ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE

EXPERIMENTAL AND MATHEMATICAL ANALYSIS OF PRODUCING CLEAR ICE IN A REFRIGERATOR

M.Sc. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

BUZ DOLABINDA SAYDAM BUZ OLUŞTURULMASININ DENEYSEL VE MATEMATİKSEL OLARAK İNCELENMESİ

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Umutcan Salih ERYILMAZ, a M.Sc. student of ITU Graduate School of ScienceEngineering and Technology 503131150 successfully defended the thesis entitled "EXPERIMENTAL AND MATHEMATICAL ANALYSIS OF PRODUCING CLEAR ICE IN A REFRIGERATOR", which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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		....

Date of Submission : **2 May 2016**
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To my family and friends,

FOREWORD

First I want to thank my academic advisor Prof. Dr. Lütfullah KUDDUSİ for his guidance and help in my thesis.

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And finally I want to thank my parents for their love and support through my whole life.

June 2016

Umutcan Salih ERYILMAZ
(Mechanical Engineer)

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ABBREVIATIONS

FDM	**:** Finite Difference Method
App	**:** Appendix
DOE	**:** Design of Experiment
ITU	**:** Istanbul Technical University

SYMBOLS

α : Angle between the gravity vector and the cold plate attached to the evaporator in degrees

α_{H2O} : Thermal diffusivity of water at 0 °C
ν_{H2O} : Kinematic viscosity of water at 0 °C
k_{H2O} : Thermal conductivity of water at 0 °C
ρ_{H2O} : Mass density of water at 0 °C
Pr_{H2O} : Prandtl number of water at 0 °C
D_{AB} : Mass diffusivity of water and oxygen at 0 °C

C_o : Initial concentration of oxygen in water
C_{max} : Saturation concentration of oxygen in water at 0 °C
U_{ice} : Freezing velocity of ice
L_{char} : Characteristic length of the water flow

Le : Lewis number
Re : Reynolds number
Nu : Nusselt number
h_T : Thermal convection coefficient
h_m : Mass convection coefficient
m''_{sweep} : Mass flux of oxygen due to forced convection
m''_{ice} : Mass flux of liberated oxygen due to solidification
U_∞ : Free flow velocity of water

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EXPERIMENTAL AND MATHEMATICAL ANALYSIS OF PRODUCING CLEAR ICE IN A REFRIGERATOR

SUMMARY

Water is essentail to life and ice - its solid form - is also very useful in our daily lives. The most common reason to use ice is cooling beverages. But the need for ice is not restricted to beverages. In many areas such as cold therapy for pain relief in medical field, keeping the products chilled in supermarkets and fisheries, numerous cooling needs in laboratories or ice sculpting require using ice.

Regular ice looks bubbly and grey, melts faster than clear ice and generally has a flavor. Clear ice melts slower because there is more ice mass in the same volume compared to bubbly ice and also it is less likely to crack and get filled with fluid so it melts slower, it is flavorless because it is pure & air free and finally it has a more aesthetic look.

Production of clear ice is an important goal because of all of these reasons. Another important goal is to produce the ice in a range of duration so that it is practical to use in daily life.

The literature survey provides useful information about the works that has been done Although an important condition to obtain clear ice is using water without impurities it is not the only condition. Even ice that is made out of pure water can end up having a bubbly look. The literature survey points to the physical phenomenon of gas liberation during solidification and accumulation of the dissolved gases as the root cause of bubble formation in ice. In order to produce clear and transparent ice this gas liberation and accumulation process should be manupilated. So the main idea behind obtaining clear, bubble free ice is preventing the accumulation of aqueous gas. Both the experimental and the numerical works in the literature mention that although the nature of bubble formation is stochastic to some degree it is possible to produce bubble free ice if the solidification process happens under certain conditions.

In the patent search several ice machine and ice apparatus designs in the patent database about producing clear ice were mentioned. The methods used in these designs include slow unidirectional cooling, the circulation of water while freezing and vibrating the ice mold while freezing. The common aspect of these methods is to prevent the gas accumulation close to the solidification front. Summaries of such designs have been mentioned at the end of the literature search.

In the theoretical calculations section the simultaneous water flow and freezing process was analyzed in termes of solute accumulation. It is assumed that in order to produce clear ice the convection mass transfer done by the water flow should be equal to the mass transfer done by the gas liberation from the solidification front. This assumption is used to calculate the minimum water flow velocity needed to produce clear ice at a freezing speed that is in the range of commercial ice machines.

An experimental setup resembling the ice mold geometry and water flow system of commercial ice machines is built. 38 parametric experiments are done in order to understand the role of 5 different parameters: the water flow rate, number of water distribution holes, evaporator plate angle, evaporator temperature and ice mold depth. A quantification scheme was used to turn visual results into numerical data.

The output data is analyzed using the Minitab software. Some cross relations between the effects of input parameters are observed and discussed. The best and worst cases in the parametric experiments are repeated using water with food dye E129.

The experimental results are in agreement with the literature survey. Prevention of solute accumulation homogeneously on the cold plate can be achieved first by sustaining a flow of water that covers the whole cold plate surface. This includes the effects of water flow rate, evaporator angle, number of header holes and the type of ice mold. When the effects of higher flow rate, a tilted cold plate surface and higher number of header holes are combined a steady flow of water film over the cold surface can be achieved. The shallow ice mold also makes it easier for the flowing water to cover the whole surface of the cold plate. Increasing the evaporation temperature also has a role in the clear ice formation but the benefits in transparency and losses in average unit time for ice production should be well balanced.
The response optimizer tool of the Minitab software is used to get the optimized input values to get the overall best results in terms of both transparency and average unit time.

The experimental setup is built, all of the experiments and analyses are done in the Central R&D Department of ARÇELİK AŞ.

BUZ DOLABINDA SAYDAM BUZ OLUŞTURULMASININ DENEYSEL VE MATEMATİKSEL OLARAK İNCELENMESİ

ÖZET

Su yaşam için vazgeçilmezdir ve aynı şekilde buz da - suyun katı hali - günlük hayatta bizim için oldukça gereklidir. Buzun en sık rastlanan kullanımı içeceklerin soğutulmasıdır. Bununla birlikte buz tüketimi yalnızca içecek soğutma ile sınırlı değildir. Tıpta ağrıları dindirme amaçlı soğuk tedavisinden, süpermarket ve manavlarda ürünleri taze tutmaya, laboratuvarlardaki sayısız soğutma uygulamasından buz heykelciliğinie kadar birçok alanda buz kullanımına ihtiyaç vardır.

Sıradan buz kabarcıklı ve gri bir görünüme sahiptir, saydam buzdan daha hızlı erir ve genellikle donma sırasında bulunduğu ortamın havasını barındırdığı için belli bir tadı ve kokusu vardır. Saydam buzda ise kabarcıklı buza göre aynı hacim içinde daha fazla buz kütlesi mevcuttur ve erime sırasında çatlayıp arasına sıvı dolma ihtimali daha azdır dolayısıyla saydam buz saydam olmayan normal buza göre daha yavaş erir. Saydam buz kokusuzdur çünkü içinde hava barındırmaz. Son olarak ise şeffaf olduğu için daha estetik bir görünüme sahiptir.

Bütün bu sebeplerden dolayı buzdolabında saydam buz üretimi önemli bir hedeftir. Diğer bir önemli hedef ise günlük kullanımda faydalı olması için buzu makul sürelerde üretebilmektir. Bu tez çalışmasının amacı buzdolabında 30dk'nın altında 300gr saydam buz üreten özel bir bölme tasarımı için gerekli verileri sağlamaktır.

Tezin giriş kısmında suyun donması sırasında oluşan kristal yapı özetlenmiştir. Buz yapım süreci anlatılmış ve piyasada yaygın olarak bulunan saydam buz üreten ticari buz makinalarının yapısından da kısaca bahsedilmiştir.

Literatür taraması kısmında buzda kabarcık oluşumunun altında yatan fiziksel süreçler araştırılmıştır. Buna göre saydam buzun oluşabilmesi için yabancı madde barındırmayan su kullanmak önemli bir şart olsa da tek koşul bu değildir. Saf sudan elde edilen buz bile donma sürecine müdahele edilmemişse - yani derin dondurucuda sıradan bir buz kalıbında donmaya bırakılmışsa - kabarcıklı bir görünüme sahip olacaktır. Literatür taraması kristalleşme sürecinde çözünmüş gazların katının içinden sıvıya doğru kaçmasının ve katı-sıvı donma arayüzüne yakın bölgede çözelti birikmesinin buzda kabarcık oluşumunun temel sebebi olduğuna işaret etmektedir. Saydam buz elde etmek için bu çözelti salınımı ve birikimi sürecinin iyi anlaşılması ve sürece müdahele edilmesi gerekmektedir. Yani saydam buz elde etmek için yapılması gereken çözünmüş gazların katı yüzey yakınında birikmesini engellemektir. Literatürdeki hem deneysel hem de sayısal çalışmalar kabarcık oluşumunun bir ölçüde olasılıksal bir doğası olduğunu belirtse de donma süreci belli şartlar altında gerçekleşirse kabarcık oluşumunu engelleyip saydam buz elde etmek mümkündür. Temel hedef çözelti birikimini engellemek olmalıdır.

Tezin patent incelemesi kısmında çeşitli buz makinası ve buz kalıbı/aparatı tasarımları anlatılmıştır. Bu tasarımlarda kullanılan yöntemler yavaş ve tek yönlü soğutma, donma sırasında eşzamanlı su sirkülasyonu ve donma sırasında buz kalıbının titreştirilmesini kapsamaktadır. Bahsedilen yöntemlerin ortak noktası donma yüzeyi yakınında çözelti birikimini engellemektir. İlk iki yönteme dayalı ticari ürünler bulunmakla beraber titreşim yöntemi ile çalışan bir ticari ürüne rastlanmamıştır. Patent incelemeleri literatür taraması kısmının sonuna eklenmiştir.

Teorik hesaplama kısmının ilk yarısında literatürden elde edilmiş olan durgun suyun donması sırasındaki gaz salınımının ifade eden bir boyutlu çözelti geçişi denklemi ve bu denklemin sabit donma hızı durumundaki analitik çözümü kullanılmıştır. Makaledeki boyutsuz çözümde gerekli fiziksel değerler yerlerine konarak belli buz büyüklüklerinde saydam buz elde edebilmek için gereken donma hızları elde edilmiştir. Teorik hesaplama kısmının ikinci yarısında ise akış sırasında donma sürecinin çözelti birikimi açısından incelemesi yapılmıştır. Saydam buz elde edebilmek için akıştan kaynaklanan taşınımla kütle geçişinin buzun içinden suya salınan çözelti geçişi ile aynı miktarda olması gerektiği kabul edilmiştir. Bu varsayımdan yola çıkarak ticari buz makinlarındaki mertebelerde bir donma hızında saydam buz elde etmek için gereken su akış hızı hesaplanmıştır.

Deneysel çalışmalar kısmında ticari buz makinalarında kullanılan yöntemler arasında en yaygını olan ve "şelale yöntemi" olarak da adlandırılabilecek olan suyun soğuk bir plaka üzerinden sürekli olarak sirküle edilmesine dayalı bir yöntem izlenmiştir. Deney yapmak için bu yönteme dayalı bir buz makinası prototipi oluşturulmuştur.

Oluşturulan düzenek üzerinde DOE yöntemi ile belirlenmiş bir deney planı doğrultusunda 5 ayrı değişkenin incelendiği 38 parametrik deney gerçekleştirilmiştir. Bu beş değişken sırasıyla şöyledir: akan suyun debisi, suyun yukarıdan aşağıya akıtıldığı deliklerin sayısı, soğuk plakanın yer çekimi vektörüne göre duruş açısı, buharlaştırıcı ısıtıcısı kullanımı ve buz kalıplarının derinliği. Deneylerin çıktısı olarak belirlenmiş değişkenler ise ortalama birim süre ve saydamlıktır. Aslında görsel bir özellik olan saydamlığı sayısal veriye dönüştürmek için bu çalışmaya özgü bir sayısallaştırma yöntemi kullanılmış ve tezin deneysel çalışma kısmında yöntemin ayrıntıları paylaşılmıştır.

Çözelti birikimi ve kabarcıklanma etkisini daha görsel hale getirmek için ilk 19 deneyin arasından saydamlık değeri en iyi ve en kötü sonuç veren sırasıyla 8 ve 15 nolu deneyler içinde gıda boyası E129 (Allura Kırmızısı) çözünmüş olan su ile tekrarlanmıştır. Deneysel çalışmalar kısmındaki fotoğraflardan da anlaşılabileceği gibi arada çok ciddi bir görsel farklılık mevcuttur.

Deney çıktıları Minitab yazılımı kullanılarak analiz edilmiştir. Faktörlerin ana etkileri haricinde bazı ikili etkileşimlerin de sonuçta etkili olduğu görülmüştür. Bu çıktılar yorumlanarak temel saydam buz elde etmek için gereken temel fiziksel şartın başta soğuk yüzey üstünde süreç ilerledikçe de buz yüzeyinin üstünde sürekli ve homojen bir su akışı sağlanması olduğu yorumu yapılmıştır. Bu gözle bakıldığında ikili etkileşimlerin saydamlık üzerindeki etkileri daha iyi anlaşılmaktadır. Bu çıktı literatür taraması ile de uyumludur.

Deney sonuçları literatür taraması ile uyumluluk içindedir. Donma arayüzü yakınında çözelti birikimini buz yüzeyinin tamamında engellemek için öncelikle soğuk yüzeyin tamamını homojen biçimde kaplayacak sürekli bir akış sağlanmalıdır. Buharlaşma sıcaklığını arttırmanın da sonuca ciddi bir etkisi olduğu görülmüştür ancak artan buharlaşma sıcaklığının saydamlığa olan olumlu etkisi ve birim süreye olan olumsuz etkisi iyi bir şekilde dengelenmelidir. Minitab yazılımındaki Tepki Eniyileyicisi (Response Optimizer) aracı kullanılarak deneydeki girdiler en iyi çıktı oluşturacak şekilde düzenlenmiş ve yeni bir buzdolabı saydam buz bölmesinin nasıl olması gerektiği konusunda bir sonuca varılmıştır.

Parametrik deney düzeneği, deneyler ve bütün analiz çalışmaları ARÇELİK AŞ Merkez ARGE Termodinamik Teknoloji Ailesi bünyesinde gerçekleştirilmiştir.

1. INTRODUCTION

Freezing - also named as solidification or crystallization - is the change of matter from liquid phase to solid phase. This happens due to the loss of latent heat and formation of new bonds between liquid molecules which otherwise move freely. These bonded molecules form a crystal structure which keeps nearly no dissolved gas unlike liquids. Due to this fact in some cases the process of crytallization is accompanied by gas segregation at the solidification front [1]. A daily example of this phenomenon is the crytallization of water, where the gas segregation happens with dissolved air and air bubbles are observed in the ice. The formation and entrapment of air bubbles in solidified water causes the ice to be opaque, easy to melt and mechanically weak. The same is true for other materials such as metals or optical crystals. Reduction in mechanical strength due to bubbles is a fundamental problem that is faced in casting processes [2]. Whereas the loss in the electrical properties due to bubble entrapment during the manufacturing process of semiconductor crystals is an important problem and the root cause is the same with the bubble formation in ice [3].

1.1 Purpose and Motivation of Thesis

The purpose of this thesis is to investigate the bubble formation during solidification of water and use this knowledge in the design of an ice making compartment in a refrigerator that produces clear, bubble free ice. The main motivation behind this work is to satisfy the need for clear/transparent ice in the appliances market - especially in the US market. Clear ice is already served in bars and restaurants mostly with alcoholic beverages. The new aspect in this work is the analysis of the physics behind the clear ice formation and the implementation of the findings in a home type refrigerator.

1.2 Properties of Ice

Water turns into ice when it is cooled below temperatures of 273K under room conditions. During this process the quadrilateral crystal structure of water changes into hexagonal crystal structure. Ice has a structure with more gaps in between molecules compared to water because of this hexagonal crystal structure. Ice floats on water because of this irregular property.

At different pressure and temperature conditions ice has different crystal structures. In our daily life and in nature the most common form of ice is "Ice Ih" (Hexagonal Ice) as it can be seen on Figure 1.1 since it is the type of ice that is produced in the pressure values lower than 10^8 Pa and temperature values higher than 80 K.

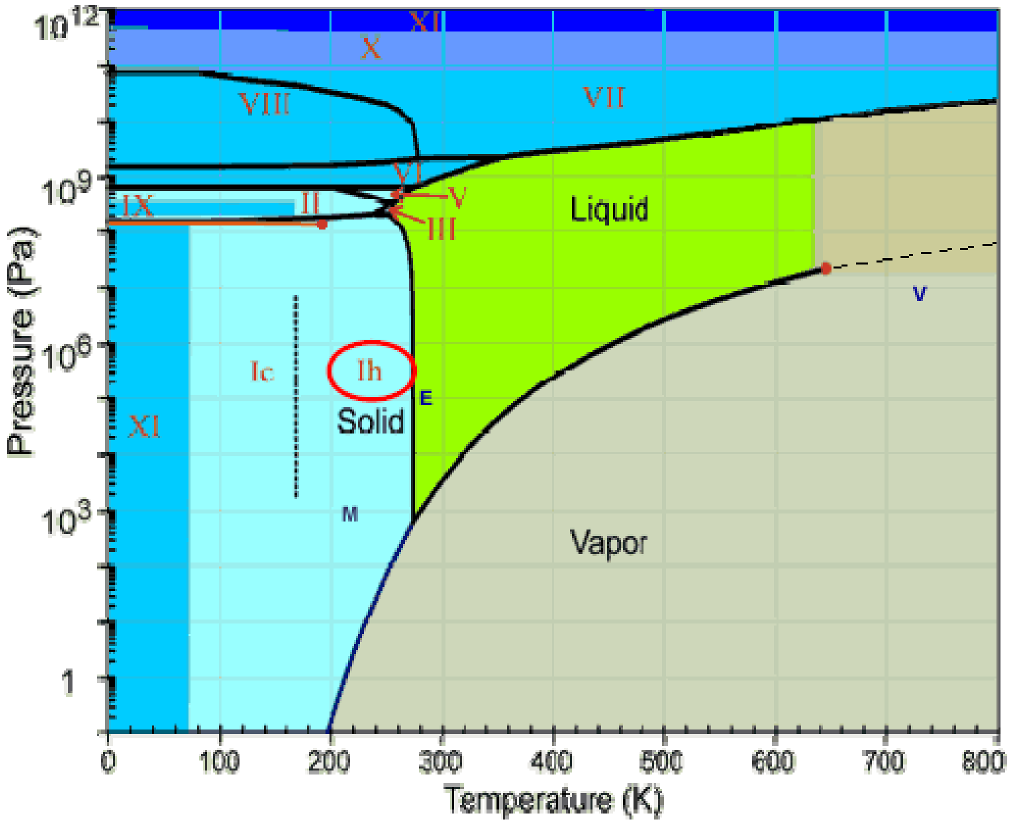

Figure 1.1 : Phase diagram of ice.

1.3 Commercial Ice Machines That Produce Clear Ice

Two different types of commerical clear ice machine designs are explained in this section. The refrigeration cycles of both designs are the same. The difference between the designs are about the water circulation systems and the geometries of the cold surfaces.

1.3.1 Cold Plate Chilling Type Ice Machines

The most common type of commercial ice machines in the market are cold plate chilling type ice machines.In this design water is circulated on the surface of a vertical cold plate directly attached to the evaporator. The water pump is placed in the water reservoir which is under the cold plate. Water is pumped from the reservoir up to the header. Header is the plastic part at the top of the water distribution system.

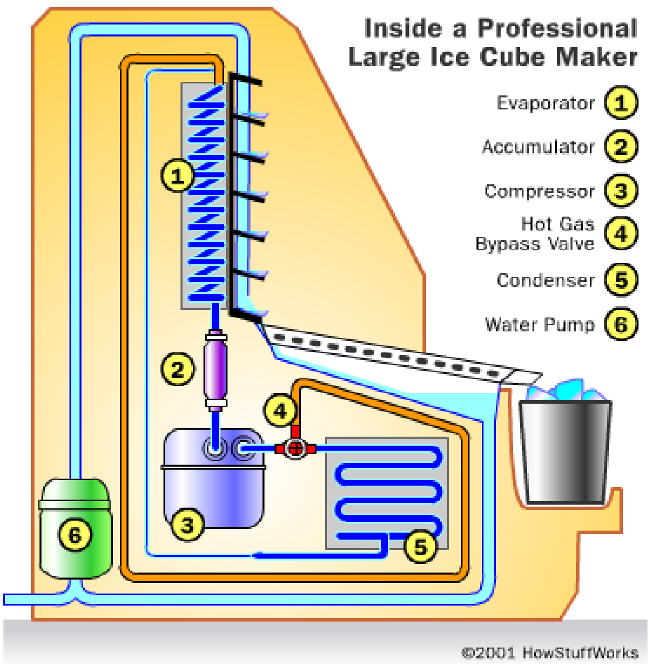

Figure 1.2 : Commercial ice machine (left) components of a cold plate chilling type commercial ice machine (right) [4].

Water is distributed through the holes under the header and falls on the cold plate. The pump in the water tank is used to send water up to the header and then water falls on the cold plate traveling in and out of the ice mold cells. The cold plate is kept under 0°C when the system is working. Therefore ice accumulates on the cold plate surface as the water keeps flowing. Keeping this flow of water during ice accumulation is the key aspect of this design.

The decision to finish the ice making process is made either by measuring ice thickness or the evaporation temperature. Evaporation temperature decreases when the evaporator gets covered with more and more ice so a lower limit to the evaporation temperature can be set to finish the ice making proess. Thickness meaasurement on the other hand, is measured with a probe that is placed in front of the cold plate surface. When the ice layer thickness becomes large enough water film on the ice touches the

Figure 1.3 : Cold plate having cube shaped cells directly attached to the evaporator.

probe, closes the circuit and the signal for finishing the process is received. Both methods are already used in the products.

When the decision to finish the ice making process is made the compressor and the pump are turned off. The cold plate is heated to remove the ice from the surface. This process is called harvesting the ice. Commercial ice machines use a method called hot-gas in order to heat the evaporator and harvest the ice. Hot-gas method is basically bypassing the condenser of the refrigeration system by using a valve placed at the exit of the compressor and connecting the compressor directly to the evaporator. When the system works in this configuration evaporator is heated not cooled. Therefore the ice cubes seperate from the plate surface, fall down from the ice cells on the cold plate and the ice production is finished.

1.3.2 Spray Type Commercial Ice Machines

This type of ice machines are comprised of nozzles that spray pressurized water up to the cooled metal cells at the ceiling. The metal cells are directly attached to the evaporator and they are cooled by the refrigerant. The ice cells are kept under 0°C when the system is working just like in the previous system.

The difference between the cold plate chilling type and spray type ice machines is that in the second design the water flow is directly from the nozzles to the cold surface at the ceiling of the cabin. This requires a higher capacity pump than the cold plate chilling type system

This upside design has one advantage and one disadvantage compared to the previous design. The advantage is that harvesting the ice is easier because of the upside orientation. The disadvantage however is the need for a larger pump capacity since there has to be enough water flow rate to cover the cooled surfaces at the ceiling. As in the first design keeping this steady flow of water during ice accumulation is the key aspect of this design.

The harvest process is done utilizing the same hot-gas method used in the cold plate type ice machines. The condenser is by-passed and gas with high temperature and pressure is sent directly to the evaporator which heats the plate surface. As a result ice cubes are seperated from the metal surface.

Figure 1.4 : Nozzles of a spray type commercial ice machine.

2. LITERATURE SURVEY AND PATENT REVIEW

The literature and patent review of this thesis work covers the following items:

- Literature survey on the physical mechanism of solute accumulation and bubble formation during freezing.
- Literature survey on the numerical modelling on the subject of bubble formation during solidification.
- Patent review on ice machines in general and clear ice machines in particular.

As it can be understood from the subjects listed above bubble formation during ice formation is a subject that has been studied extensively before - both experimentally and numerically. Additionally there are various ice machines having alternative designs in the market that produce clear ice. Different machines have different clear ice producing techniques, daily capacities and ice geometries.

2.1 Solute Accumulation and Bubble Formation During Solidification

Solidification means the formation of a crystal structure by molecules that do not have an ordered structure in their liquid form. Freezing of water is the most common example of this phenomenon. Water molecules form a crystal – or lattice structure - during the formation of ice. This lattice structure keeps nearly no dissolved gas in itself therefore the air that is normally dissolved in water is pushed out of the newly formed ice crystals during solidification. The air that is pushed out of the ice accumulates at the vicinity the solid-liquid interface. Accumulation of dissolved air above a certain concentration leads to the formation of air bubbles at the solid-liquid interface. In the paper “Air Bubble Formation In Ice Crystals” by Meano et al [5], it is stated that bubbles are trapped in the ice if the solidification rate is high and they freely rise to the surface if the solidification rate is low. Therefore the ice would be clear or cloudy/bubbly depending on the solidification rate. But recent literature states that this explanation is only partially true [6].

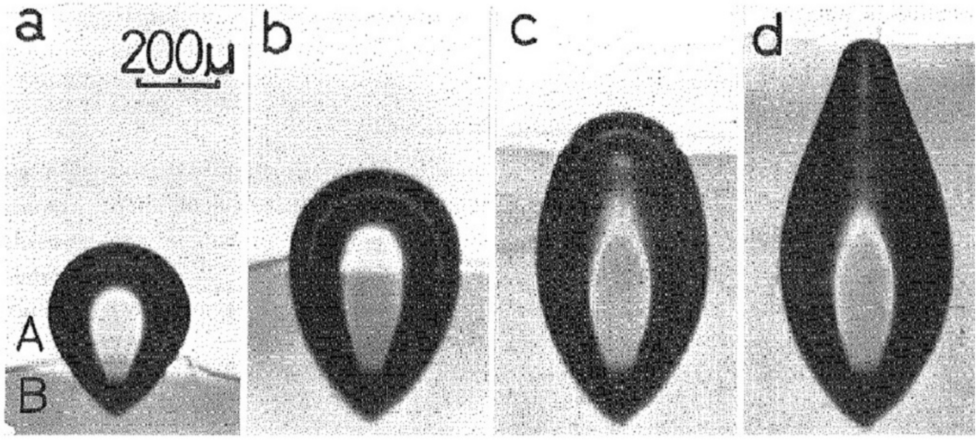

Figure 2.1 : Entrapment of an air bubble during unidirectional solidification of stagnant water [5].

In the paper “Pore Shape Development From A Bubble Captured By A Solidification Front” by Wei et al [6] it is stated that the explanation in [5] is missing a crucial point. Once an air bubble is formed on the solid-liquid interface, it sticks on the ice surface independent of the solidification rate. That being said the solidification rate affects the shape of the bubble. In the high solidification rate situation the bubbles get covered with ice faster so they cannot suck the dissolved air around and stay small. Whereas in the low solidification rate situation there is more time for bubbles to suck the dissolved air from the surrounding water and expand. When the solidification rate is lowered even more the diffusion is enough to prevent the accumulation of liberated air into the bulk water and therefore supersaturation never happens.

In the paper by Fedorchenko et al “Exact solution of the problem of gas segregation in the process of crystallization” the gas segregation is modeled as a 1-D boundary-value problem [1]. The convection term is neglected therefore in the unidirectional solidification the equation reduces to unsteady diffusion equation. It is solved analytically for the simple case of unidirectional flat solidification front with constant solification rate.

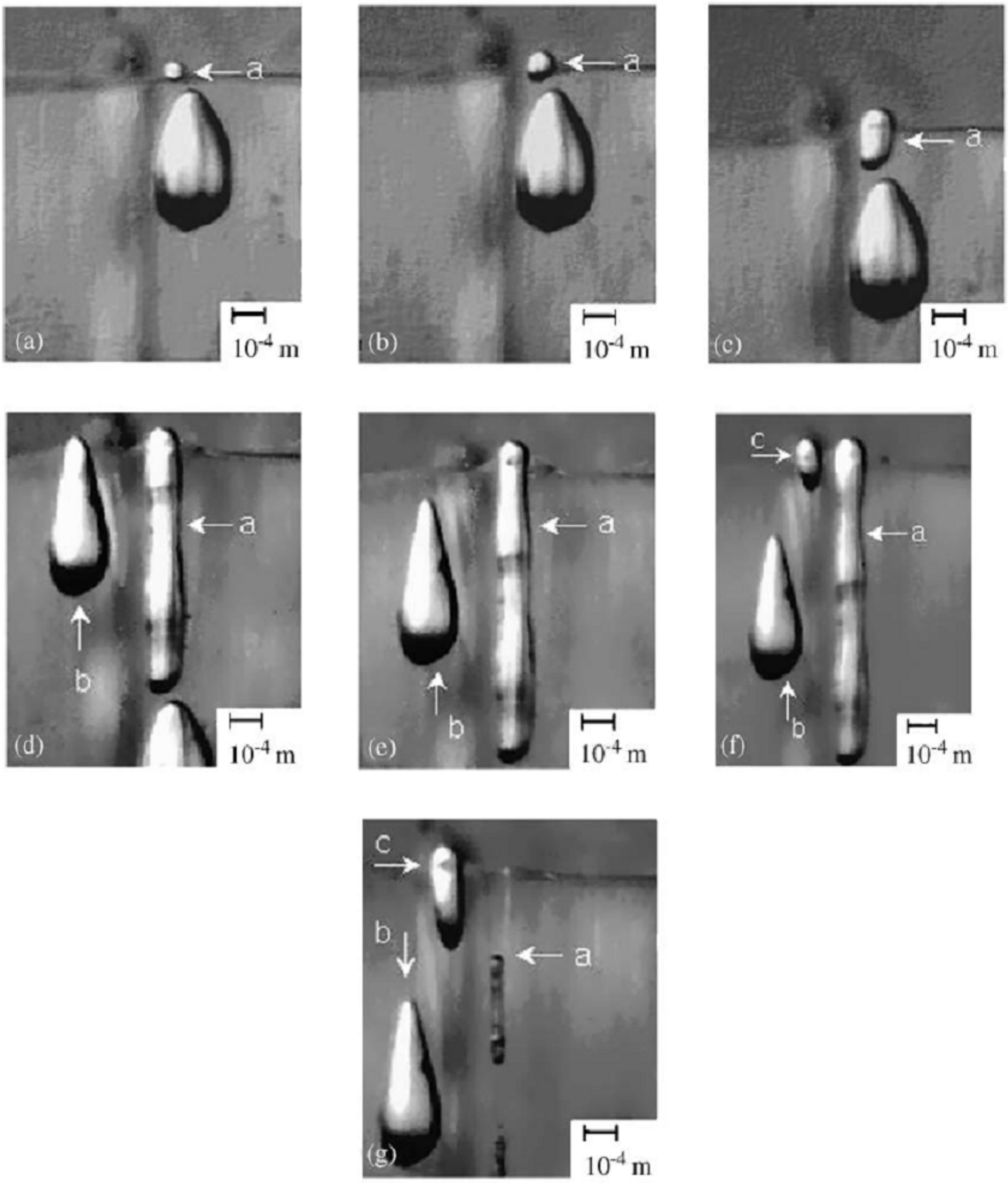

Figure 2.2 : Nucleation, growth and disapperance of several different bubbles. [7]

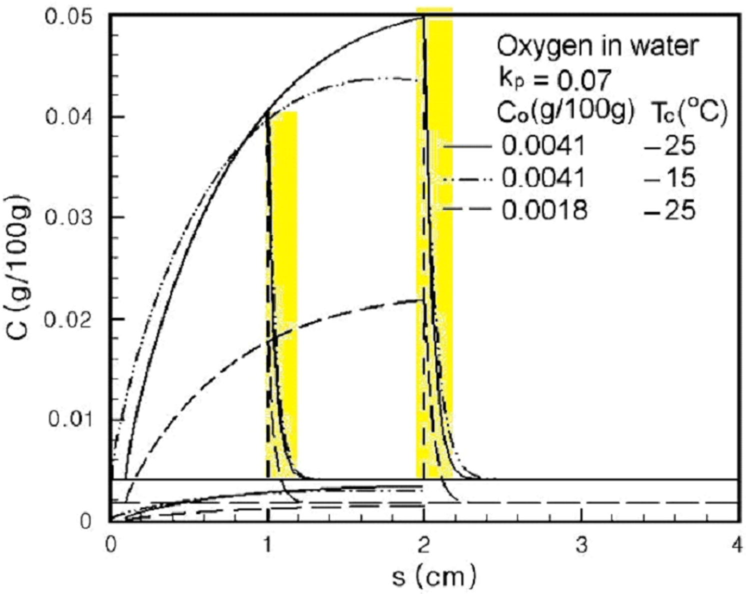

Figure 2.3 : The predicted concentration distribution of oxygen dissolved in water during unidirectional solidification of stagnant water. The 1mm vicinity of solification fronts are shaded in yellow. [7]

2.2 Numerical Modeling of Bubble Formation

There are a few different approaches to the modelling of bubble formation during solidification. [8]

In the paper "Visual Simulation of Freezing Ice with Air Bubbles" by Nishino et al [8] a simulation code based on the solution of heat transfer equation, tracking of the solidification front and modelling of the bubble formation has been described. The whole physical process has been divided into two parts: freezing and bubble formation.

Convection heat transfer was neglected during the freezing calculations which makes the process simpler and faster. The local velocity vector of the solidification front (v) has been calculated using the normal vector of the interface (n), temperature gradient (∇ T),latent heat of water (L), density of water (ρ) and thermal conductivity of water (K_{ice}) :

$$v = \frac{K_{ice}}{L\rho}(\nabla T.n)n \tag{2.1}$$

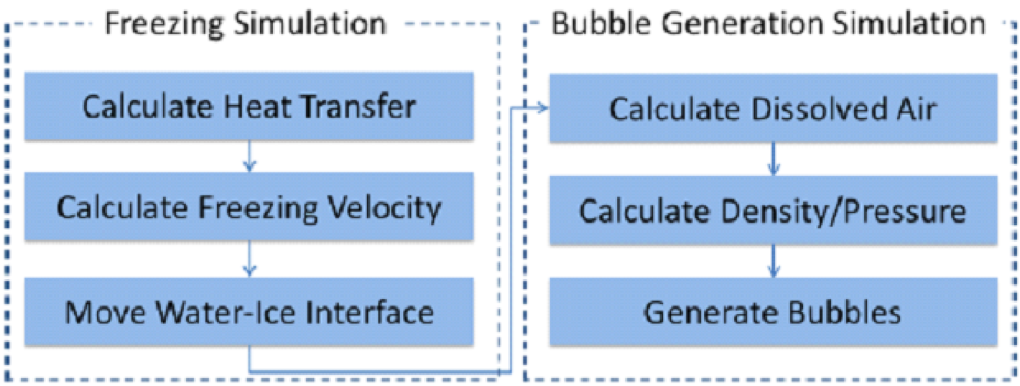

Figure 2.4 : The flowchart of the simulation code. (Nishino 2012) [8]

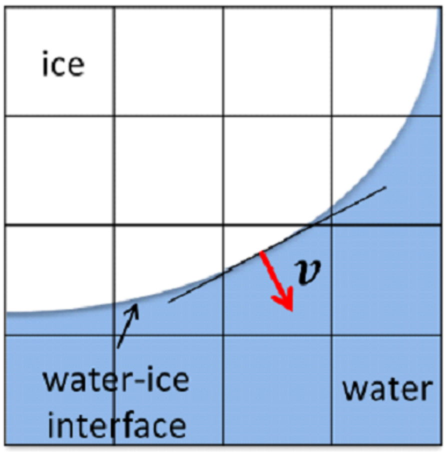

Figure 2.5 : Normal vector of solid-liquid interface. (Nishino 2012) [8]

In the second phase of the simulation the displacement of the dissolved air is calculated. Due to the freezing process air at each newly solidified cell is distributed evenly to the neighbouring liquid cells.

In the paper “A mathematical model for atmospheric ice accretion and water flow on a cold surface” by Myers et al a correlation based method is used for determining the structure of the ice that is accumulated on an aircraft wing. The main purpose is to model the ice accumulation on the aircraft wing since ice accumulation is an important problem in aviation. Accumulation of clear ice is an even bigger problem than the accumulation of cloudy ice since clear ice is mechanically stronger. The solidification of the collected water droplets on the wing is modeled with the assumption that the incoming water particles are subcooled. So the convection heat transfer is not calculated. This simplifies the procedure significantly because the determination of the heat transfer coefficient with a changing geometry is a very complex task.

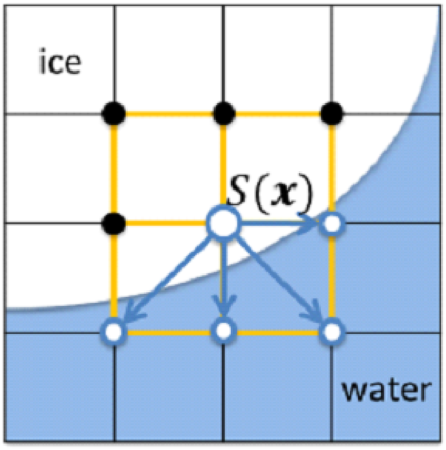

Figure 2.6 : Distribution of dissolved air from solidified cells to neighbouring fluid cells. (Nishino 2012) [8]

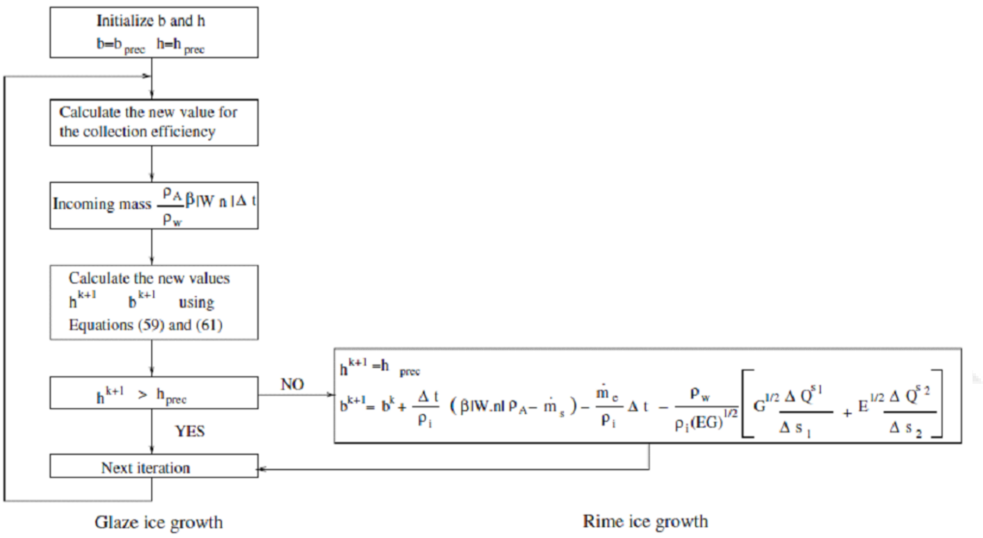

Figure 2.7 : The flowchart of the algortithm described in (Myers 2014) [7]

2.3 Patent Review

2.3.1 Clear Ice Spheres

Patent No : US 9074803 (B2)

Date of Patent : 2015-07-17

Inventor : CULLEY BRIAN K (US)

Applicant : WHIRLPOOL CO (US)

The patent is about a spherical ice mold that is made up of two seperate parts and the technique to produce ice spheres using this aparatus. The aparatus is used in the closed position by circulating water inside. One of the mold parts is also cooled during the circulation. This leads to the freezing of water while its moving. Since this process happens inside a spherically shaped mold the ice is formed with the shape of the mold. Basically this method can be described as “fractional freezing used for producing spherical ice”. Simultaneous circulation and solidification of water causes a velocity gradient on the solidification surface and prevents solute accumulation. Therefore the produced ice is free of bubbles.

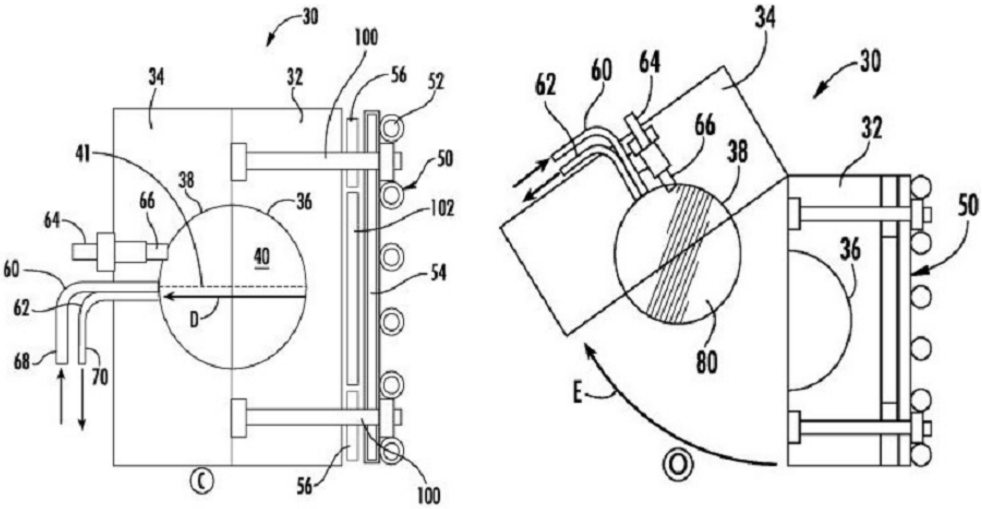

Figure 2.8 : The closed and open forms of the spherical ice mold.

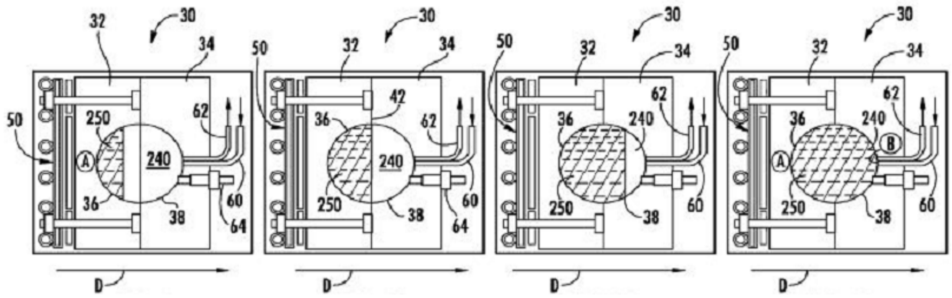

Figure 2.9 : Water keeps circulationg inside the mold while solidification front advances.

2.3.2 Device and Method for Producing Clear Ice Spheres

Patent No : US 20150027142 (A1)

Date of Publication : 2015-01-29

Inventor : LITTLE CHRISTOPHER W, LITTLE PATRICK W (US)

Applicant : LITTLE CHRISTOPHER W, LITTLE PATRICK W (US)

The patent is about an insulated ice mold that is used for The mold is designed to insulate the siddes of water and let only the upper part of water be exposed to cold air. This causes the water inside the mold to freeze in one direction: from top to bottom. Especially after the formation of a thin layer of ice at the top the solidification rate would decrease significantly and the overall solidification process will happen very slowly . This will give enough time to the liberated dissolved air at the solidification front to diffuse into the bulk water mass. As a result clear ice having a shape of the mold will be prodcued.

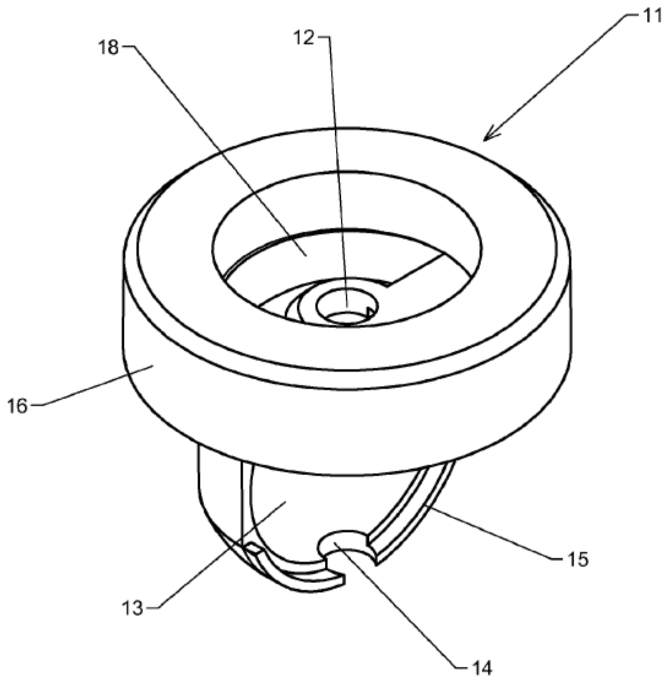

Figure 2.10 : The upper half of the silicon mold to cover the water.

3. THEORETICAL CALCULATIONS

As it can be understood from the literature review a fast and effective way of producing clear ice would be to prevent solute accumulation at the vicinity of the solidification line between ice and water. A 1D nondimensional analytical solution of the unsteady diffusion equation for the constant solidification velocity case is given in ref [1].

3.1 Solidification of A Stagnant Fluid

The distribution of gas concentration can be modeled with the 1D diffusion equation [1]:

$$\frac{\partial C}{\partial t} = D\frac{1}{x}\frac{\partial}{\partial x}(x\frac{\partial C}{\partial x}) \tag{3.1}$$

with the following initial and boundary conditions:

$$\begin{aligned} C &= C_o \text{ for } t = 0, \\ -D\frac{\partial C}{\partial t} &= V(C - C_o) \text{ for } x = X, \\ C &\to C_o \text{ for } x \to \infty. \end{aligned} \tag{3.2}$$

where X is the position of the solidification front. The open form of equation 3.1 is :

$$\frac{\partial C}{\partial t} = D(\frac{\partial^2 C}{\partial x^2} + \frac{1}{x}\frac{\partial C}{\partial x}) \tag{3.3}$$

which can be solved with the implicit finite difference method.

3.2 Solidification of A Moving Fluid

In the case of solidification of a moving fluid the minimum fluid velocity is calculated. The minimum flow velocity is defined as : minimum free flow velocity U_∞ that is enough to sweep the liberated gas from the ice and prevent gas accumulation to reach the saturation concentration. The aim of this calculation is to have an idea about the flow velocities at the vicinity of the solidification front needed to have a clear ice.

The physical properties of water at 0 °C:

$$\alpha_{H2O} = 1,33x10^{-7} m^2/s$$
$$\nu_{H2O} = 1,79x10^{-6} m^2/s$$
$$k_{H2O} = 5,61x10^{-1} W/m.K \tag{3.4}$$
$$\rho_{H2O} = 1000 kg/m^3$$
$$Pr_{H2O} = 13,4$$

Water-oxygen mass diffusion coefficient at 0 °C:

$$D_{AB} = 1,97x10^{-9} m^2/s \tag{3.5}$$

Initial and saturation oxygen concentrations in water at 0 °C:

$$C_o = 4,1x10^{-5} g/g$$
$$C_{max} = 6,65x10^{-5} g/g \tag{3.6}$$

Assumptions of the calculation - the velocity of the freezing surface and the characteristic length of the flow:

$$U_{ice} = 1mm/min = 1,67x10^{-5} m/s$$
$$L_{char} = 2cm = 2x10^{-2} m \tag{3.7}$$

Note that U_{ice} can be interpreted as the velocity of the solid surface perpendicular to the water flow. If there were not any flow, U_{ice} would be the ice surface velocity with respect to stagnant water.

Definitions of dimensionless numbers are taken from reference [9]. The definition of Nusselt number eq (3.8c) is done assuming a flow over a flat plate:

$$Le = \frac{\alpha_{H2O}}{D_{AB}} = \frac{1,33x10^{-7}}{1,97x10^{-9}} = 6,75x10^1 \tag{3.8a}$$
$$Re = \frac{U_\infty L_{char}}{\nu_{H2O}} \tag{3.8b}$$
$$Nu = 0,664 Re^{\frac{1}{2}} Pr^{\frac{1}{3}} \tag{3.8c}$$
$$h_T = \frac{Nu k_{H2O}}{L_{char}} \tag{3.8d}$$
$$h_m = \frac{h_T}{k_{H2O}} D_{AB} Le^{\frac{1}{3}} \tag{3.8e}$$
$$\tag{3.8f}$$

The convection mass transfer between the vicinity of the solidification front and the free flow should be equal to the mass transfer of solute liberated from the ice. Therefore condition for producing clear ice can be expressed as:

$$m''_{sweep} = m''_{ice} \tag{3.9}$$

The minimum free flow velocity U_∞ needed to produce clear ice can be found by calculating the mass flux liberated from the ice surface during solidification at a certain freezing velocity:

$$\begin{aligned} m''_{ice} &= (C_{max} - C_o)U_{ice}\rho_{H2O} \\ &= (6,65x10^{-5} - 4,1x10^{-5})x1,67x10^{-5}x1000 = 4,25x10^{-7}kg/m^2s \end{aligned} \tag{3.10}$$

and then suing eq 3.9. Then the mass flux of the solute that sweeped off from the solidification front can be calculated as:

$$m''_{sweep} = (C_{max} - C_o)\rho_{H2O}h_m \tag{3.11}$$

Therefore combining eq 3.9, eq 3.10 and eq 3.11 we can get the following equation:

$$h_m = \frac{m''_{ice}}{(C_{max} - C_o)\rho_{H2O}} = 1,67x10^{-5}m/s \tag{3.12}$$

Using the results found in eq 3.8 and eq 3.12:

$$h_T = \frac{h_m k_{H2O}}{D_{AB}Le^{\frac{1}{3}}} = \frac{1,67x10^{-5}x5,61x10^{-1}}{1,97x10^{-9}x67,5^{\frac{1}{3}}} = 1,17x10^3W/m^2s \tag{3.13}$$

Using the previous results :

$$Nu = \frac{h_T L_{char}}{k_{H2O}} = \frac{1,17x10^3x2x10^{-2}}{5,61x10^{-1}} = 41,5 \tag{3.14}$$

Obtaining the minimum Re required for producing clear ice:

$$Re = (\frac{Nu}{0,664Pr^{\frac{1}{3}}})^2 = (\frac{41,5}{0,664x13,4^{\frac{1}{3}}})^2 = 693 \tag{3.15}$$

The minimum U_∞ required for producing clear ice can now be obtained:

$$U_\infty = \frac{Re\nu_{H2O}}{L_{char}} = \frac{693x1,79x10^{-6}}{0,02} = 5,79x10^{-2}m/s \tag{3.16}$$

which is approximately 6 cm/s. This means under the assumption of freezing during flow on a cold plate the minimum freestream velocity required for producing clear ice at a freezing speed of 1mm/min is nearly 6cm/s.

4. EXPERIMENTAL SETUP & PARAMETRIC EXPERIMENTS

4.1 Experimental Setup & Procedure

An experimental setup resembling the cold plate chilling type commercial ice machines is built. Preliminary experiments are performed and as a result 5 input parameters are decided to be included in the experiments as it can be seen on Table 4.1. 2 output variables are used as experimental results : average unit time for producing unit mass of ice and % transparency. The details about quanitification of transparency are described in section 4.1.2. The measurement uncertainity and gage R&R studies are performed before creating the using the DOE method for planning the parametric experiments. 38 parametric experiments are performed according to this plan and the results are analyzed again with the Minitab software.

Figure 4.1 : The undercounter type refrigerator that was used as the cabin for the ice making device.

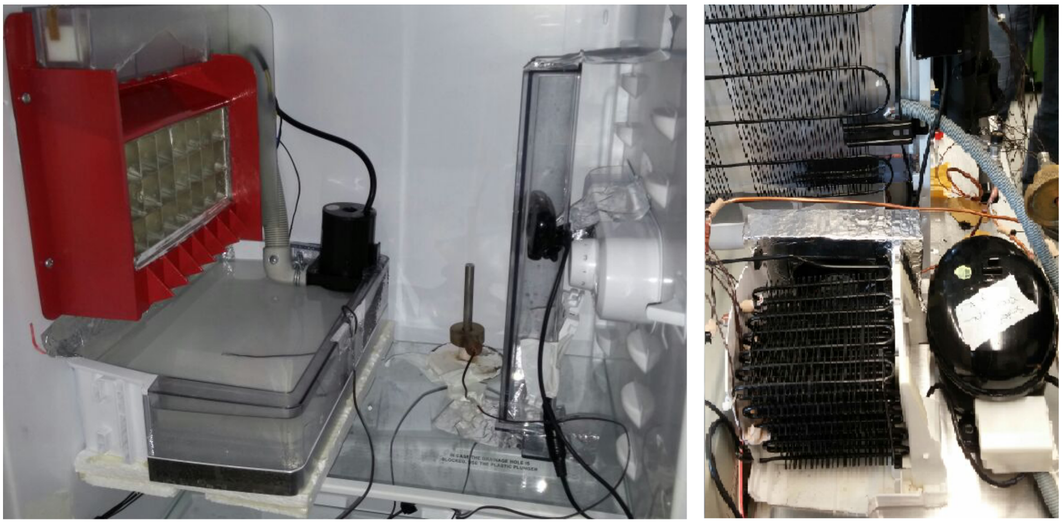

Figure 4.2 : The water distribution system and the cold plate (left). The condensator and compressor of the ice making cycle (right).

4.1.1 Preliminary Experiments and Determination of Factors

Several preliminary experiments are carried out. Using the experience obtained from the preliminary experiments the following properties of the system are set as the experiment factors:

- Water Flow Rate : Water is circulated using a pump. The water circulation can be seen in Figure 4.2. The voltage of the pump is changed to supply the system with two different flow rates.
- Evaporator Angle : When the cold plate attached to the evaporator stands upright and when it is positioned with a certain angle to the gravity vector the flow of water is affected by this difference. Sustaining a homogeneous water flow on the cold plate turned out to be very important in the preliminary experiments. That is the reason the angle between the back wall of the cold plate and the gravity direction is taken as a factor.
- Number of Header Holes : Header is the plastic part at the top of the water distribution system. Water is distributed through the holes under the header and falls on the cold plate. During the preliminary experiments the number of holes on the header was observed to affect the water flow on the cold plate. Thus it is included as a factor independent of water flow rate. The header part is modular and it can changed at every experiment according to the experiment plan.

- Heater Set Temperature : The 100W cable type heater that is normally used for harvesting the ice cubes is set to two different temperatures while producing ice. In the preliminary experiments it is observed that turning the heater on during the ice production has a positive effect on the visual quality of the ice cubes although it has an adverse effect on the average unit time. A proper optimization should be done so heater set temperature is taken as one of the factors.
- Ice Mold : Two type of ice molds are used in the experiments. Their cross-sectional areas are equal whereas their depth are not the same. This depth difference affects the water flow on the cold plate so it is included as one of the factors.

Table 4.1 : Table of factors.

Factors	Level - 1	Level - 2
Water Flow Rate [lt/min]	5Q	7Q
Evaporator Angle [°]	0	2α
Number of Header Holes	2H	4H
Heater Set Temperature [°C]	-30	0
Type of Ice Mold	Shallow	Deep

Table 4.2 : Table of outputs.

Outputs
Average Unit Time [s/g]
Transparency [%]

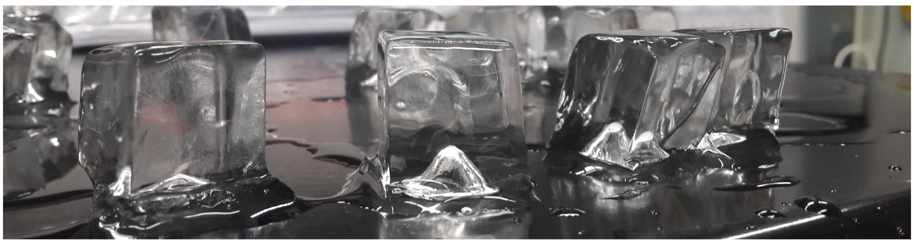

Figure 4.3 : Clear ice cube samples from the preliminary experiments.

4.1.2 Quantifying the Transparency of the Ice

Using the information obtained from the preliminary experiments it is concluded that the defects in the visual quality of the ice includes but are not limited to the opaqueness related to bubble formation. Cracks that form inside the ice cubes and hollowness at the back faces of the ice cubes also spoil the visual quality. Plus there is no straightforward way to measure the transparency of the ice cubes since the surfaces of the ice cubes

Figure 4.4 : A whole 3 by 7 ice block harvested from the cold plate during a preliminary experiment.

are not always planar. Therefore a systematic and repeatable method of quantifying the visual quality of the ice cubes is formed and two operators independently do the measurement using the following criteria:

- Ice cubes that have a hollowness at their back face get a score of 2.
- Ice cubes having a foggy/gray back face get a score of 1.
- Ice cubes having a crack inside get a score of 1.
- Ice cubes having a foggy/gray inside volume get a score of 1.
- Two or more of these criteria may be satisfied simultanesously. In that case the scores are simply added.
- An ice cube that has none of the listed defects gets a score of 0.

Inner parts and back faces of the cubes are observed seperately since on the preliminary experiments it is observed that those two visual results can behave independently. According to these criteria a block of ice having 21 cubes can get a total score of 5 x 21 = 105 in the worst case and 0 at the best case. After the total score of a block is obtained it is normalized using the formula :

$$NormalizedScore = (105 - OriginalScore)\frac{100}{105} \tag{4.1}$$

After the normalization the best case gets a score of 100% and worst case gets a score of 0%. These normalized total scores are used to evaluate the transparency

Figure 4.5 : Back faces of clear ice cube samples that get different scores on the scale. Cube with foggy back face and hollowness gets 3 (left), cube with only foggy back face gets 1 (center), cube with clear back face and clear inside gets 0 (right).

quantitavely. The same two operators performed all the experiments together and did the quantifications at the end of each experiment independently. The calculated score is used as the final % transparency value. The Gage R&R analysis of these measurements are successfully done and the results are discussed in section 4.2.2.

4.2 Measurement Uncertainity Analyses

The parametric experiments are designed to measure two output values: Unit Average Time and Transparency. Calculation of UAT requires measuring two quantitave data: time and mass. Therefore an analytical measurement uncertainity analysis should be done. Whereas transparency calculation requires qualitative measurement of two operators so a gage R&R study should be done before starting the experiments.

4.2.1 Measurement Uncertainity Analysis for Unit Average Time

The calculations for the unit time require the measurement of ice production time using the thermocouple data and the weighing of the ice block removed from the cold surface. The unit time is calculated as:

$$\alpha = \frac{t}{m} \tag{4.2}$$

and the total measurement uncertainity for the unit time α can be calculated as:

$$\omega_\alpha = \sqrt{(\frac{\partial \alpha}{\partial t}\omega_t)^2 + (\frac{\partial \alpha}{\partial m}\omega_m)^2} \tag{4.3}$$

which can be written more explicitly as:

$$\omega_\alpha = \sqrt{(\frac{1}{m}\omega_t)^2 + (\frac{-t}{m^2}\omega_m)^2} \tag{4.4}$$

where $\omega_t = 30s$ and $\omega_m = 0.5gr$ are uncertainities of time and mass measurements respectively. The ω_α value is calculated for each experiment seperately and the uncertainity values are included in Table 4.4 along with other results.

4.2.2 Gage R&R Study for the Measurement of Transparency

Transparency measurements of ice cubes are considered to be destructive testing since ice cubes melt during the measurements. Therefore the reproducibility of the measurements are zero by definiton and Nested Gage R&R approach is chosen to evaluate the validity of the measurement technique. Measurement validity analysis results are given in Figure A.1. Total Gage R&R turned out to be 2,91%. A total Gage R&R value under 30% is considered to be enough to have a valid measurement in industrial applications.

In Figure A.2.a it can be seen that by far the largest contribution to the measurements is from the parts. This is a favorable result since the contribution from repeatibility is very low.

From Figure A.2.b it can be seen that the measurements of similar ice cubes are quite consistent.

In Figure A.2.c both operators stay in between the upper and lower limits.

In Figure A.2.d the measurment averages of the two operators are shown. The line connecting the two average values is nearly horizontal. This can be interpreted as a good consistency between the two operators.

In Figure A.2.e all the parts are outside the band defined by lower and upper limits. This indicates that the ice cubes - or experimental inputs - are quite different than each other and this is a desired situation.

4.3 Full Factorial Design for the Parametric Experiments

The experiment plan is created in the Minitab software using the DOE tools. The full factorial design is chosen in order to have the best results. The Minitab output is as follows:

Factors : 5 (1 qualitative, 4 quantitative)

Base Design : 2^5 –> 32

Runs : 38

Center pts (total) : 6

5 Factors – 2 Levels – 6 Center Points – Full Factorial DOE = 38 Total Experiments

Look at Table 4.3 for the full list of experiments.

4.4 Parametric Experiments & Results

4.4.1 Temperature Distribution Plots

Temperature measurements are done using thermocouples placed at each component of the prototype. Inlet and outlet temperatures of evaporator, condenser, compressor, accumulator in addition to the cabin air and water reservoir temperatures are measured. A thermocouple is placed at the central point of the evaporator. In Figures 4.6 and 4.7 the evaporator, water reservoir and cabin temperatures are plotted.

It should be noted that in Figure 4.6 the temperature disribution in experiment 1 is plotted in which the heater was set to -30 °C. In practice this means the heater is turned off. In Figure 4.7 the temperature disribution in experiment 8 is plotted in which the heater was set to 0 °C. The differences in evaporation temperatures are affected by the heater and in experiment 1 the average evaporation temparature is -18,4 °C whereas in experiment 8 the average evaporation temparature is -10,8 °C. The difference can also be seen on the temperature plots in Fig 4.6 and Fig 4.7.

The cause of the oscillations in the evaporation temperatures are the oscillations in the ambient air temperature which affect the condenser temperatures. It should be noted that the oscillations in the inlet and outlet temperatures are less drastic in experiment 8 compared to experiment 1. The heater stabilizes the temperatures as well as increasing the overall evaporator temperature.

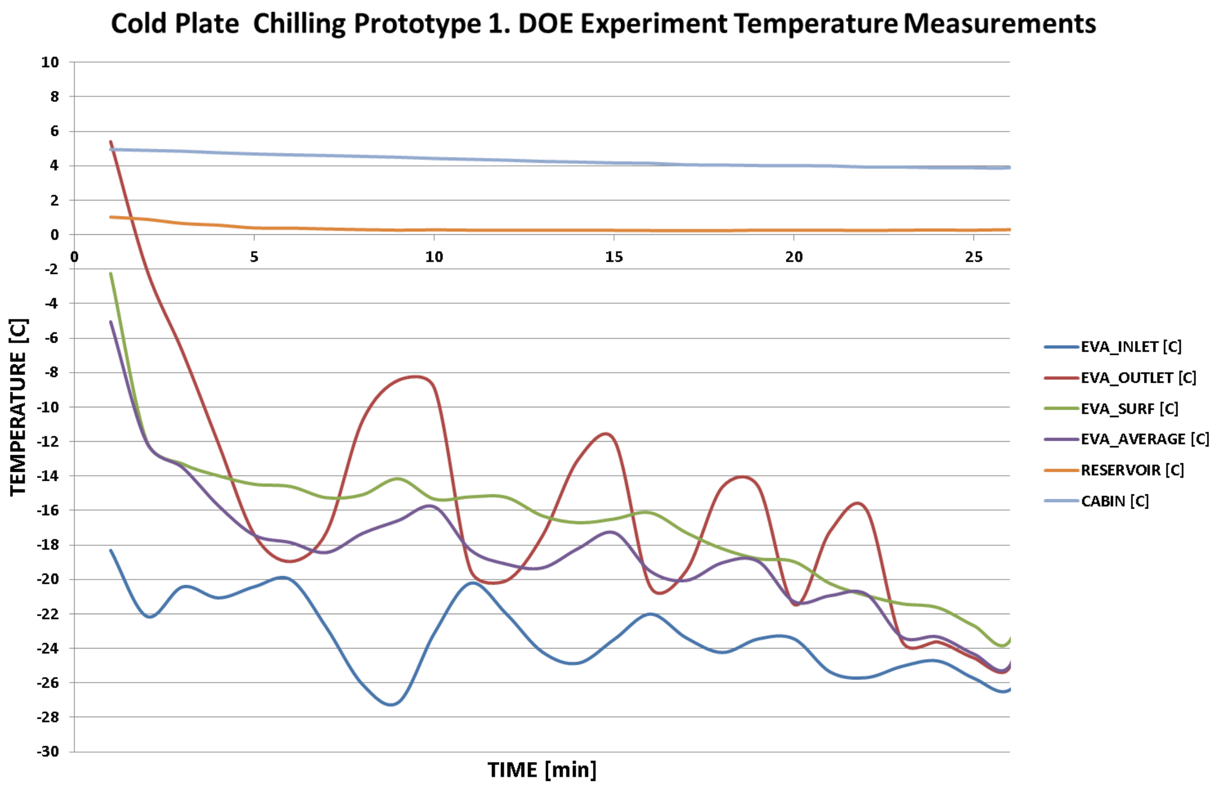

Figure 4.6 : Temperature measurements for experiment 1 obtained from the thermocouple data.

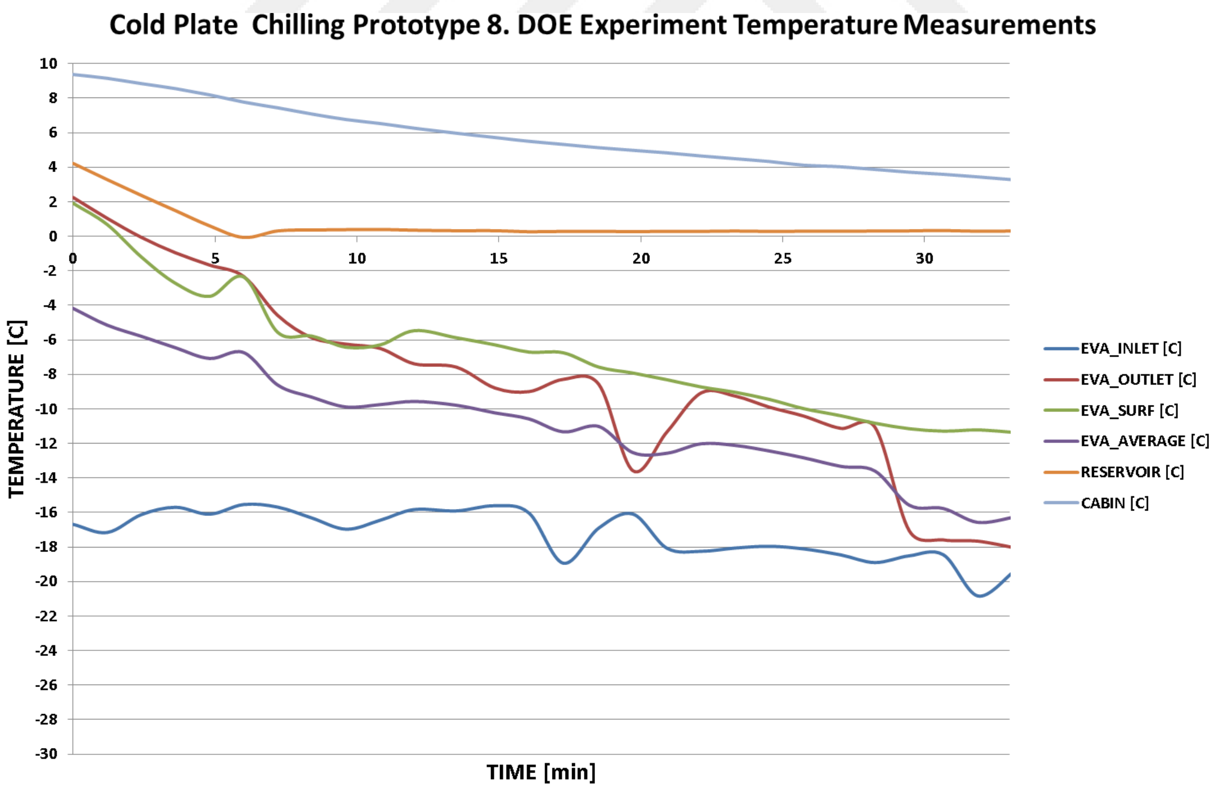

Figure 4.7 : Temperature measurements for experiment 8 obtained from the thermocouple data.

Table 4.3 : List of the inputs of the parametric experiments

Exp No	Ice Mold	Flow Rate [lt/min]	Evap Angle [°]	Header Holes	Heater Set [°C]
1	1	5Q	0	4H	-30
2	1	7Q	0	4H	0
3	1	7Q	2α	4H	-30
4	1	5Q	2α	4H	0
5	1	7Q	0	4H	-30
6	1	5Q	0	4H	0
7	1	5Q	2α	4H	-30
8	1	7Q	2α	4H	0
9	1	7Q	2α	2H	0
10	1	7Q	0	2H	-30
11	1	5Q	0	2H	0
12	1	5Q	2α	2H	-30
13	1	7Q	0	2H	0
14	1	7Q	2α	2H	-30
15	1	5Q	0	2H	-30
16	1	5Q	2α	2H	0
17	1	6Q	α	3H	-15
18	1	6Q	α	3H	-15
19	1	6Q	α	3H	-15
20	2	5Q	0	3H	-30
21	2	7Q	0	4H	0
22	2	7Q	2α	4H	-30
23	2	5Q	2α	4H	0
24	2	7Q	0	4H	-30
25	2	5Q	0	4H	0
26	2	5Q	2α	4H	-30
27	2	7Q	2α	4H	0
28	2	7Q	0	2H	-30
29	2	5Q	0	2H	0
30	2	7Q	2α	2H	0
31	2	5Q	2α	2H	-30
32	2	5Q	0	2H	-30
33	2	7Q	0	2H	0
34	2	5Q	2α	2H	0
35	2	7Q	2α	2H	-30
36	2	6Q	α	3H	-15
37	2	6Q	α	3H	-15
38	2	6Q	α	3H	-15

4.4.2 Final Factorial Fits for Average Unit Time and Transparency

All the 38 experiments are done according to the plan in 4.3. After performing the 38 experiments according to the DOE full factorial design the results were analyzed using the Minitab software. Note that at the beginning all the terms including the inputs, binary combinations of the inputs and ternary combinations of the inputs are listed. The hypothesis criterion is p < 0,05 so only the terms having P values less than 0.05 were left after several rounds of elimination and recalculation. The single input terms are an exception to this rule. The final factorial fits are given here in Figure 4.8 and Figure 4.9.

Estimated Effects and Coefficients for Average Unit Time [s/gr] (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		6,595	0,1859	35,47	0,000
Water Flow Rate [L/min]	-0,944	-0,472	0,1859	-2,54	0,017
Evaporator_Angle	0,183	0,091	0,1859	0,49	0,627
Heater_Set_Temperature_[C]	3,155	1,577	0,1859	8,48	0,000
Number_of_Header_Holes	-0,136	-0,068	0,1859	-0,37	0,718
Ice_Mold	-0,770	-0,385	0,1706	-2,26	0,032
Water Flow Rate [L/min]* Evaporator_Angle	1,308	-0,654	0,1859	-3,52	0,002
Water Flow Rate [L/min]* Number_of_Header_Holes	-1,035	-0,518	0,1859	-2,78	0,010
Heater_Set_Temperature _[C]* Number_of_Header_Holes	0,883	0,442	0,1859	2,37	0,025
Ct Pt		-1,029	0,4680	-2,20	0,036

S = 1,05188 PRESS = 61,8473
R-Sq = 80,35% R-Sq(pred) = 60,76% R-Sq(adj) = 74,03%

Figure 4.8 : Final factorial fit of the Minitab software for Average Unit Time.

Estimated Effects and Coefficients for TRANSPARENCY (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		50,476	1,026	49,19	0,000
Water Flow Rate [L/min]	6,964	3,482	1,118	3,11	0,004
Evaporator_Angle	18,214	9,107	1,118	8,14	0,000
Heater_Set_Temperature_[C]	20,893	10,446	1,118	9,34	0,000
Number_of_Header_Holes	8,274	4,137	1,118	3,70	0,001
Ice_Mold	-13,083	-6,541	1,026	-6,37	0,000
Water Flow Rate [L/min]* Evaporator_Angle	-5,536	-2,768	1,118	-2,48	0,020
Water Flow Rate [L/min]* Number_of_Header_Holes	8,214	4,107	1,118	3,67	0,001
Evaporator_Angle* Ice_Mold	5,893	2,946	1,118	2,63	0,014
Heater_Set_Temperature_[C]* Ice_Mold	6,667	3,333	1,118	2,98	0,006

S = 6,32618 PRESS = 2113,75

R-Sq = 90,04% R-Sq(pred) = 81,21% R-Sq(adj) = 86,83%

Figure 4.9 : Final factorial fit of the Minitab software for the Transparency.

Table 4.4 : List of the results of parametric experiments

Exp No	Normalized Transp. [%]	Exp. Time [min]	Ice Mass [gr]	Unit Time [s/gr]	Unit Time Meas. Uncer. [%]
1	12,4	28	313	5,4	1,8
2	53,3	35	315	6,7	1,4
3	49,0	17	284	3,6	2,9
4	67,1	51	291	10,5	1,0
5	34,8	20	295	4,1	2,5
6	41,0	45	306	8,8	1,1
7	36,2	25	286	5,2	2,0
8	87,1	33	285	6,9	1,5
9	58,1	41	317	7,8	1,2
10	19,0	30	316	5,7	1,7
11	41,0	28	317	5,3	1,8
12	44,8	21	296	4,3	2,4
13	46,2	42	299	8,4	1,2
14	37,6	21	300	4,2	2,4
15	9,0	27	304	5,3	1,9
16	69,5	40	301	8,0	1,3
17	44,3	29	317	5,5	1,7
18	47,6	22	305	4,3	2,3
19	36,7	25	305	4,9	2,0
20	37,6	22	285	4,6	2,3
21	80,0	40	296	8,1	1,3
22	61,9	21	292	4,3	2,4
23	72,9	56	286	11,7	0,9
24	59,0	22	290	4,6	2,3
25	58,6	44	314	8,4	1,1
26	56,2	26	289	5,4	1,9
27	78,1	36	302	7,2	1,4
28	36,2	39	298	7,9	1,3
29	36,2	41	306	8,0	1,2
30	53,3	55	301	11,0	0,9
31	72,4	32	300	6,4	1,6
32	57,6	23	295	4,7	2,2
33	33,8	43	318	8,1	1,2
34	58,1	28	289	5,8	1,8
35	49,5	30	310	5,8	1,7
36	66,7	40	304	7,9	1,3
37	52,4	29	299	5,8	1,7
38	50,5	24	291	4,9	2,1

4.5 Discussion of Experimental Results

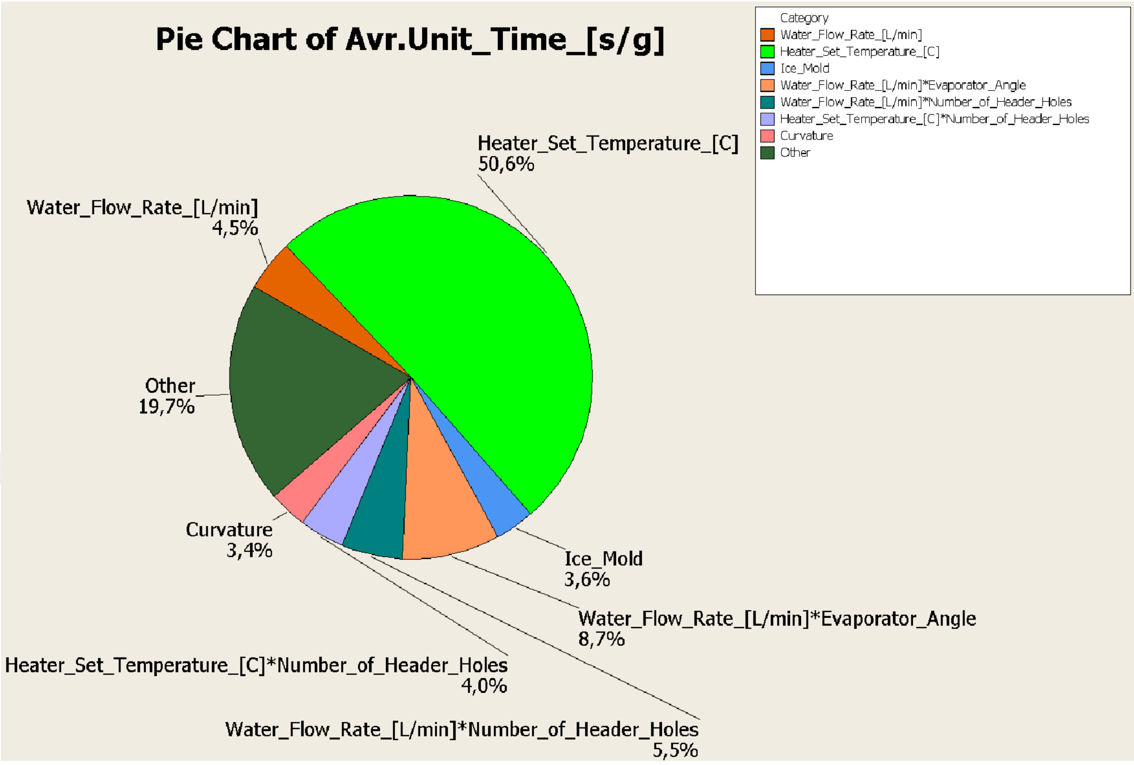

Figure 4.10 : Pie chart of factors that affect the Unit Average Time.

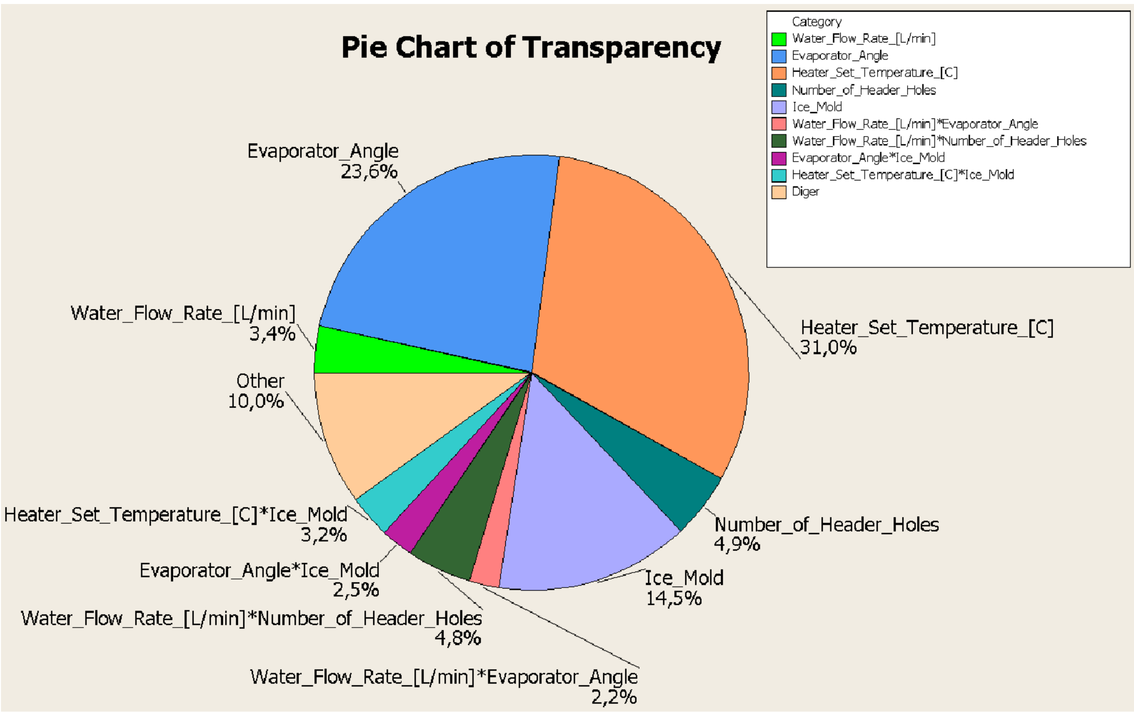

Figure 4.11 : Pie chart of factors that affect the Transparency.

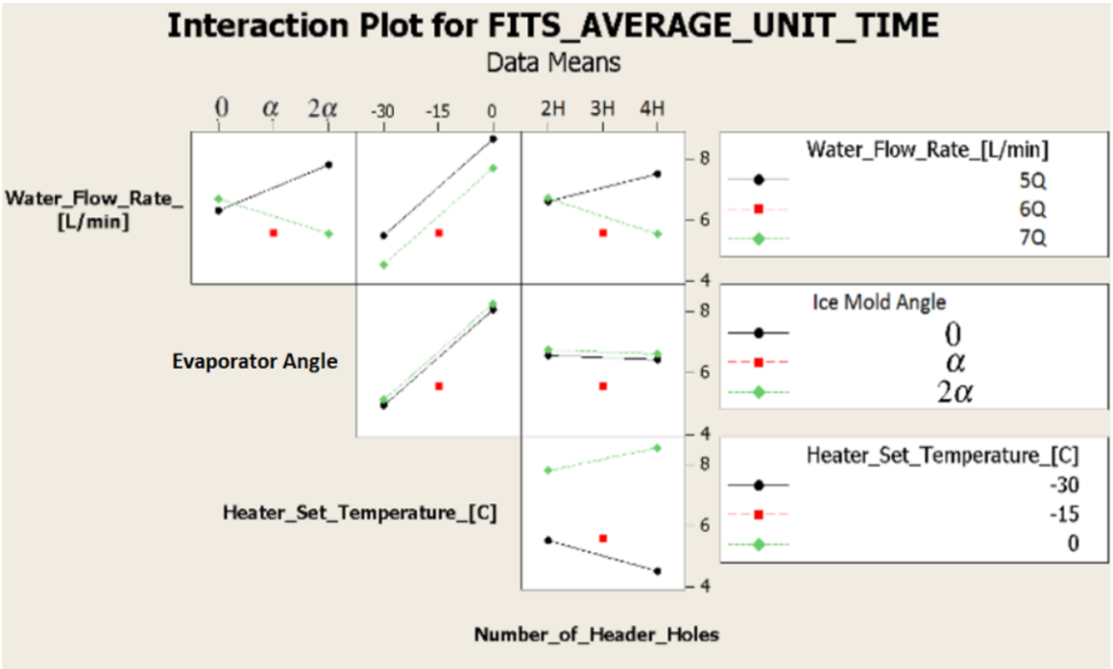

Figure 4.12 : Interaction plot for Average Unit Time.

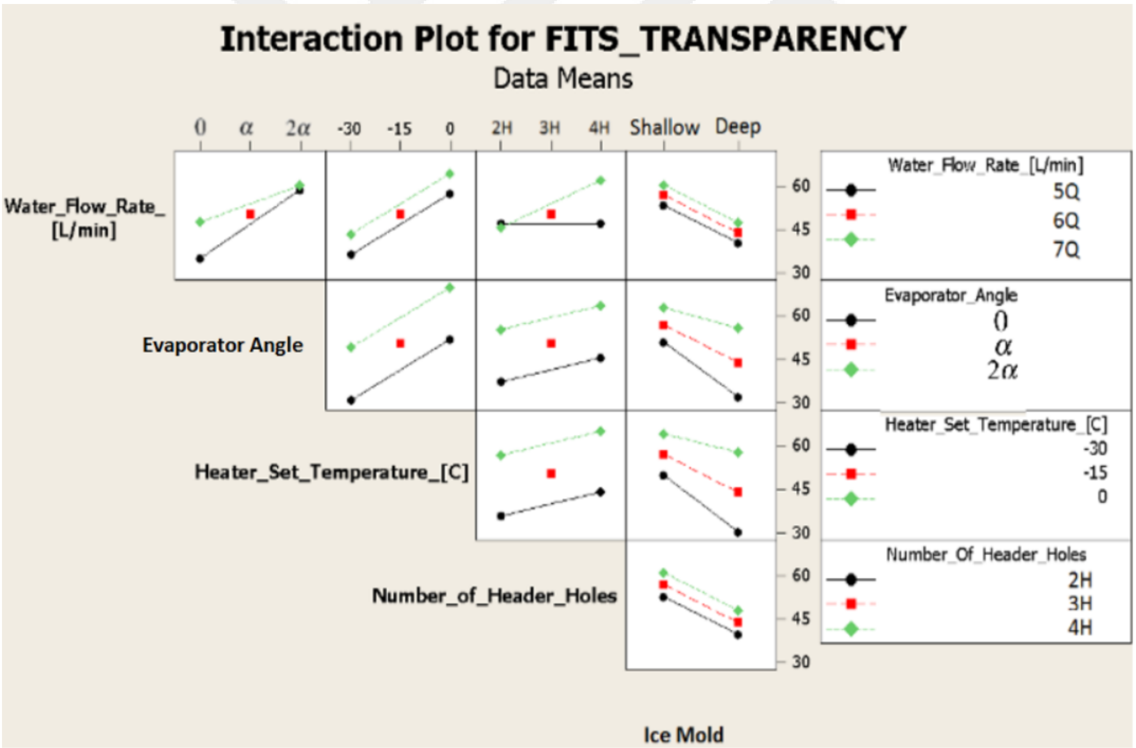

Figure 4.13 : Interaction plot for Normalized Transparency.

The interaction plots for transparency can be used to identify the interaction of the effects of different parameters. In general the parameters seem to be independent of each other except two cases:

- Number of Header Holes and Water Flow Rate turned out be rather ineffective by themselves but the combined effect of the two variables has more importance on the results. Both should be at the high values for a high transparency value.

- Evaporator Angle and Water Flow Rate both seem to affect the transparency positively. The interesting point is that when one of the variables has a high value the other one does not have a significant effect on the result.

These two observations lead us to the idea that the overall factor that affects transparency is not only Water Flow Rate, Evaporator Angle or the Number of Header Holes. The actual important parameter is the homogeneous, steady flow of water on the entire cold front surface of the evaporator. That is why either the evaporator angle or the high flow of water rate is enough to cover all the cold surface with water. Their effects do not combine when both are set to high values.

Same logic applies also to the Number of Header Holes and Flow Rate of Water but this time they both have to be set to high values in order to have the best result. Doubling the number of holes by itself is not enough when there is not enough water to cover the entire cold surface whereas having a higher flow rate is not e ffective when it is not distributed evenly on the surface.

4.5.1 Supplementary Experiments Using Food Dye E129

The best and worst cases of the first 19 experiments are repeated with water mixed with Food Dye Allura Red (E129) to highlight the differences in the solute accumulation characteristics and justify the previous experimental results. The E129 concentration in water is 10.25 mg/lt which is approximately 1.025 x 10^{-5} g/g in terms of mass concentration. This value is at the same order of magnitude as oxygen concentration in water 4.1 x 10^{-5} g/g.

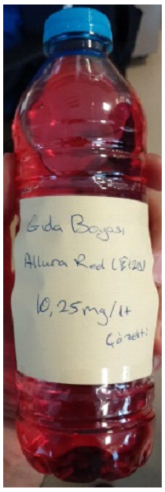

Figure 4.14 : The bottle of colored water using Allura Red E129.

Experiment 8 with 87% normalized transparency value and experiment 15 with 9% normalized transparency value are repeated with food dye E129 and the visual results - which are in quite good agreement with the previous results - can be seen and compared in Figure 4.15.

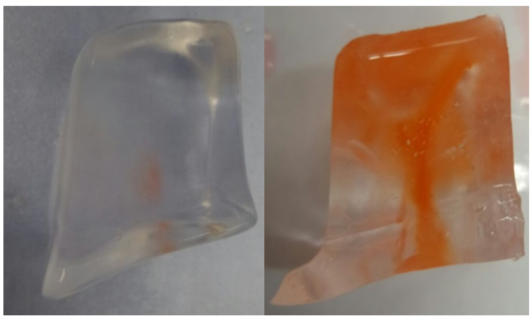

Figure 4.15 : Ice cube samples from experiment 8 (left) and experiment 15 (right) repeated with food dye E129.

5. CONCLUSION

In this master's thesis the parameters that affect clear and rapid ice production in a cold plate chilling type ice making compartment inside a refrigerator are experimentally and theoretically investigated.

In order to achieve this goal the literature search on solidification, bubble formation and bubble entrapment is done. It can be concluded from the literature search that the reason behind bubble formation is the accumulation of liberated gas during solidification. Bubble formation can be avoided if this dissolved gas accumulation at the solid-liquid interface can be prevented.

In addition to the literature research a theoretical calculation is done to obtain an approximate minimum water flow velocity reqired to prevent solute accumulation and bubble formation.

Using the information gathered from the literature an experimental setup similar to the cold plate chilling type commercial clear ice machines is designed and built, afterwards parametric experiments are done with this system. The factors that are investigated in the experimental studies include water flow rate, evaporator angle, number of header holes, heater set temperature and the depth of the ice mold. The output of the experiments are the unit average time needed for producing ice and the visual quality of the ice - which includes but is not limited to bubble formation. A quantification method is formed to have a numerical %tranparency value at the end of the measurements. Both the Gage R&R of the transparency quantification and the measurement uncertainity analysis of the average unit time are successfully done. The results of the Gage R&R study can be found in the Appendix.

Experimental results are analyzed in the Minitab software. The effects of each factor and their combinations on the unit average time and %transparency are calculated.

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APPENDICES

APPENDIX A.1 : Gage R&R Results and Plots
APPENDIX A.2 : Residual Plots

APPENDIX A.1

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0,438	0,08
Repeatability	0,438	0,08
Reproducibility	0,000	0,00
Part-To-Part	514,479	99,92
Total Variation	514,917	100,00

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	0,6614	3,969	2,91
Repeatability	0,6614	3,969	2,91
Reproducibility	0,0000	0,000	0,00
Part-To-Part	22,6821	136,093	99,96
Total Variation	22,6918	136,151	100,00

Number of Distinct Categories = 48

Gage R&R (Nested) for Results

Figure A.1 : Analysis results for the Gage R&R measurement validity study.

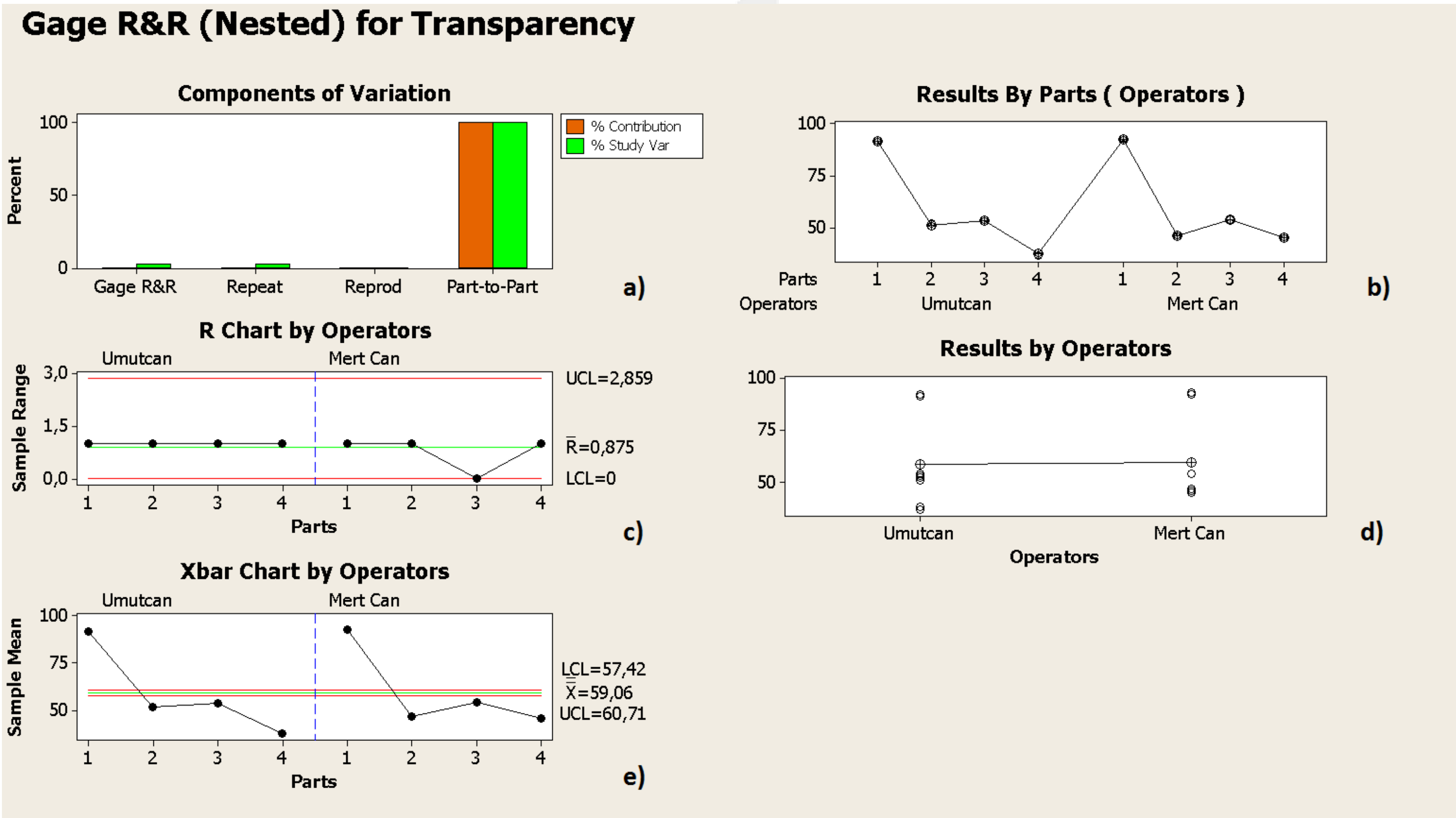

Figure A.2 : Result plots for the Gage R&R study for Transparency.

APPENDIX B.1

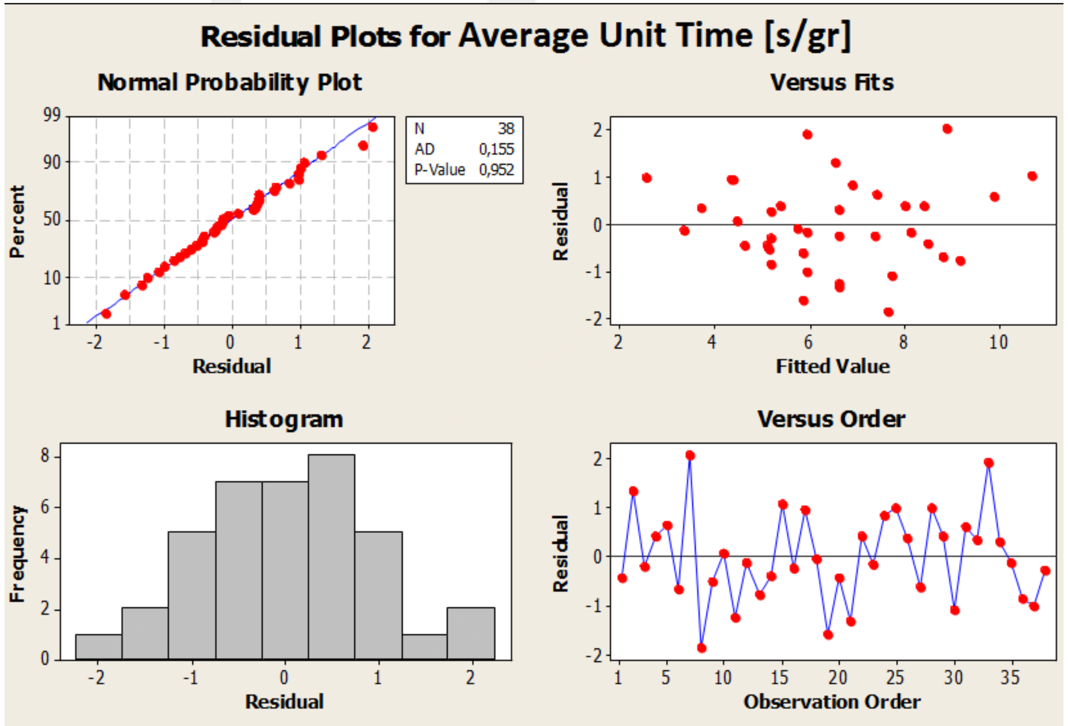

Figure B.1 : Residual plots for Average Unit Time.

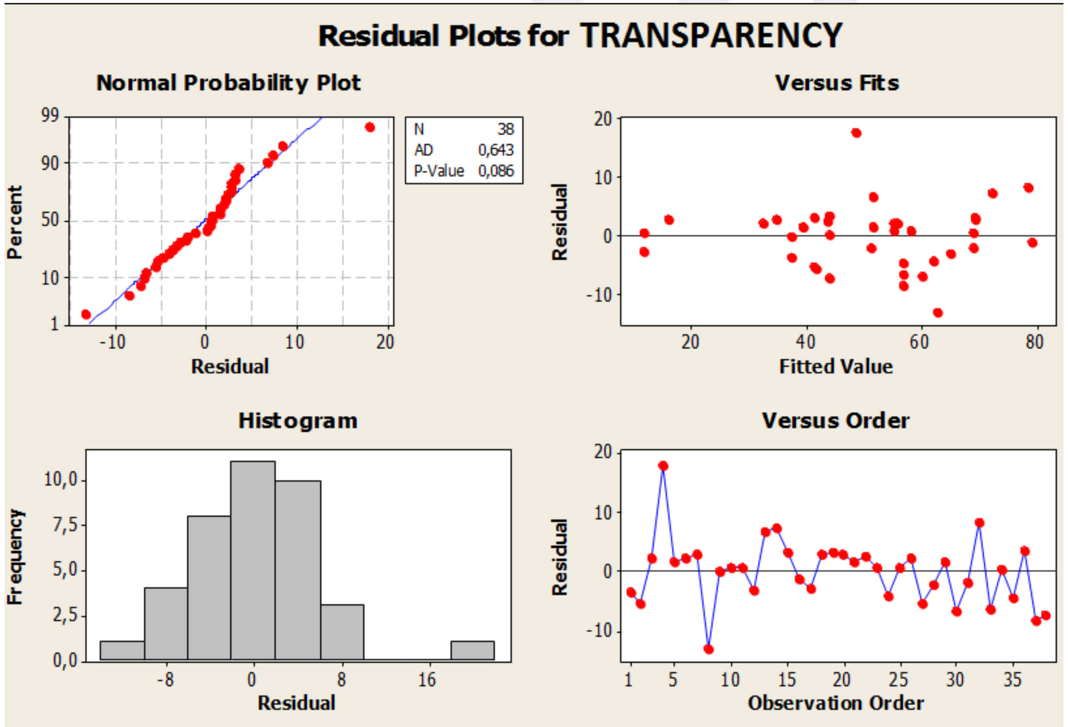

Figure B.2 : Residual plots for Transparency.

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