12.72	$877/MG	14.1% variable
Carbon	16.76	Total cost including debt:	
Repair & replacement	28.54	$1,136/MG	10.9% variable
Total variable cost	$123.67		

Table 9.2: Itemization of water supply costs in Brockton, Massachusetts [54].

2.5 *kWh* or, at the prevailing electricity cost of about 15 *cents/kWh*. This brings the total variable cost of the meltwater to about 27 *cents per* 1000 *gallons* of meltwater.

To compare the WIM meltwater cost to the current cost of water, the fixed capital cost of the meltwater should be less than $87.7-27 \cong 60$ *cents per* 1000 *gallon*. To supply competitively 1.35 *billion gallons* of meltwater per year, the total fixed cost of the WIM system per year should be less than $810,000. These calculations do not include revenues from potential applications for the ice such as cooling for industrial purposes.

The analysis above has some faults. It analyzes and compares the use of WIM to supply additional water capacity against the current method for water supply for which capital costs were incurred in the past. If one plans today to add annual water supply capacity of 1.35 *billion gallons* using the traditional method of water supply, most likely the cost today would be different and higher than what had been paid in the past. Therefore, complete feasibility studies for WIM should compare it to various alternatives for water supply built at the present time. Furthermore, the economics of water supply projects is site-specific and it is unlikely that the water economics of Brockton resembles the water economics of other areas where the WIM concept may be applicable.

9.8 Size of ice stockpile for Brockton, Massachusetts

The cross section area of the 60 *meters* high ice stockpile is 6,341 m^2 (Figure 7.2). To manufacture and store 10 *million* m^3 of ice, the length of the pile should be 1,580 *meters* or about a mile. The total land area for the ice is 300,000 m^2 or about 75 *acres*. The maximum height of the ice is 60 *meters* and the average height is 33.2 *meter*. Considering that the ice density is half that of water, the average height of equivalent water is 16 *meters*. The average depth of the water reservoir of Brockton now is 3-5 *ft*. Per unit area, the ice stockpile provides a storage capacity, which is an order of magnitude higher than that of the current reservoir.

10. Conclusions

10.1 Introduction

This thesis provides insights into the process of snowmaking. It includes a comprehensive quantitative analysis of the snowmaking process, starting from first principles. It suggests that mass production rate could drastically be increased if the water is sprayed from high altitude. Relationships for the mass production rate, geometry and dimensions of the spraying area and weather conditions were developed. Quantitative expressions for water drop size as a function of ambient weather conditions and spraying height were developed. Analysis of nucleation techniques, appropriate for this process were searched, and some useful insights explaining existing nucleation in snowmaking have also been developed.

An inexpensive insulation cover using air as an insulation material has been suggested. Operational scenarios that include mobility and retrieveability of the winter ice manufacture (WIM) system were developed. The economics of water supply has been reviewed in general and in relation to the concept of WIM that is intended to alleviate summer water shortages in northern United States.

One conclusion is that the production of ice for the single purpose of utilization of its meltwater is a low-value commercial proposal. The economics of this process, undoubtedly, can be vastly improved if the ice is used for additional applications. Such applications have been proposed, researched and developed for the past 25 years by many individuals. For instance, the ice may be used first for cooling purposes that provide a better economic return. The cooling capability of the ice may be used for air-conditioning of commercial buildings and to provide cooling for industrial foods processing such as cheese making, brewing and food storage. Using the ice for recreation is potentially the best economic alternative. The potential use of the meltwater is better described as a by-product of the high value applications for ice described above.

The physical principles for the massive productions of ice by this method are sound. Large quantities of ice can be manufactured even at marginal subfreezing weather conditions. However, the success or failure to materialize this concept relies on the many details that seem to be secondary, but may determine the fate of actual development. These details include: the ability to employ a short term workforce when, for example the ice requires covering or uncovering; the feasibility in anchoring or attaching the cover to the ice and preventing it from being blown by the wind; protecting nearby residential areas from fog and icing; addressing environmental protection to wildlife and responding promptly to changes in weather conditions by revising operational conditions *in situ* and on time.

Like every other new technological development, a new implementation project may start small, addressing niche markets. As for the WIM, an implementation project may initially address the need of a small community in the range of a few thousand inhabitants that may require both additional water supply and cooling capacity that should be marketed to nearby industries. Then, by technological evolution, the concept may be improved and progresses to include large communities such as Brockton. If the ice cannot be used for cooling purposes in Brockton, it is unlikely that Brockton's water shortages can be addressed in the near future by this concept.

10.2 Future research and development

The WIM operation is not done indoors, but in the open. Many technologies that operate in the open attract objection from environmental groups, even if these technologies seem to have a minor effect on the environment. Consider, for example, wind and hydro power that seem to be safe to the environment; nevertheless, at the present time there are plans to dismantle hydro dams and plants across the country, and wind power is under a similar attack.

The WIM process causes the evaporation of about 5% of the sprayed water. An operation producing a million tons of ice in 500 subfreezing hours would cause the evaporation of $100\ tons$ of water per hour. If such a system were to operate in Brockton, $5\ million\ tons$ of stored ice would be required, and the operation would cause evaporation of about $500\ tons$ of water per hour. This represents a substantial amount of evaporation and most likely fog and impaired visibility would result. In further research before actual testing, it may be possible to compare the evaporation during winter from cooling towers of power plants that operate in the northern US. Such a comparison may lead to an insight on the magnitude of this potential problem.

Section 6 outlines a control volume analysis of the WIM site and the spraying area. Implicitly, it has been stated that within the control volume there are significant changes of temperature and humidity relative to the ambient air. Temperature and humidity of the ambient air and spraying height determine the drop size, according to the analysis in section 4. Because of the change of temperature and humidity within the control volume, it is necessary that the size of the sprayed drop be changed from nozzle to nozzle in the x direction, see Figure 6.1. In addition, as weather conditions fluctuate, there is a theoretical need for a nozzle that can change the size of the sprayed drop as necessary on time. Such adjustable nozzles are not available and further development is necessary to determine the optimal size of water drops during various changing weather conditions. Nozzles that can spray various drop sizes may be needed in different locations over the spraying site.

The design of a structure that supports the pipes leading to the nozzles and the array of spraying nozzles would be a challenging task. This structure may be about 100 *meters* and should be constructed for easy assembly and disassembly to enable mobility and relocation. Such a structure may resemble TV or radio towers, or poles for high voltage transmission lines. The framework should be designed to account for possible icing that may increase the load on the structure.

The proposed insulation cover is also a challenging task, since using it for repeated coverings, including folding, unfolding and relocation, will cause wear and tear that may decrease its durability and shorten its lifetime.

Another point that determines the efficiency of the ice accumulation process and its storage is the angle that the ice surface makes relative to the horizontal due to avalanche and natural inclination. In the calculations section 6 and 7 this angle was chosen as 35^0. This choice for angle may be right for soft fresh snow and most likely it could be steeper for the ice produced by the WIM process.

The analysis in section 4 on heat transfer assumed that the freezing drop is spherical. In reality, an ice shell that thickens during the freezing process, as shown in Figure 4.4 coats the freezing drop. Because of the expansion of the ice phase, the pressure of the liquid in the drop core is increased, eventually causing the drop to shatter. The pressurized liquid forms thin water jets that freeze instantly when coming in contact with the subfreezing ambient air and form thin filaments or thorns that are attached to the drop mass. Clearly, the shape of the freezing drop is not spherical after shattering and the spherical model for the freezing drop used in section 3 and 4 is therefore an approximation. It is not clear at the present time if the hydrodynamics and heat transfer of the shattered drop can be modeled at all due to shape irregularities. In future research, this point should be studied in more detail.

Snowmaking continues to be a trail and error enterprise and with exception of a couple of papers written 20 and 30 years ago, nobody developed comprehensive physical and mathematical models for the process. The author believes that this work will serve as a foundation for future in-depth analytical investigations leading to better understanding of the process of snowmaking.

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