

**İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY**

**SURFACE TENSION AND ITS INFLUENCE ON WETTABILITY OF LiCl,  
CaCl<sub>2</sub> AND CELD SOLUTIONS IN AIR CONDITIONING SYSTEMS**

**MSc Thesis by  
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**Department : Chemical Engineering**

**Programme : Chemical Engineering**

**JUNE 2009**



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**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ**

**İKLİMLENDİRME SİSTEMLERİNDE LiCl, CaCl<sub>2</sub> VE CELD ÇÖZELTİLERİNİN  
ISLATILABİLİRLİĞİNE YÜZEY GERİLİMİNE ETKİSİ**

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Tuğba AVİNÇ  
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## TABLE OF CONTENTS

	<u>Page</u>
<b>ABBREVIATIONS</b> .....	<b>viii</b>
<b>LIST OF TABLES</b> .....	<b>ix</b>
<b>LIST OF FIGURES</b> .....	<b>x</b>
<b>SUMMARY</b> .....	<b>xiii</b>
<b>ÖZET</b> .....	<b>xv</b>
<b>1. INTRODUCTION AND AIM</b> .....	<b>1</b>
<b>2. LITERATURE REVIEW</b> .....	<b>3</b>
2.1 HVAC Systems .....	3
2.2 Air-Conditioning Systems.....	4
2.2.1 Absorption Air-Conditioning Systems.....	5
2.2.2 Liquid Desiccant Cooling Desiccants .....	8
2.3 Surface Tension.....	11
2.4 Capillary Rise.....	13
2.5 Interfacial Tension .....	16
2.6 Surface Free Energy and Wettability .....	18
2.7 Surface Tension Measurement Methods.....	22
2.7.1 Methods Measure the Force .....	23
2.7.1.1 Du Noüy Ring Method.....	23
2.7.1.2 The Wilhelmy Plate Method .....	24
2.7.2 Methods Measure the Pressure.....	26
2.7.2.1 The Capillary Height Method .....	26
2.7.2.2 Maximum Bubble Pressure Method.....	28
2.7.3 Methods Measure the Size or Dimensions of a Drop .....	28
2.7.3.1 The Pendant Drop Method.....	28
2.7.3.2 The Spinning Drop Method .....	28
2.7.3.3 The Sessile Drop Method.....	28
2.7.3.4 The Drop Volume/weight Method.....	29
2.8 Most Commonly Liquid Desiccant .....	30
2.9 Similar Studies Made by Scientist .....	34
2.10 Stuttgart University of Applied Sciences Studies .....	38
<b>3. EXPERIMENTAL STUDY</b> .....	<b>41</b>
3.1 Aim of the Experiments .....	41
3.2 Surface Tension Measurements .....	42
3.3 Wettability Measurements.....	43
3.4 Contact Angle Measurements .....	44
<b>4. RESULTS AND DISCUSSION</b> .....	<b>47</b>
<b>5. CONCLUSION AND RECOMMENDATION</b> .....	<b>51</b>
<b>REFERENCES</b> .....	<b>53</b>
<b>APPENDICES</b> .....	<b>57</b>
<b>CURRICULUM VITAE</b> .....	<b>77</b>

## ABBREVIATIONS

<b>100C</b>	: 100% CaCl <sub>2</sub> solution
<b>100L</b>	: 100% LiCl
<b>30C+70L</b>	: 30% CaCl <sub>2</sub> solution+70% LiCl solution
<b>50C+50L</b>	: 50% CaCl <sub>2</sub> solution+50% LiCl solution
<b>70C+30L</b>	: 70% CaCl <sub>2</sub> solution+30% LiCl solution
<b>ASHRAE</b>	: American Society of Heating Refrigerating Air-Conditioning Engineers
<b>CELD</b>	: Cost-Effective Liquid Desiccant
<b>CER</b>	: Clean Environment Rooms
<b>COP</b>	: Coefficient of Performance
<b>HfT</b>	: Hochschule für Technik
<b>HVAC</b>	: Heating Ventilating and Air Conditioning
<b>ITU</b>	: İstanbul Technical University
<b>LDACS</b>	: Liquid Desiccant Based Air Conditioning Systems
<b>Poly</b>	: Trendline of the figures
<b>Pp</b>	: Polypropylene
<b>R-D</b>	: Research and Development
<b>SENCE</b>	: Sustainable Energy Competence
<b>TEG</b>	: Triethylene glycol

## LIST OF TABLES

	<b><u>Page</u></b>
<b>Table 2.1 :</b> Surface tension values	14
<b>Table 2.2 :</b> Interfacial tensions of liquid against water at 20°C	17
<b>Table 2.3 :</b> The literature surface tension values at 20°C	32
<b>Table 2.4 :</b> The inlet conditions of air and salt solutions	39
<b>Table 4.1 :</b> Average surface tension results of pure water and groups at 20°C	47
<b>Table 4.2 :</b> The liquids compared with the pure water's wettability	48
<b>Table 4.3 :</b> Average contact angle values of solutions on different paddings	48
<b>Table A.1:</b> The surface tension values for CaCl <sub>2</sub> , LiCl and different concentrations of CELD solutions	58
<b>Table A.2.1 :</b> The collected liquid levels in the cups	63
<b>Table A.2.2 :</b> The approximation of the average liquid levels to 100 percentage	64
<b>Table A.3.1 :</b> Contact angle values on plexiglass plate	68
<b>Table A.3.2 :</b> Contact angle values on polypropylene plate	69
<b>Table A.3.3 :</b> Contact angle values on glass plate	70

## LIST OF FIGURES

	<u>Page</u>
<b>Figure 2.1</b> : A typical absorption refrigeration cycle	7
<b>Figure 2.2</b> : A conceptual liquid-desiccant cooling system	10
<b>Figure 2.3</b> : A molecule within the bulk liquid and at the surface	12
<b>Figure 2.4</b> : C-shaped wire frame and a wire slider system	12
<b>Figure 2.5</b> : Capillary rise	15
<b>Figure 2.6</b> : Oil-water interface	16
<b>Figure 2.7</b> : Classification of surface tension curves	18
<b>Figure 2.8</b> : The wettability of droplets	19
<b>Figure 2.9</b> : The goniometer for measuring the contact angle	19
<b>Figure 2.10</b> : The tensiometer measuring surface and interfacial tension of liquids	22
<b>Figure 2.11</b> : The stalagmometer for surface tension measurements	22
<b>Figure 2.12</b> : The ring that is used in Du Noüy Ring Method	23
<b>Figure 2.13</b> : The steps to measure the force for Du Noüy Ring Method	24
<b>Figure 2.14</b> : The Wilhelmy Plate Method	25
<b>Figure 2.15</b> : Water rises in a glass capillary	27
<b>Figure 2.16</b> : Mercury falls in a glass capillary	27
<b>Figure 2.17</b> : A schematic diagram of Drop Volume/Weight Method	29
<b>Figure 2.18</b> : The drops falling down	30
<b>Figure 2.19</b> : The vapor pressure of air and different concentration of LiCl and CaCl <sub>2</sub>	33
<b>Figure 2.20</b> : The absorption process studied in SENCE	38
<b>Figure 2.21</b> : The liquid desiccant cooling system studied in SENCE	40
<b>Figure 3.1</b> : The setup of the drop volume/weight method	42
<b>Figure 3.2</b> : The breaking-off the droplet	43
<b>Figure 3.3</b> : The glass made surface wetting system	44
<b>Figure 3.4</b> : The wettability of liquids on the glass	44
<b>Figure 3.5</b> : Contact angle measurement device, goniometer	45
<b>Figure 4.1</b> : Comparison of surface wetting values of groups and pure water	49
<b>Figure 4.2</b> : The solutions' contact angles on different paddings	50
<b>Figure A.2.1</b> : Comparison of wettability of 100C and pure H <sub>2</sub> O on glass plate	65
<b>Figure A.2.2</b> : Comparison of wettability of 70C+30L and pure H <sub>2</sub> O on glass plate	65
<b>Figure A.2.3</b> : Comparison of wettability of 50C+50L and pure H <sub>2</sub> O on glass plate	66
<b>Figure A.2.4</b> : Comparison of wettability of 30C+70L and pure H <sub>2</sub> O on glass plate	66
<b>Figure A.2.5</b> : Comparison of wettability of 100L and pure H <sub>2</sub> O on glass plate	67
<b>Figure A.3.1</b> : 100C's contact angles on different packings	71
<b>Figure A.3.2</b> : 70C-30L's contact angles on different paddings	71
<b>Figure A.3.3</b> : 50C-50L's contact angles on different paddings	72
<b>Figure A.3.4</b> : 30C-70L's contact angles on different paddings	72
<b>Figure A.3.5</b> : LiCl's contact angles on different paddings	73
<b>Figure A.3.6</b> : Pure water's contact angles on different paddings	73
<b>Figure A.3.7</b> : CaCl <sub>2</sub> % in the solution vs. contact angles on plexiglass	74

<b>Figure A.3.8</b> : CaCl <sub>2</sub> % in the solution vs. contact angles on polypropylen	74
<b>Figure A.3.9</b> : CaCl <sub>2</sub> % in the solution vs. contact angles on glass	75



## **SURFACE TENSION AND ITS INFLUENCE OF WETTABILITY OF LiCl, CaCl<sub>2</sub> AND CELD SOLUTIONS FOR AIR CONDITIONING SYSTEMS**

### **SUMMARY**

Safe and comfy work environment for people' thermal comfort is provided by heating, ventilating, and air conditioning systems. ASHRAE, the American Society of Heating, Refrigerating and Air Conditioning Engineers, has found standards about indoor comfort conditions. Air conditioning refers to the cooling and dehumidification of indoor air for thermal comfort. For achieving full air conditioning, heating, cooling, humidifying, dehumidifying, cleaning, ventilating and air movement are required. Absorption air conditioning system is one of the important air conditioning system and it is related to solar energy because a large part of the energy required is thermal energy that solar collectors can easily provide. A liquid desiccant cooling system is the important solar cooling method, humidity is absorbed directly from the process air with the desiccant. Then the desiccant is regenerated, again in direct contact by solar heat. As a liquid desiccant, commonly ionic liquids are used. They are preferred because of their miscible or creation ability. The liquid desiccant have some requirements that are low vapor pressure, low regeneration temperature, low cost, low viscosity and high wettability capacity, etc. Wettability is related to surface tension. In this study, the important parameters for liquid sorption air conditioning systems, surface tension and wettability of some desiccants, are investigated and measured. The CaCl<sub>2</sub>, LiCl and "Cost-Effective Liquid Desiccant" (CELD) are used as desiccants. CELD solutions are prepared by the different weight percentages of LiCl and CaCl<sub>2</sub> solutions. Drop volume/weight method is used to measure the surface tension. For a reference, the pure water is tried firstly. For wettability measurements, the glass rough plate is used to compare the surface wetting of the liquids on glass. Paddings, used in absorption process in liquid desiccant cooling system, are taken to compare the wettability capability of liquids by goniometer.



# İKLİMLENDİRME SİSTEMLERİNDE LiCl, CaCl<sub>2</sub> VE CELD ÇÖZELTİLERİNİN İSLATILABİLİRLİĞİNE YÜZEY GERİLİMİNİN ETKİSİ

## ÖZET

İnsanların termal konforu için, güvenli ve rahat çalışma ortamı ısıtma, havalandırma ve air conditioning sistemleri tarafından sağlanır. Amerikan Isıtma, Soğutma ve İklimlendirme Mühendisleri Derneği (ASHRAE) tarafından ev içi hava konforu şartları belirlenmiştir. İklimlendirme sistemleri, termal konfor için ev içi havasının nemini almak ve soğutmak ile ilgilidir. İyi bir iklimlendirme sağlamak için; ısıtma, soğutma, nemlendirme, nemini alma, temizleme, havalandırma, hava hareketi gibi sistemler gerekmektedir. Absorpsiyon iklimlendirme sistemi, iklimlendirme sistemleri içinde önemli bir yere sahiptir ve solar enerji ile alakalı olup gerekli olan solar enerji solar kollektörler tarafından kolayca sağlanabilir. Sıvı desikant soğutma sistemi önemli solar soğutma metodudur. Proses havası ile sıvı desikant sistemde karşılarak nem proses havasından desikanta absorbe olur. Daha sonra, desikant solar enerji ile tekrardan rejenerasyona tabi tutularak absorpsiyon işlemine hazır hale getirilir. Sıvı desikantların, sıvı desikant soğutma sistemlerinde kullanılmaları için bazı özelliklere ihtiyacı vardır. Bunlar düşük buhar basıncı, rejenerasyon sıcaklığı ve viskozite, düşük fiyat ve yüksek ıslatılabilirlik özelliği en önemli gerekçelerdendir. Islatılabilirlik ise yüzey gerilimi ile alakalı bir konudur. Bu çalışmada, iklimlendirme sistemlerindeki sıvı sorpsiyon için önemli parametreler olan desikantların yüzey gerilimi ve ıslatılabilirliği araştırılmış ve ölçülmüştür. Sıvı desikant olarak; CaCl<sub>2</sub>, LiCl ve CELD (fiyat açısından verimli sıvı desikant) çözeltileri kullanılmıştır. CELD solüsyonları, LiCl ve CaCl<sub>2</sub> sıvılarının farklı ağırlık yüzdelerinde karışımı ile elde edilmiştir. Sıvıların “Damlacık Ağırlık/Hacim Metodu” kullanılarak yüzey gerilimleri hesaplanmıştır. Referans olarak saf su kullanılmıştır. Islatılabilirlik deneylerinde, sıvıların pürüzlü cam yüzey üzerindeki ıslatılabilirlikleri karşılaştırılmıştır. Sıvı desikant soğutma sistemlerindeki absorpsiyon prosesinde dolgu maddeleri kullanılır. Farklı dolgu maddeleri üzerinde sıvıların ıslatılabilirlikleri karşılaştırılmıştır.



## **1. INTRODUCTION AND AIM**

Heating, ventilating and air conditioning systems provide a comfortable and safe work environment to the people in buildings. In addition to heating, ventilating and air conditioning systems, the architectural design of the building has significant influence on thermal comfort. Human thermal comfort is established by American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) and defined by ASHRAE Standard 55-2004 Thermal Environment Conditions for Human Occupancy. To provide the excellent thermal comfort in buildings, R-D studies are continued. Air conditioning systems are investigated for supplying the thermal comfort and the climatization of the building's indoor air.

The term air conditioning means the total control of temperature, moisture in the air, supply of outside air for ventilation, filtration of airborne particles and air movement in the occupied space. Air conditioning refers to the cooling and dehumidification of indoor air for thermal comfort.

One of the important air conditioning system is absorption air conditioning system. Absorption air conditioning is compatible with solar energy which solar collectors can easily provide.

The other important air conditioning system for clean environment is liquid desiccant cooling systems. A liquid desiccant cooling system is the solar cooling method that humidity is absorbed directly from the process air by direct contact with the desiccant. Then the liquid desiccant is regenerated again by solar heat. Liquid desiccant cooling systems have lots of advantages when compared with the other air conditioning methods. In liquid desiccant cooling systems, liquid desiccants are used as LiCl, CaCl<sub>2</sub>, LiBr, TEG and the mixtures of these solutions. The liquid desiccants have some requirements for cooling systems, one of the important one is wettability of the liquids. Wettability has an importance for efficiency absorption and is related to surface wetting.

Surface tension is a force that pulls all the liquid molecules together and caused by the attraction between the liquids' molecules by various intermolecular forces. Surface tension measurement methods measure the force, pressure and drop size. Surface tension is calculated from these methods.

In HfT Stuttgart-Stuttgart University of Applied Sciences, the project of a liquid desiccant cooling system is going on. Salt solutions of  $\text{CaCl}_2$  and  $\text{LiCl}$  and CELD solution are used as a liquid desiccant for absorption process. For improving the absorption efficiency, different paddings are tested such as plexiglass, polypropylene, and normal glass. This master thesis is a subset of this project. The aim of this project that is studied in HfT Stuttgart is to improve the absorption efficiency in a liquid desiccant cooling system. The aim of this thesis is to find the convenient solution and paddings for air conditioning systems.

In the experimental part, different surface wetting characteristics of  $\text{LiCl}$  solutions,  $\text{CaCl}_2$  solutions and mixtures as potential CELDs are investigated and compared and confirmed by surface tension and contact angle experiments. Also the influence of different surface material on the surface wetting potential of the different desiccants is researched.

## **2. LITERATURE REVIEW**

In this part, the results of the literature review of my study is shown below:

- Heating Ventilating and Air-Conditioning Systems
- Air-Conditioning Systems
- Absorption Air Conditioning Systems
- Liquid Desiccant Cooling Systems
- Surface Tension
- Capillary Rise
- Interfacial Tension
- Surface Energy and Wettability
- The Studies Made by Scientists
- Stuttgart University of Applied Sciences Studies

### **2.1 HVAC Systems**

Heating, ventilating, and air conditioning (HVAC) systems provide a comfortable and safe work environment to the people in buildings. People's health, attitude and productivity are affected by their work environment. Two important factors for people's comfort are "Air quality" and the "condition of the air". By "conditioned air" and "good air quality", it is meant that air should be clean and odor-free and the temperature, humidity, and movement of the air will be within certain acceptable comfort ranges. ASHRAE, the American Society of Heating, Refrigerating and Air Conditioning Engineers, has established standards which indoor comfort conditions that are thermally acceptable to 80% or more of a building's occupants. These "comfort zone" conditions are between 68°F and 75°F for winter and 73°F to 78°F for summer. The room air's relative humidity is approximately 50% and velocity is 30 ft/mn or less.

Thermal comfort is controlled by a building's heating, ventilating and air-conditioning systems, though the architectural design of the building may also have significant influences on thermal comfort. Maintaining thermal comfort for

occupants of buildings or enclosures is one of the important goals of HVAC design engineers. Human thermal comfort is defined by *ASHRAE Standard 55-2004 Thermal Environment Conditions for Human Occupancy*. There are seven factors affect thermal comfort as activity level, clothing, expectation, air temperature, radiant temperature, humidity and air speed [1, 2].

## 2.2 Air Conditioning Systems

Air conditioning is a form of air treatment whereby temperature, humidity, ventilation and air cleanliness are all controlled within limits determined by the requirements of the air conditioned enclosure [3]. Air conditioning refers to the cooling and dehumidification of indoor air for thermal comfort. The term “air conditioning” means the total control of temperature, moisture in the air (humidity), supply of outside air for ventilation, filtration of airborne particles and air movement in the occupied space. Thermodynamics, fluid mechanics, electricity, electronics, construction, materials, medicine, controls and social behavior are helped to develop the air conditioning systems. For achieving full air conditioning, seven main processes are required as heating, cooling, humidifying, dehumidifying, cleaning, ventilating and air movement. These seven processes are varied by the climate’s conditions [1].

- *Heating*: It is defined by the process of adding thermal energy (heat) to the conditioned space to raise and maintain the temperature of the space.
- *Cooling*: It is defined by the process of removing thermal energy (heat) from the conditioned space to lower or maintain the temperature of the space.
- *Humidifying*: It is defined by the process of adding water vapor (moisture) to the air in the conditioned space to raise or maintain the moisture content of the air.
- *Dehumidifying*: It is defined by the process of removing water vapor (moisture) from the air in the conditioned space to lower or maintain the moisture content of the air.
- *Cleaning*: It is defined by the process of removing particles, (dust, etc.) and biological contaminants, (insects, polens, etc.) from the air delivered to the conditioned space to improve or maintain the air quality.
- *Ventilating*: It is defined by the process of exchanging air between the outdoors and the conditioned space to dilute the gaseous contaminants in the air and

improve or maintain air quality, composition and freshness. Natural ventilation or mechanical ventilation can be used for ventilation. While natural ventilation is driven by natural attraction, mechanical ventilation can be accomplished by fans for taking air inside from outside or exhausting air from the space to outside.

- *Air movement:* It is defined by the process of circulate and mix air through conditioned spaces in the building to succeed the proper ventilation and get the thermal energy transfer easier [1].

The first successful air conditioning system for room temperature and humidity control was placed into operation in Brooklyn in 1902. Willis Carrier took innovations to advance the system. In 1902, Carrier built the first air conditioner to combat both temperature and humidity for cooling, controlling humidity control and designing the system. Four years later, in 1906, Carrier was granted a patent for his air conditioner the “Apparatus for Treating Air.” Whereas, Willis Carrier did not invent the very first system to cool an interior structure. Stuart Cramer, a textile engineer, invented the term “air conditioning.” And used it in a 1906 patent for a device that added water vapor to the air. In 1911, Mr. Carrier, father of air conditioning, presented his “Rational Psychrometric Formula” to the American Society of Mechanical Engineers. For the air conditioning industry, the formula is the principle in all fundamental psychrometric calculations today. Nevertheless Mr. Carrier did not invent the first air conditioning system, his cooling and humidity control system and psychrometric calculations started the science of modern psychrometrics and air conditioning. Air “cooling” was only part of the air conditioning system. The thing that wants to be known was how to regulate the indoor humidity. In the 1900s, many industries began to develop with the new accomplishments to control the indoor temperature and humidity levels. Today, air conditioning is required in most industries and the places that need highly controllable environments, such as clean environment rooms (CER) for medical or scientific research, product testing, and sophisticated computer and electronic component manufacturing [4].

### **2.2.1 Absorption Air Conditioning Systems**

Absorption air conditioning is compatible with solar energy because a large fraction of the energy required is thermal energy at temperatures that solar collectors can

easily provide. Low and medium temperature solar collectors have been used to drive several absorption air conditioning systems.

In absorption air conditioning systems, the pressurization is achieved by dissolving the refrigerant in the absorber and then pumping the solution with a liquid pump. The low-boiling refrigerant is got out from solution by the addition of heat in the generator. Hereby, the refrigerant vapor is compressed without the large input of high-grade shaft work. The effective performance of an absorption cycle depends on the two materials that comprise the refrigerant–absorbent pair. The required characteristics for the refrigerant–absorbent pair are like these:

- Absence of a solid-phase sorbent
- A refrigerant more volatile than the absorbent so that separation from the absorbent occurs easily in the generator
- An absorbent that has a strong affinity for the refrigerant under conditions in which absorption takes place
- A high degree of stability for long-term operations
- Nontoxic and nonflammable fluids for residential applications; this requirement is less critical in industrial refrigeration
- A refrigerant that has a large latent heat so that the circulation rate can be kept low
- A low fluid viscosity that improves heat and mass transfer and reduces pumping power
- Fluids that do not have long-term environmental effects

Lithium bromide–water (LiBr–H<sub>2</sub>O) and ammonia–water (NH<sub>3</sub>–H<sub>2</sub>O) are the two pairs that meet most of the requirements and have been used commercially in several applications. In the ammonia–water system, ammonia (NH<sub>3</sub>) serves as the refrigerant and water (H<sub>2</sub>O) as the transport medium, whereas in the LiBr–H<sub>2</sub>O system, water serves as the refrigerant. Other refrigerant–absorbent pairs include ammonia–salt, methylamine–salt, alcohol–salt, ammonia–organic solvent, sulfur dioxide–organic solvent, halogenated hydrocarbons–organic solvent, water–alkali nitrate and ammonia–water–salt [5].

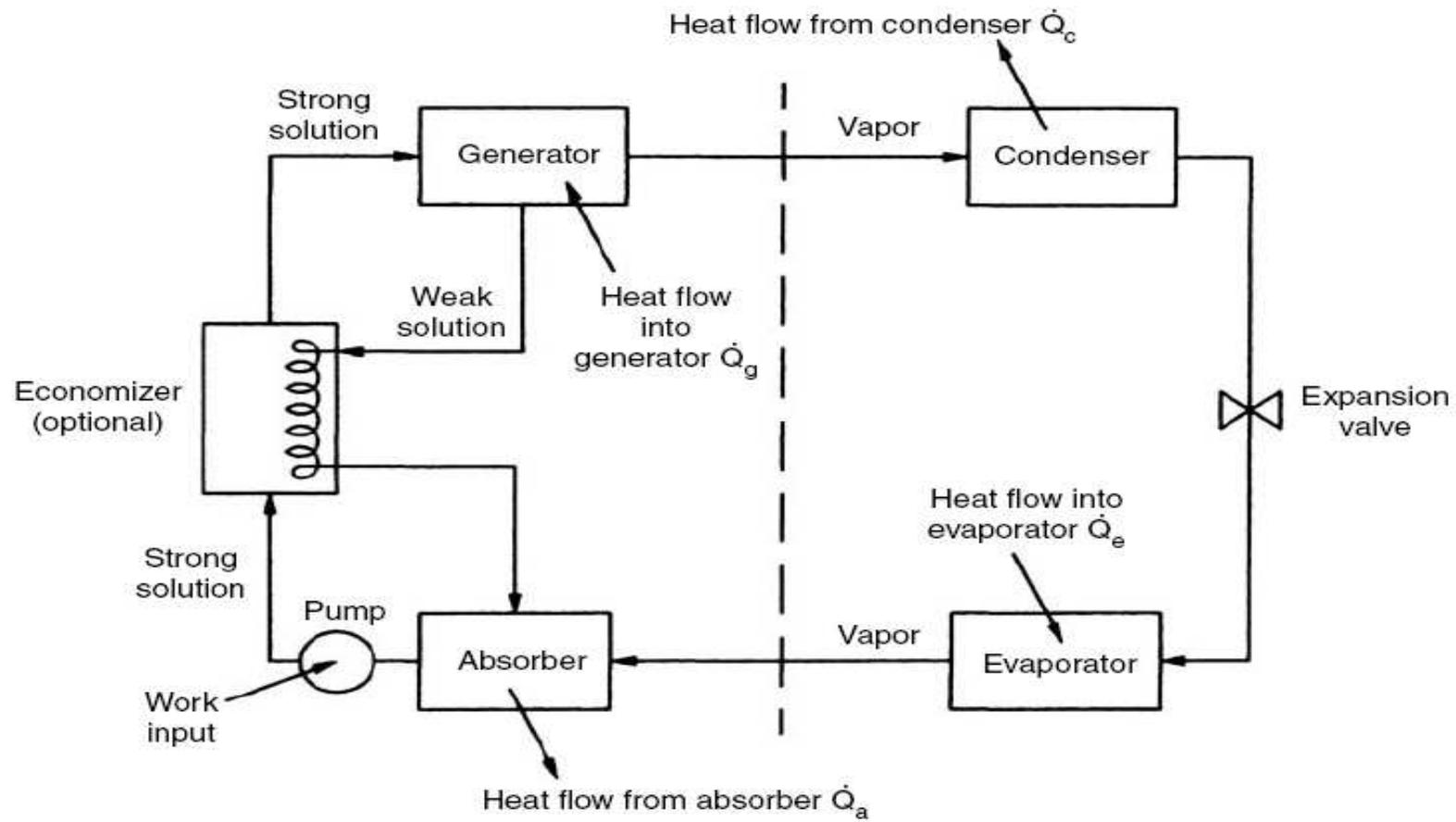


Figure 2.1 : A typical absorption refrigeration cycle [5].

Coefficient of performance (COP) of an absorption air conditioner can be calculated from:

$$COP = \frac{\text{cooling effect}}{\text{heat input}} = \frac{Q_e}{Q_g + W_{\text{pump,in}}} \cong \frac{Q_e}{Q_g} \quad (2.1)$$

The COP values for absorption air conditioning range from 0.5 for a small, single-stage unit to 0.85 for a double-stage, steam-fired unit. The maximum COP of an absorption refrigeration system is determined by assuming that the entire cycle is totally reversible [5, 6].

### 2.2.2 Liquid Desiccant Cooling Systems

A liquid desiccant cooling system is the solar cooling method that humidity is absorbed directly from the process air by direct contact with the desiccant. Then the desiccant is regenerated, again in direct contact with an external air stream, by solar heat at relatively low temperatures. The liquid desiccant system has many potential advantages over other solar air conditioning systems and can provide a promising alternative to absorption or to solid desiccant systems [7]. The ability to pump a liquid desiccant makes it possible to use solar energy for regeneration more efficiently. It also allows several small dehumidifiers to be connected to a single regeneration unit. Because a liquid desiccant does not require simultaneous regeneration, the liquid may be stored for regeneration later when solar heat is available.

In a desiccant air conditioning system, moisture is removed from the air by bringing it in contact with the desiccant, followed by sensible cooling of the air by a vapor compression cooling system, vapor absorption cooling system, or evaporative cooling system. The driving force for the process is the water vapor pressure. When the vapor pressure in air is higher than on the desiccant surface, moisture is transferred from the air to the desiccant until an equilibrium is reached. To regenerate the desiccant for reuse, the desiccant is heated, which increases the water vapor pressure on its surface. If air with lower vapor pressure is brought into contact with this desiccant, the moisture passes from the desiccant to the air. Two types of desiccants are used: solids such as silica gel and lithium chloride, or liquids such as salt solutions and glycols [6].

As a liquid desiccant, ionic liquids are used commonly. The reason why ionic liquids are used or preferred for sorption processes or the advantage of ionic liquids is that they can be mixed or created on user-specific requirements.

A schematic of a liquid desiccant system is shown in Figure 2.2. Air is brought into contact with concentrated desiccant in a countercurrent flow in a dehumidifier. The dehumidifier may be a spray column or packed bed. The packings provide a very large area for heat and mass transfer between the air and the desiccant. After dehumidification, the air is sensibly cooled before entering the conditioned space. The dilute desiccant exiting the dehumidifier is regenerated by heating and exposing it to a countercurrent flow of a moisture-scavenging air stream. Liquid desiccants commonly used are aqueous solutions of lithium bromide, lithium chloride, calcium chloride, mixtures of these solutions, and triethylene glycol (TEG) [6, 8].

Different liquid types of liquid are available in the market. The suitable desiccant for using in hot and humid climates affects the dehumidification efficiency. The difference between the partial pressure of water in the air and the vapour pressure of water above the desiccant is the driving potential for the dehumidification process. The liquid desiccant's vapour pressure is a function of its temperature and concentration. The common requirements of liquid desiccants are:

- The vapor pressure depression of water in the solution must be great and the vapour pressure of the solute itself should be low.
- The liquid must have the capability of maintaining its dehydrating ability over a considerable range of concentration.
- Its regeneration temperature should be low.
- Its heat conductivity should be high.
- It should be non-corrosive to the components and construction materials to the system (corrosion resistance), chemically stable and non-hydrolyzing.
- It should be harmless and non-toxic to people.
- It should be available at low cost.
- Its viscosity must be low and its solubility must be high over a considerable range of temperature to insure no solidification.

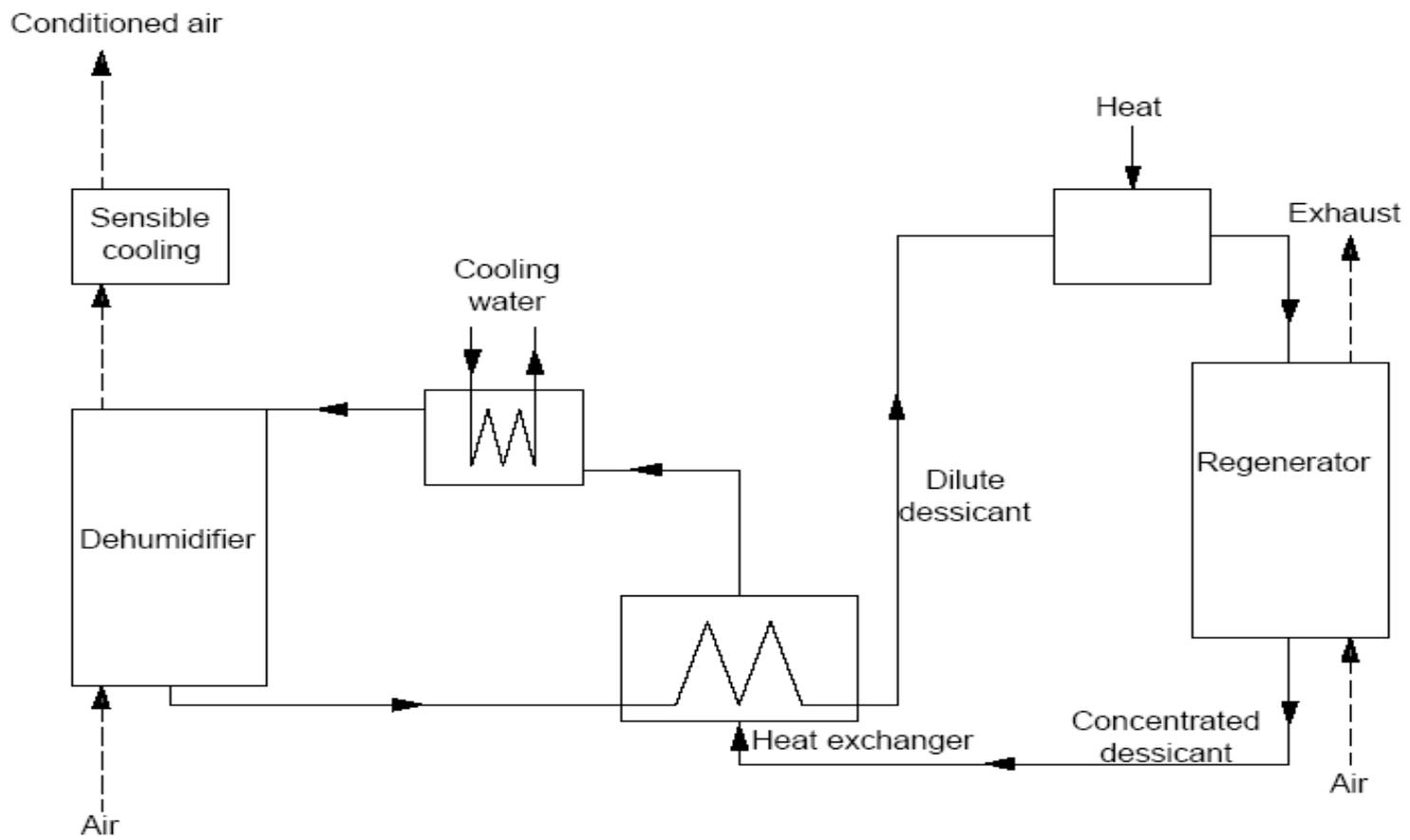


Figure 2.2 : A conceptual liquid-desiccant cooling system [6].

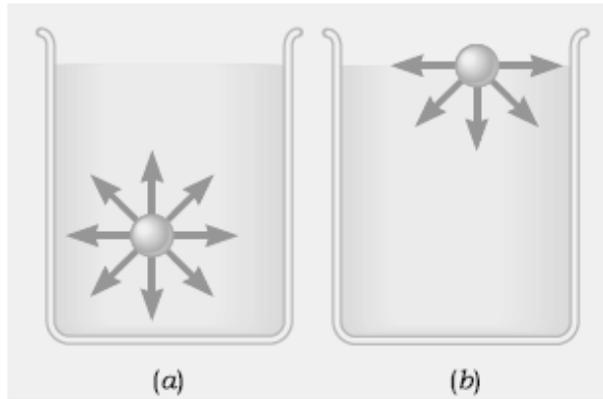
- Its surface wetting should be high and its surface tension should be low [9].

### 2.3 Surface Tension

An interface is a two dimensional area where two phases of different substances or compositions contact each other. There are five different two-component combinations of interfaces:

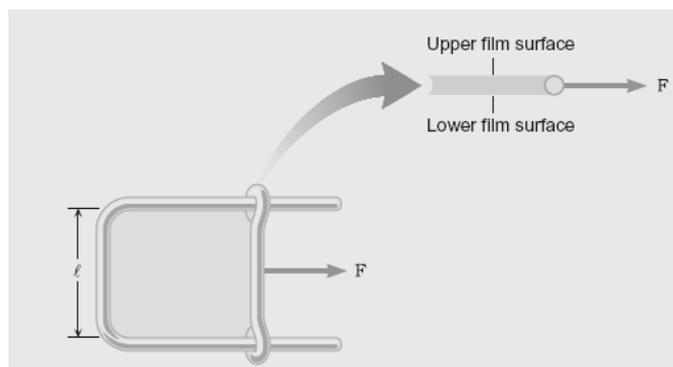
- liquid-gas
- liquid-liquid (classical interface)
- liquid-solid
- solid-gas
- solid-solid [1].

The term surface tension is used for solid-vapor or liquid-vapor interfaces whereas the term interfacial tension is more generally used for the interface between two liquids (liquid-liquid interfaces), two solids (solid-solid interfaces) or a liquid and a solid (liquid-solid interfaces) [10]. The molecular basis for surface tension is explained by considering the attractive forces in which molecules in a liquid transfer on one another in Figure 2.3. Part *a* shows a molecule within the bulk liquid, so other molecules surrounds on all sides of this molecule. The surrounding molecules attract the central molecule equally in all directions; it leads to a zero net force. In contrast, part *b* shows a molecule in the surface. There are no molecules of the liquid above the surface; this molecule experiences a net attractive force pointing toward the liquid interior. This net attractive force causes the liquid surface to narrow toward the interior until repulsive collisional forces from the other molecules halt the contraction at the point when the surface area is a minimum. If external forces don't act upon the liquid, a liquid sample forms a sphere, which has the minimum surface area [2].



**Figure 2.3 :** a) A molecule within the bulk liquid is surrounded on all sides by other molecules, which attract it equally in all directions, leading to a zero net force.

(b) A molecule in the surface experiences a net attractive force pointing toward the liquid interior, because there are no molecules of the liquid above the surface [11].



**Figure 2.4 :** C-shaped wire frame and a wire slider system is used to measure the liquid's surface tension [11].

Figure 2.4 illustrates the apparatus which consists of a c-shaped wire frame and a wire slider; contain a thin film of liquid. The surface tension causes the liquid surface to contract, a force  $F$  is needed to move the slider to the right and extend the surface. The surface tension is shown by the Greek letter gamma ( $\gamma$ ) and it is the magnitude  $F$  of the force exerted parallel to the surface of a liquid divided by the length of the line over which the force acts [11]. Customary units may either be ergs per square centimeter ( $\text{ergs/cm}^2$ ) or dynes per centimeter ( $\text{dyn/cm}$ ). The corresponding SI units are joules per square meter ( $\text{J/m}^2$ ) or newtons per meter ( $\text{N/m}$ ). Surface tensions reported in  $\text{dyn/cm}$  and in  $\text{mN/m}$  have the same numerical value [12].

$$\gamma = \frac{F}{L} \quad (2.2)$$

In the other words, the wire slider is moved to the right side. Since the tendency of the liquid is to maintain a minimum surface, a force  $F$  will be required to do this. The work done is

$$W = Fd \quad (2.3)$$

$d$  is the difference of movement.

$$F = 2\gamma l \quad (2.4)$$

$$W = Fd = 2\gamma ld = \gamma(2ld) = \gamma\Delta S \quad (2.5)$$

where  $\Delta S$  is the increase in the area. Thus

$$\gamma = \frac{W}{\Delta S} \quad (2.6)$$

Surface tension may be defined as the work in ergs necessary to generate one square centimeter of surface. It can be also defined as the force in dynes acting along 1 cm length of surface [10].

In table 2.1, the surface tension values of some liquids are shown [12].

## 2.4 Capillary Rise

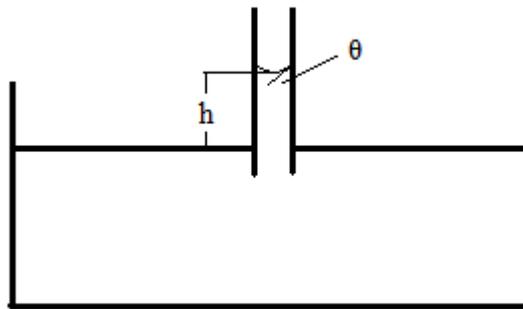
The phenomenon of capillary rise is a result of surface tension. Capillary rise is the most widely used and proper method for measuring the surface tension. A capillary tube of radius  $r$  and immersed in a liquid of density  $d$  is shown in the Figure 2.5. If the liquid wets the capillary's walls, the liquid's surface is increased and the liquid will rise in the capillary in order to reduce its surface. When the liquid rises, new wall areas are wetted. The surface again increases and the liquid again rises. This cycle process stops when the surface tension force acting upward is balanced by the gravitational force acting downward on the column of liquid.

**Table 2.1** : Surface tension values [12].

Liquid	Substance	Temperature (°C)	$\gamma$ (mN/m)
	Water	20	72.80
		25	72.13
Organic Compounds	Methylene iodide	20	67.00
	Glycerine	24	62.60
	Ethylene glycol	25	47.30
		40	46.30
	Dimethyl sulfoxide	20	43.54
	Propylene carbonate	20	41.10
	1-Methyl naphthalene	20	38.70
	Dimethyl aniline	20	36.56
	Benzene	20	28.88
		30	27.56
	Toluene	20	28.52
	Chloroform	25	26.67
	Propionic acid	20	26.69
	Butyric acid	20	26.51
	Carbon tetrachloride	25	26.43
	Butyl acetate	20	25.09
	Diethylene glycol	20	30.90
	Nonane	20	22.85
	Methanol	20	22.50
	Ethanol	20	22.39
		30	21.55
	Octane	20	21.62
	Heptane	20	20.14
	Ether	25	20.14
	Perfluoromethylcyclohexane	20	15.70
	Perfluoroheptane	20	13.19
Hydrogen sulfide	20	12.30	
Perfluoropentane	20	9.89	
Low-Boiling Substances	<sup>4</sup> He	-272,15	0.365
	H <sub>2</sub>	-253,15	2.01
	D <sub>2</sub>	-253,15	3.54
	N <sub>2</sub>	-198,15	9.41
	Ar	-183,15	11.86
	CH <sub>4</sub>	-163,15	13.71
	F <sub>2</sub>	-188,15	14.84
	O <sub>2</sub>	-196,15	16.48
	C <sub>2</sub> H <sub>6</sub>	-92,55	16.63
	Xe	-110,15	18.60
	N <sub>2</sub> O	-90,65	24.26
	Cl <sub>2</sub>	-30	25.56
	NOCl	-10	13.71
	Br <sub>2</sub>	20	31.90

**Table 2.1 : Surface tension values (continued)**

Metals	Hg	20	486.5
		25	485.5
		30	484.5
	Na	130	198.0
	Ba	720	226.0
	Sn	332	543.8
	Ag	1100	878.5
	Cu	Mp	1300.0
	Ti	1680	1588.0
Salts	Pt	Mp	1800.0
	Fe	Mp	1880.0
	NaCl	1073	115.0
	KClO <sub>3</sub>	368	81.0
	KNCS	175	101.5
	NaNO <sub>3</sub>	308	116.6
	K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub>	397	129.0
Ba(NO <sub>3</sub> ) <sub>2</sub>	595	134.8	

**Figure 2.5 : Capillary rise [13]**

The upward acting force, surface tension force  $F_1$ , is treating at an angle  $\theta$  as the contact angle or meniscus angle to the wall. This force is shown as

$$F_1 = 2\pi r\gamma \cos \theta_1 \text{ (dyn/cm)} \quad (2.7)$$

The downward acting force  $F_2$  is equal to the mass of the column of liquid in the capillary as

$$F_2 = \pi r^2 h d g \quad (2.8)$$

$d$  is the liquid's density,  $h$  is the height of rise in the capillary and  $g$  is the acceleration of gravity ( $981 \text{ cm/s}^2$ ). When the forces are balanced, there will be no any rise in the capillary and the forces will be equal to each other.

$$F_1 = F_2 \quad (2.9)$$

$$2\pi r\gamma \cos \theta = \pi r^2 h d g \quad (2.10)$$

$$\gamma = \frac{r h d g}{2 \cos \theta} \quad (2.11)$$

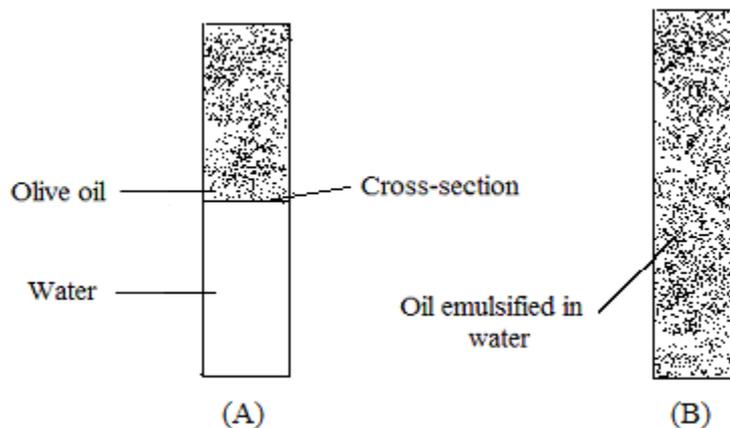
If the  $\theta$  is equal to zero,  $\cos 0=1$ . So the equation 2.11 becomes as:

$$\gamma = \frac{1}{2} r h d g \quad (2.12)$$

In this equation, it is seen that, the capillary rise of the liquid in the capillary tube is proportional to the surface tension and it is inversely proportional to the density of the liquid [11, 13].

## 2.5 Interfacial Tension

Interfacial tension is the liquid-liquid interface such as oil-water interface shown in the Figure 2.6.



**Figure 2.6 :** Oil-water interface A) The interface area between oil and water is quite small,

B) The interface area in oil emulsified in water is more than in Figure (A) [14].

In figure 2.6, oil's molecule at the interface is not surrounded symmetrically with other oil molecules and the forces acting on this molecule is not balanced. This molecule is affected with the water's molecules. The attraction of the water and oil molecules must be smaller than the attraction of the oil molecules. Because if the

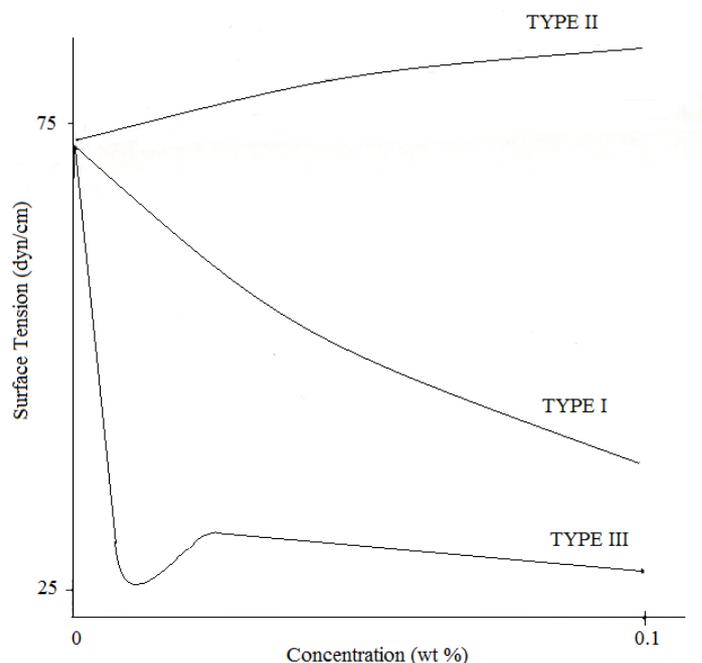
attraction is sizable, the liquids will not be immiscible and they do not form any interface.

It is expected that liquid-gas surface tensions are stronger than the liquid-liquid interfacial tension because of the unbalanced forces acting on the oil molecule in the surface. Some interfacial tensions of liquids against water are exhibited in Table 2.2.

**Table 2.2 :** Interfacial tensions of liquid against water at 20°C (dyn/cm) [14].

Carbon Tetrachloride	45.0
Benzene	35.0
Nitrobenzene	25.7
Olive Oil	22.9
Ethyl Ether	10.7

In Figure 2.7, the effect of the added solute to pure liquids is indicated. It is shown idealized curves of different types of solutions. In Type II curve, there is an increase with going up concentration and it is a characteristic of *inorganic salts* as sodium chloride. The curve of Type I is corresponding to decline in surface tension and it can be *water-soluble organic compounds* such as glycerine and the lower aliphatic acids. The most interesting curve is Type III. It is convenient for *soaps* such as sodium oleate. In literature research, the minimum point of Type III is not explained yet. It is investigated to be caused by the impurities [11, 14].



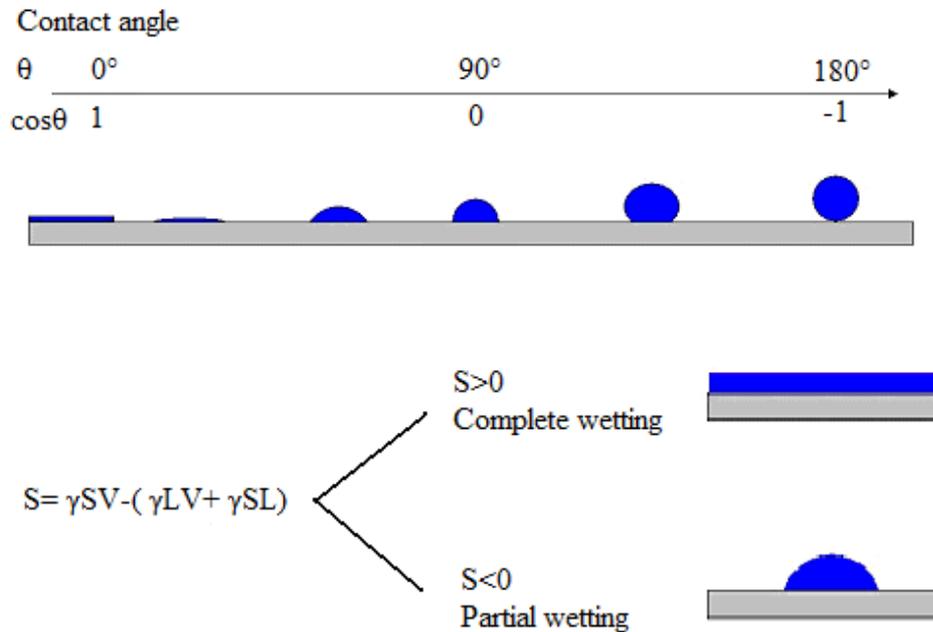
**Figure 2.7 :** Classification of surface tension curves. Type I) Water-soluble organic compounds Type II) Inorganic salts Type III) Soaps [11].

## 2.6 Surface Free Energy and Wettability

When surface is occurred, the intermolecular bonds decay. Surface energy measures these disruption of intermolecular bonds. Surfaces must be less energetically convenient than the bulk of a material. Because if not, there would be a driving force for surfaces to be created. The surface tension and the surface energy density are same such as water's surface tension is 0.072 N/m and its surface energy density is 0.072 J/m<sup>2</sup> [12]. Free energy, surface free energy and interfacial free energy are the same meaning [11].

The liquid material's one of the important characteristics is its ability to freely wet the surface of the inspected. In 1805 in the Philosophical Transactions of the Royal Society of London, Thomas Young first described the interaction between the forces of cohesion and the forces of adhesion which determines whether wetting or not wetting, the spreading of a liquid over a surface. At the liquid-solid surface interface, if the molecules of the liquid have a stronger attraction to the molecules of the solid surface than to each other (the adhesive forces are stronger than the cohesive forces), wetting of the surface occurs. Alternately, if the liquid molecules are more strongly attracted to each other than the molecules of the solid surface (the cohesive forces are

stronger than the adhesive forces), the liquid beads-up with a contact angle which is a function of the surface energies of the system and does not wet the surface of the part [6, 15].



**Figure 2.8 :** The wettability of droplets [14].

One way to quantify a liquid's surface wetting characteristics is to measure the contact angle of the liquid's droplet placed on the surface. The contact angle is formed by the solid/liquid interface and the liquid/vapour interface measured from the side of the liquid. Liquids wet surfaces when the contact angle is less than 90 degrees. To be effective, the contact angle should be as small as possible. Generally, the contact angle for most liquid penetrants is very close to zero degrees [6].



**Figure 2.9 :** The goniometer for measuring the contact angle [14].

Contact angle measurements can be used to determine the surface energy of a material. To measure the surface energy of a liquid, Young's Equation defines the balances of forces caused by a wet drop on a dry surface. If the surface is hydrophobic, the contact angle of water's drop will be larger. Hydrophilicity is concerned by smaller contact angles and higher surface energy. (Water has rather high surface energy by nature; it is polar and forms hydrogen bonds). The Young equation is,

$$\gamma_{SL} + \gamma_{LV} \cos \theta_C = \gamma_{SV} \quad (2.13)$$

In equation 2.13,  $\gamma_{SL}$ ,  $\gamma_{LV}$ , and  $\gamma_{SV}$  are the interfacial tensions between the solid and the liquid, the liquid and the vapor, and the solid and the vapor, respectively.  $\theta_c$  is the equilibrium contact angle between the liquid and solid surface. In a smooth surface, a drop will assume a wide spectrum of contact angles ranging from the so called advancing contact angle,  $\theta_A$ , to the so called receding contact angle,  $\theta_R$ . The equilibrium contact angle ( $\theta_c$ ) can be calculated from  $\theta_A$  and  $\theta_R$ :

$$\theta_c = \arccos\left(\frac{r_A \cos \theta_A + r_R \cos \theta_R}{r_A + r_R}\right) \quad (2.14)$$

where

$$r_A = \left(\frac{\sin^3 \theta_A}{2 - 3 \cos \theta_A + \cos^3 \theta_A}\right)^{1/3}; r_R = \left(\frac{\sin^3 \theta_R}{2 - 3 \cos \theta_R + \cos^3 \theta_R}\right)^{1/3} \quad (2.15)$$

To measure the surface energy of a solid, the high temperatures are used. At high temperatures, the surface is deformed whereas the volume is approximately constant, not changed. Gibbs free energy defines this as:

$$\delta G = -P\delta l + \gamma\delta A = 0 \Rightarrow \gamma = P \frac{\delta l}{\delta A} \quad (2.16)$$

$\gamma$  : surface energy density

$r$  : radius of cylindrical rod

$l$  : length of cylindrical rod

$P$  : constant uniaxial tension

$G$  : Gibbs free energy

$A$  : surface area of the rod

$$A = 2\pi r^2 + 2\pi r l \Rightarrow \delta A = 4\pi r \delta r + 2\pi l \delta r + 2\pi r \delta l \quad (2.17)$$

If the volume of the rod remains constant, the  $\delta V$  will be zero, such as like this:

$$V = \pi r^2 l = \text{constant} \Rightarrow \delta V = 2\pi r l \delta r + \pi r^2 \delta l = 0 \Rightarrow \delta r = -\frac{r}{2l} \delta l \quad (2.18)$$

The surface energy density can be expressed as

$$\gamma = \frac{P}{\pi r(l - 2r)} \quad (2.19)$$

The solid's surface energy density is calculated by measuring  $P$ ,  $r$ , and  $l$  at equilibrium [16, 17].

The other way to quantify a liquid's surface wetting characteristics is to measure the capillary action. The phenomenon is related to that of capillary rise, where the driving force is that of the pressure difference across the curved surface of the meniscus. The equation is shown as

$$\Delta P = \frac{2\gamma_{LV} \cos \theta}{r} \quad (2.20)$$

where  $r$  is the radius of the capillary. It can be written as a detailed like that

$$\Delta P = \frac{2(\gamma_{SV} - \gamma_{SL})}{r} \quad (2.21)$$

The principal requirement for a large  $\Delta P$  is that  $\gamma_{SL}$  be made as small as possible since for practical reasons it is not usually possible to choose  $\gamma_{SV}$ . On the other hand, if  $\theta$  is zero, the Equation 2.20 takes this form

$$\Delta P = \frac{2\gamma_{LV}}{r} \quad (2.22)$$

the requirement for a large  $\Delta P$  is that  $\gamma_{LV}$  be large.

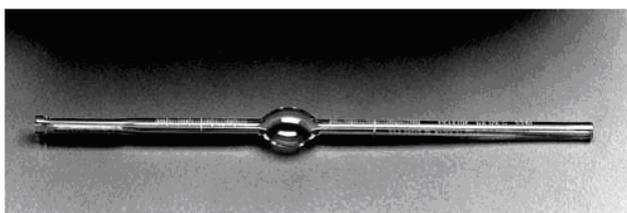
## 2.7 Surface Tension Measurement Methods

The surface tension is measured by tensiometers and stalagmometers as seen in the Figure 2.10 and 2.11, respectively. If stalagmometers are compared with tensiometers, they are cheaper and more easy to use. But tensiometers are more scientific devices for controlling the sensitive measurements. Tensiometers are also used for interfacial surface tension measurements that is not convenient for stalagmometers [2].

Modern tensiometers are coordinated with computers to increase the accuracy of the measurement and provide dynamic surface tension readings with short and accurate time [18].



**Figure 2.10** : The tensiometer measuring surface and interfacial tension of liquids using the Wilhelmy Plate or Du Noüy Ring Method [2].



**Figure 2.11** : The stalagmometer for surface tension measurements [2].

Surface tension methods measure either static or dynamic surface tension. In the static surface tension, the shape or amount of surface area is changed only one time in the beginning in the course of a static measurement of interfacial tension. Surface tension is measured at equilibrium, if sufficient time is allowed for the measurement and characterize the system. Dynamic surface tension methods provide information on adsorption kinetics of surfactants at the air-liquid interface or at a liquid-liquid interface. Dynamic surface tension can be measured in a time scale ranging from a

few milliseconds to several minutes. However, a limit line between static and dynamic methods is not very sharp because static methods can also obtain dispersant adsorption kinetics. It has been argued that sufficient time is not available to reach equilibrium [18].

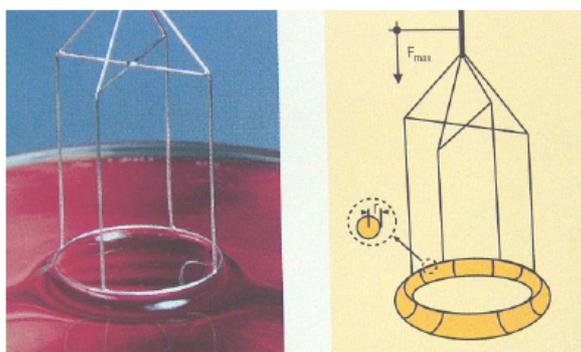
The surface tension methods measure a force, a pressure or drop size (volume, weight or dimensions). Methods, the Du Noüy Ring Method and the Wilhelmy Plate Method, are mostly used for measuring the surface tension with a force. Capillary Height and the Maximum Bubble Pressure Method measure pressure. Pendant Drop, Sessile Drop, Drop Volume/Weight and Spinning Drop Methods measure the size or the dimensions of a drop. Special techniques for dynamic surface tension include the Oscillating Jet, the Dynamic Drop Volume, the Inclined Plate, the Strip Method, the Free Falling Method, the Pulsed Drop, the Dynamic Maximum Bubble Pressure and the Dynamic Capillary Methods [18].

### 2.7.1 Methods Measure the Force

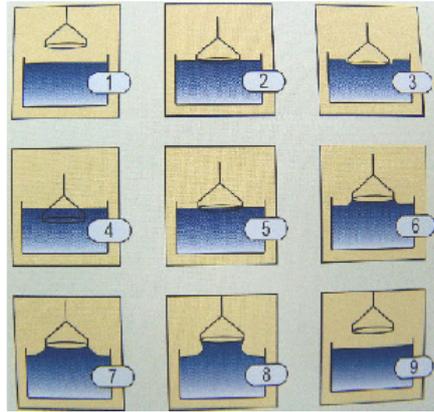
One of the measurement method for surface tension is methods measure the force. The force is used for surveying.

#### 2.7.1.1 Du Noüy Ring Method

It is the classical method that defines the surface tension by measuring the maximum towaway at a platinum/iridium ring. The platinum/iridium ring is immersed completely into the liquid and pulled slowly until the force reaches the maximum value. After the maximum force is attained, the liquid leaves the ring. At that break point the force is measured. (Figure 2.13)



**Figure 2.12** : The ring that is used in Du Noüy Ring Method [2].



**Figure 2.13 :** The steps to measure the force for Du Noüy Ring Method [2].

$$\gamma = \frac{F_{\max}}{(4\pi R f_{\text{corr}})} \quad (2.23)$$

$\gamma$  = Surface tension

$F_{\max}$  = Maximum force at the ring detected during pull out of the liquid

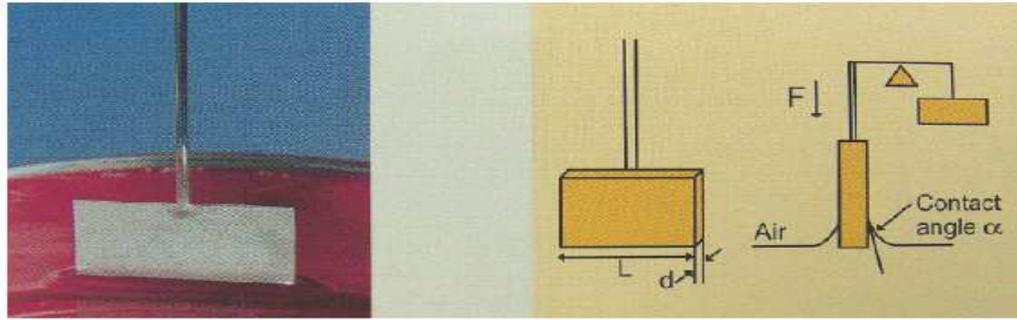
$R$  = The radius of the ring

$f_{\text{corr}}$  = The ring correction factor ( It depends on the ring's geometry and density)

The contact angle, between liquid and the platinum ring, should be zero and this is acceptable for all common liquids. The du Noüy Ring Method attains experimentally about 2-100 mN/m surface/interfacial tensions [2].

### 2.7.1.2 The Wilhelmy Plate Method

The Wilhelmy Plate Method is similar to the ring method except that the plate is a flat piece of platinum instead of a ring and that a meniscus is formed only on the perimeter of the plate. A platinum plate is brought into contact with the liquid surface, setted stable and wetted completely along the vertical edge. The force, between the plate and the liquid, is measured. The plate remains at the liquid's surface height zero during the measurement. There is no need to make a correction about above the zero height due to buoyancy or liquid withdrawn [17].



**Figure 2.14 :** The Wilhelmy Plate Method [2].

$$\gamma = \frac{F}{2(L + d)\cos \alpha} \quad (2.24)$$

F = force the plate is objected to by the liquid

L = wetted length (vertical circumference)

d = wetted width

$\alpha$  = contact angle between liquid and plate

There are some important points to measure the force of the Wilhelmy Plate Method. The contact angle, between the liquid and the plate, should be zero before beginning the measurement. The cleaning of the plate affects the angle. The other point is about the position of the plate. It is important to set the plate position correctly. The bottom part of the plate has to be at the same line with the liquid. If the plate is dipped in the liquid, there is a need to measure flotation effect [19].

Ring and Plate Methods in Comparison:

Advantages of the ring method:

- In the many values of literature, the ring method is obtained and preferred for comparison purposes.
- The wetted length of the ring outperforms when it is compared with the wetted length of plate. It leads a higher force on the balance and a better accuracy. This does not affect the surface tension measurements but small interfacial tensions can be performed more accurately with the ring method.
- Some substances have poor wetting characteristics on platinum. The surface line between a ring and the liquid is more even than that of a plate.

Advantages of the plate method:

- Unlike the ring method, correction calculations are not necessary with the plate method.
- The densities of the liquids do not have to be known contrary to ring method.
- The surface is only touched and not pressed into and pulled out of the other phase. So the phases do not mix each other [2].

## **2.7.2 Methods Measure The Pressure**

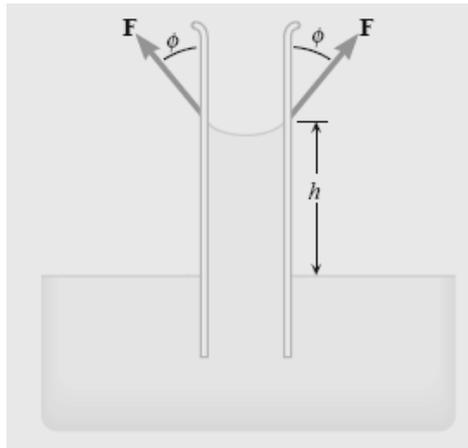
Methods measure the pressure are used for measuring the surface tension with pressure.

### **2.7.2.1 The Capillary Height Method**

The capillary height method is competent of good accuracy when convenient precautions are taken. Because the calibration of capillary is difficult as it requires a traveling microscope [20].

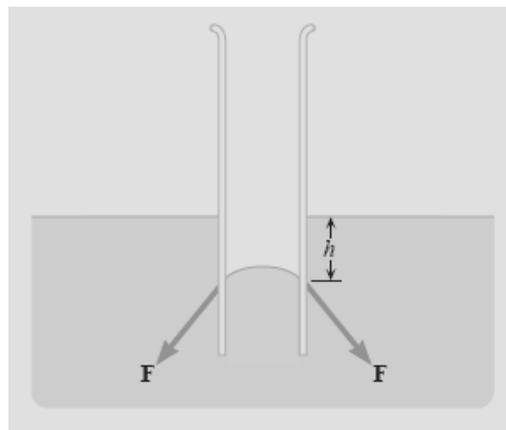
The surface tension is formed because of the intermolecular forces of attraction that molecules in a liquid apply on one another. Cohesive forces are these forces that are between like molecules. A liquid is often in contact with a solid surface. Additional forces of attraction come into play. Adhesive forces are formed between unlike molecules which are molecules of the liquid and molecules of the solid surface.

When both ends opened capillary tube is inserted into a liquid, the result of the competition between cohesive and adhesive forces can be observed. In the figure 2.15, a glass capillary is inserted into water. The adhesive forces are stronger than the cohesive forces. So water molecules are attracted to the glass more strongly than to each other. It is shown that the water surface curves upward against the glass. The water wets the glass. Force  $F$ , oriented at an angle  $\theta$ , is acting on the circular boundary between the water and the glass and pulls the water up a distance  $h$  in the tube.



**Figure 2.15 :** Water rises in a glass capillary due to the surface tension of the water and the fact that the water wets the glass surface. Adhesive forces are stronger than cohesive forces [16].

Figure 2.16 shows a glass capillary inserted into mercury. In this case, the cohesive forces are stronger than the adhesive forces. The mercury atoms are attracted to each other more strongly than they are to the glass. So the mercury surface curves downward against the glass and it is shown that mercury does not wet the glass. Unlike the behavior of the liquid in Figure 2.15, force  $F$  pulls the mercury down into the tube to a height  $h$ .



**Figure 2.16 :** Mercury falls in a glass capillary due to the surface tension of the mercury and the fact that the mercury does not wet the glass surface. Cohesive forces are stronger than adhesive forces [16].

The liquids' behavior in both Figures 2.15 and 2.16 is called capillary action [16].

### **2.7.2.2 Maximum Bubble Pressure Method**

Pressure is measured in a bubble formed at the end of the capillary when air or a gas is blown through the capillary into the liquid. The bubble grows and reaches its maximum value, at the same time the pressure decreases when the bubble provides the shape of a hemisphere. The pressure decreases when the bubble grows further and finally bursts [16].

### **2.7.3 Methods Measure the Size or Dimensions of a Drop**

The size or dimensions of a drop is also used for measuring the surface tension.

#### **2.7.3.1 The Pendant Drop Method**

For the pendant drop method, the apparatus is simple. The liquid is injected from a needle. So a drop is formed on the tip of the needle. The drop is optically seen and surface tension is measured from the size and shape of the drop [5]. The technique requires skill for forming the drop and maintaining its size and shape during the measurement of its narrowest and widest diameters  $d_1$  and  $d_2$  [18].

#### **2.7.3.2 The Spinning Drop Method**

This method is used to determine interfacial tensions between two liquids when the surface tension values are so low [21].

A small drop of a sample is injected inside a thin capillary tube with another liquid. The tube is then rotated at a high speed (about 2000 rpm) and a drop of the other liquid having a lower density is placed into the capillary. The drop moves into the center of the capillary tube and assumes generally the shape of a cylinder with curved edge. The interfacial surface tension is calculated from the angular speed of the tube and the radius of the drop [18].

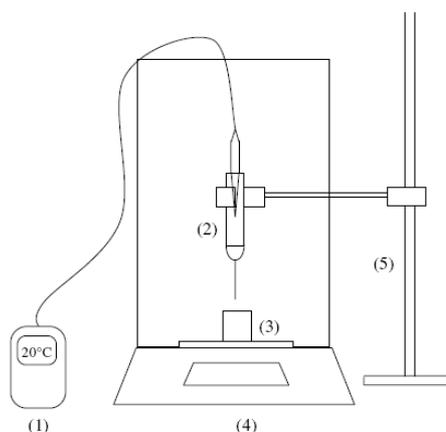
#### **2.7.3.3 The Sessile Drop Method**

The sessile drop method is measured by a contact angle goniometer (Figure 2.9) using an optical subsystem to capture the profile of a pure liquid on a solid substrate. The angle formed between the liquid/solid interface and the liquid/vapor interface is the contact angle. Angle between the baseline of the drop and the tangent at the drop

boundary is measured. Current-generation systems employ high resolutions cameras and software to capture and analyze the contact angle [18].

#### 2.7.3.4 The Drop Volume/Weight Method

The drop volume/weight method requires a buret or a syringe. Either the volume required to form the drop is measured or the number of drops formed by a measured volume of liquid is counted [18]. The sample is loaded firstly into the syringe and drops of the sample are allowed to fall and collected in a beaker (Figure 2.17). Approximately 20 drops of the sample are enough to collect in each experiments [22].



**Figure 2.17 :** A schematic diagram of the overall experimental set-up. (1) Digital thermometer; (2) Syringe; (3) Beaker; (4) Digital balance; (5) Stand [22].

Surface tension is calculated by the equation:

$$\gamma = \frac{V \rho g}{2\pi r \psi} = \frac{mg}{2\pi r \psi} \quad (2.25)$$

V = volume of a liquid detached in the form of a single drop from the tip of a syringe.

g = acceleration of gravity.

r = the radius of the outer edge of the tip.

$\rho$  = the density of the liquid.

$\psi$  = the Harkins-Brown correction factor [10].



**Figure 2.18 :** The drops falling down [10].

$\psi$  is determined with semi-empirical methods by Harkins and Brown.  $\psi$  is accepted as a function of  $r$  and  $V$  only. Conventionally  $\psi$  is explained in two functional forms:

$$\psi = f(r/V^{1/3}) \quad (2.26)$$

$$\psi = f(r(\psi/V)^{1/3}) \quad (2.27)$$

For surface tension measurements with drop weight/volume method technique, Wilkinson and Kidwell developed the correction factor of Harkins-Brown equations. The equation 2.25 is suggestive the most as long as the measurement system satisfies the condition that  $r/V^{1/3} \leq 0.7$ . If  $r/V^{1/3} > 0.7$ , equation 2.26 give the best results [21, 22].

$$\text{For } r/V^{1/3} \leq 0.7 \quad \psi = 0.6 + 0.4\left(1 - \frac{r}{V^{1/3}}\right)^3 \quad (2.28)$$

$$\text{For } r/V^{1/3} > 0.7 \quad \psi = 0.9054 - 0.7249\left(\frac{r}{V^{1/3}}\right) + 0.4293\left(\frac{r}{V^{1/3}}\right)^2 \quad (2.29)$$

## 2.8 Most Commonly Used Liquid Desiccants

Desiccants have the speciality of removing and retaining moisture from air brought into contact with them. Moisture in the air is extracted and the end dry air can be used for air conditioning systems.

Most commonly used liquid desiccants are LiCl, LiBr, CaCl<sub>2</sub> and the mixtures of these solutions. In this study, LiCl, CaCl<sub>2</sub> and the mixtures of these liquids are used.

In literature and scientific publications LiCl solutions despite of their significant higher costs, are widely recommended as the optimal desiccant for liquid absorption cooling systems due to their better absorption characteristics compared to alternatives

such as  $\text{CaCl}_2$  solutions or CELD, which for example can be mixtures between LiCl and  $\text{CaCl}_2$  solutions [23].

Lithium chloride is the most stable liquid desiccant and has a large dehydration concentration. It has a low vapour pressure and low viscosity. However its cost is very high if it is compared with the other desiccants. Calcium chloride is the most readily available and also the cheapest desiccant. But the bad thing is that calcium chloride is unstable depending on the air inlet conditions and the concentration of the desiccant in the solution. It has also relatively high vapour pressure and high viscosity. To make the low cost, more stable and more effective desiccant, calcium chloride and lithium chloride are mixed in different weight conditions and the new liquid desiccant is created. This new liquid desiccant is cost-effective liquid desiccant (CELD) [7, 16].

The low surface wetting capability compared to the alternatives, as another disadvantage of pure LiCl solutions in desiccant optimization research has been neglected up to now. Surface wetting capability to a high degree effects the liquid absorption cooling aggregate design and aggregate costs. For example the heat and mass transfer surfaces have to be increased in LiCl aggregates and the surfaces have to be specially treated and optimized for improved desiccant distribution followed by higher material and manufacturing costs. These surface wetting effects in combination with the significantly higher costs for LiCl, may lead to a new approach in the selection of desiccants for the liquid absorption cooling aggregates, probably away from pure LiCl solutions to  $\text{CaCl}_2$  solutions or CELDs and make deeper research in the surface wetting characteristics of LiCl and  $\text{CaCl}_2$  solutions and mixtures between them necessary.

For absorption, vapor pressure of air must be higher than the liquid's vapor pressure. In Figure 2.19, it is seen the vapor pressures of different concentrations of LiCl and  $\text{CaCl}_2$  solutions at different temperatures. The higher concentration, the the best absorption [24].

The literature surface tension values, for 40% weight  $\text{CaCl}_2$  and 40% weight LiCl, are 0.09025 and 0.09058, respectively as seen in the Table 2.3

**Table 2.3** : The literature surface tension values at 20°C [6]

Samples	Surface Tension (N/m)
40% CaCl <sub>2</sub>	0.09025
40% LiCl	0.09058
Pure H <sub>2</sub> O	0.0728

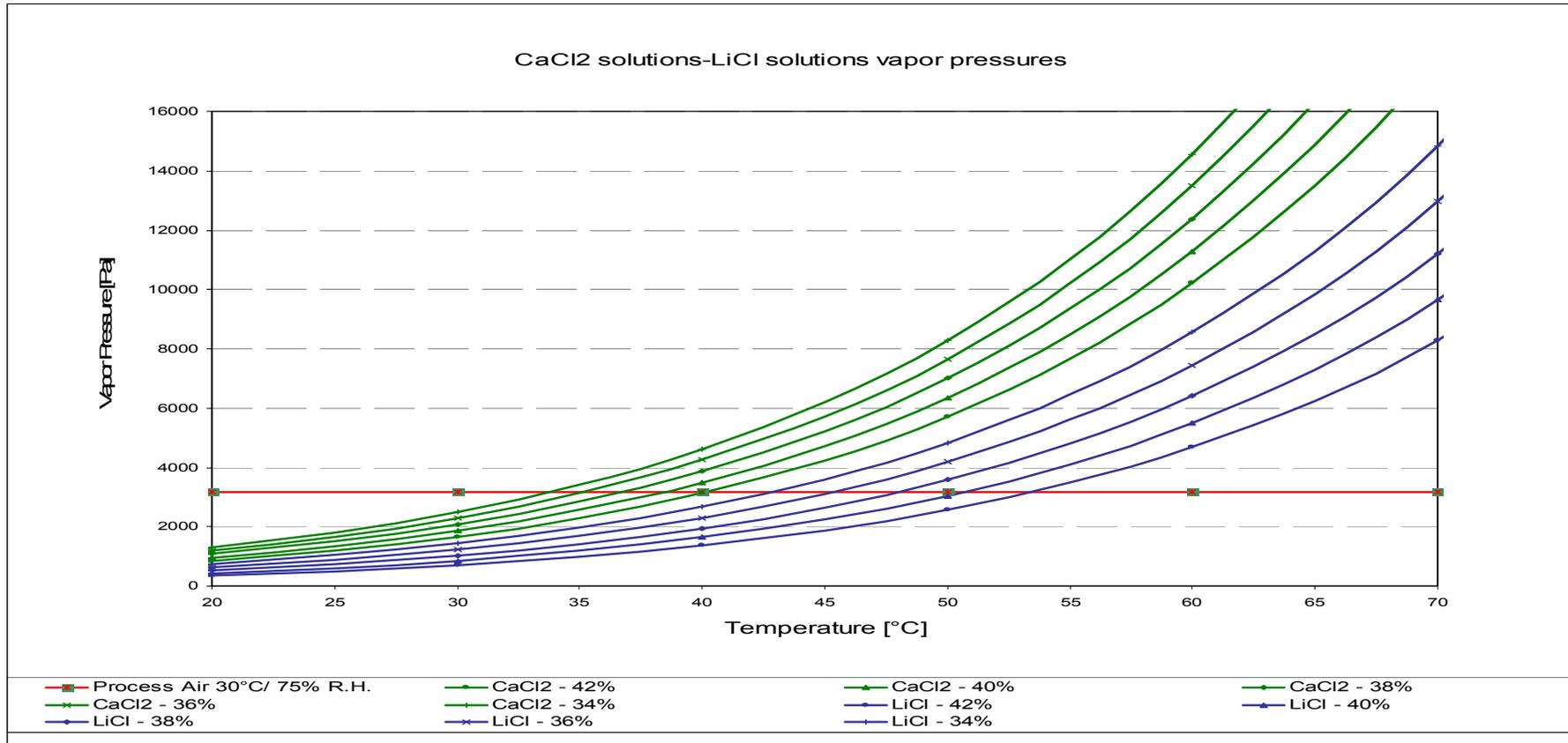


Figure 2.19 : The vapor pressure of air and different concentration of LiCl and CaCl<sub>2</sub> [24].

## 2.9 Similar Studies Made By Scientist

Grossman and his friends constructed a 16 kWt solar driven liquid desiccant system for cooling, dehumidification and air conditioning in the Mediterranean city of Haifa. The system comprises a dehumidifier and a regenerator. Working fluid is LiCl-water. The system monitored operation conditions for five summer months and they described the operation of the experimental system and presented the measured data and the calculated performance parameters. The thermal COP was found about 0.8 and it was anticipated to achieve better COP's in the future [7].

Pietruschka and his friends investigated an experimental performance analysis and modelling of liquid desiccant cooling systems for air conditioning in residential buildings. Solid rotating desiccant wheels were compared with liquid sorption systems using contact matrix absorbers and cross flow exchangers in four system. The best performance was achieved for a cross flow heat exchanger for simultaneous dehumidification and indirect evaporative cooling.  $\text{CaCl}_2$  and LiCl solutions were used for as liquid desiccants and LiCl solution gave 40-50% higher dehumidification rates [8].

Dai and his friends proved liquid desiccant dehumidification for air conditioning application. A detailed account of the general features of the major desiccant dehumidification techniques and configurations of the related systems, a summary of the experimental and analytical studies to optimize the system performance were explored [25].

Conde searched liquid desiccant based air conditioning systems (LDACS) on the market. He found that air conditioning is needed to improve living conditions and productivity, to warrant safe hygienic conditions in hospitals and sports facilities, to make many manufacturing processes at all possible, to avoid material losses in long term storage of some goods and etc. [26].

Jain and his friends studied about performance analysis of liquid desiccant dehumidification systems. They compiled experimental performance data of liquid desiccant dehumidifiers for triethylene glycol, lithium chloride and calcium chloride and empirical dehumidification effectiveness and mass transfer correlations [27].

Conde reported the development of calculation models for the thermophysical properties of aqueous solutions of the chlorides of lithium and calcium in sorption based air conditioning equipment. He reviewed solubility boundary, vapour pressure, density, surface tension, dynamic viscosity, thermal conductivity, specific thermal capacity and differential enthalpy of dilution for the purpose of providing calculation models of the aqueous solutions [24, 28].

Ahmed and his friends researched the thermodynamic analysis of liquid desiccants in order to analyze the performance of the system. They predicted the vapour pressure property based on a classical thermodynamics approach and found that the predicted values for lithium chloride agree very well with the experimented results. They mixed the desiccants to create CELD for developing the method and used simple mixing rules to predict the vapour pressure, density and viscosity of the desiccant mixture. The inclusion of the interaction parameter worked very well for calculating the viscosity of the desiccant mixture and not so well for density and vapor pressure of the desiccant mixture [29].

Hassan and his friend investigated the dehumidification of air with a newly suggested liquid desiccant-CELD. The aim of this study is stabilize the solution of calcium chloride by mixing with calcium nitrate in different weight combinations. Density, viscosity and vapour pressure of the mixture were obtained and heat and mass transfer analysis between a thin liquid layer of the desiccant were studied. The mixture of 50% weight of calcium chloride and 20% weight of calcium nitrate gave a significant increase in vapor pressure depression [30].

Al-Farayedhi and his friends made an experimental study of an aqueous desiccant mixture system on the performance of a structured packing dehumidifier and the regenerator system. Different proportions of an aqueous desiccant mixture of chlorides of calcium and lithium solutions with an overall concentration of 40%. It is found that the lithium chloride content in the solution increased, the effectiveness of the dehumidifier and the regenerator increased and the regeneration of lithium chloride solution was more effective than that of calcium chloride solution. The dehumidifier effectiveness using the desiccant mixture of 20 weight %  $\text{CaCl}_2$  and 20 weight %  $\text{LiCl}$  was found to be close to that of 45 weight % solution of  $\text{CaCl}_2$  [31].

Ertas and his friends inquired the properties of a new liquid desiccant solution: lithium chloride and calcium chloride mixture. They mixed calcium and lithium

chlorides in different weight concentrations to make more stable, low cost liquid desiccant. They measured the density, viscosity, solubility and vapour pressure of different combinations of the mixtures. It is found that the vapour pressure of the CELD solution lower than that of a pure calcium chloride and CELD has low viscosity and highly soluble over a considerable temperature range [32].

Li and his friends made a research on ratio selection of a mixed liquid desiccant of LiCl-CaCl<sub>2</sub> solutions for better dehumidification effect under certain working conditions. They found that the dehumidification effect could be raised by more than 20% with mixed LiCl and CaCl<sub>2</sub> solution compared to single LiCl solution [33].

Gerilakan explained surface tension and the factors effects surface tension. Surface tension, contact angle, the importance of surface tension, how to measure surface tension, factors effect surface tension, ink and material, the treatments apply to material were expressed [19].

Tekin and her friend investigated concentration and temperature relationship between refractive index and surface tension. They found that increasing concentration of solution increased the surface tension values. Increasing the medium temperature decreased the surface tension. Generally the surface tension of liquids decreased proportional to temperature. As a result, the refractive index measurements were shown to be more accural than surface tension measurements [34].

Flury and his friends compared different methods to measure contact angles of soil colloids. They compared five different methods such as static sessile drop, dynamic sessile drop, Wilhelmy plate, thin-layer wicking and column wicking. Five different colloid films and three different test liquids were chosen for experiments. The static and dynamic sessile drop methhods yielded the most consistent contact angles. For porous films, the contact angles decreased with time. The thin-layer and column wicking methods were the least consistent methods [35].

Chan and his friends analysed new drop weight method for surface tension determination of liquids. They aimed to verify the validity of the Harkins-Brown correction factors and the Bond number correlation. The LCP coefficient method was developed to eliminate the influence of liquid properties on the drop weight method. As a result, they found that the LCP coefficient method gave the best reliability and accuracy among the drop weight analysis for the liquids examined [36].

Mori and his friend researched the drop volume method and described the formulation of the Harkins-Brown correction factor for drop volume method. They investigated two methods of Harkins-Brown correction factor. One of them is for the drop weight technique for determining the surface tension of liquids and the second one is for the prediction of the volume of each drop to detach from a nozzle tip when the surface tension is known [37].

Ozdemir and her friend studied about wetting characteristics of aqueous rhamnolipids solutions. They comprised wetting performance of rhamnolipids and sodium dodecyl sulfate on a hydrophilic glass surface, a hydrophobic polymer, a polyethylene terephthalate and a gold surface. Better wetting properties obtained at lower concentration of rhamnolipids than sodium dodecyl sulfate solutions. The best liquid wettability capacity was on glass, then gold and polyethylene terephthalate, respectively [38].

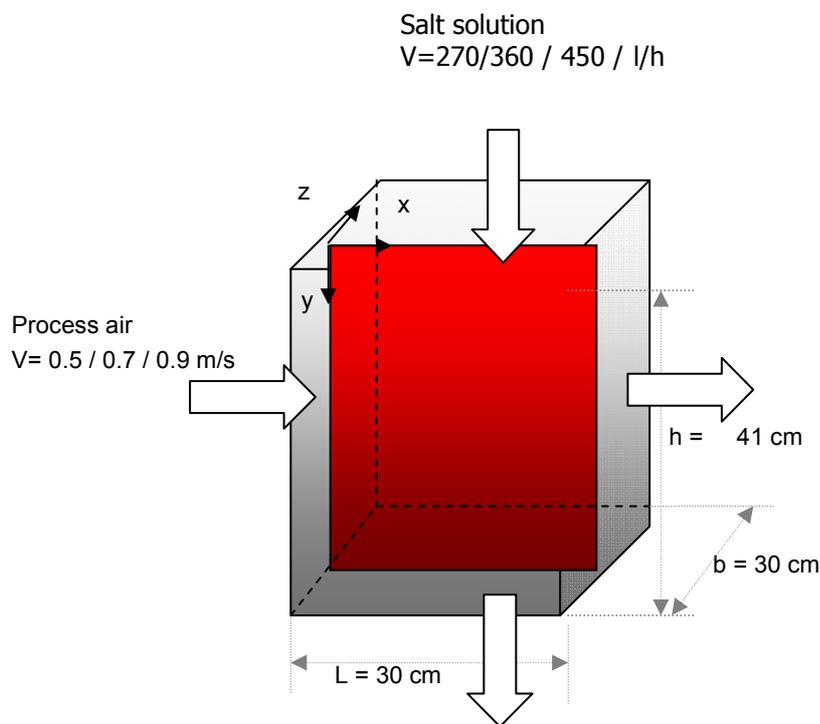
Starov and his friends explained kinetics of wetting and spreading by aqueous surfactant solutions. They aimed to give an overview on some dynamic wetting and spreading phenomena in the presence of surfactants in case of smooth or porous substrates. Spreading over hydrophobic substrates, spontaneous rise and imbibition of surfactant solutions into hydrophobic capillaries, capillary imbibition into partially wetted porous medium, spreading of surfactant solutions over thin aqueous layers, instabilities in the course of spreading, spreading of surfactant solutions over porous substrates and superspreading were explained [39].

Hay and his friends explained the theoretical model for the wetting of a rough surface. Using the model presented, they predicted the rate of liquid spreading and geometry of the surface roughness. The model was shown to work very well for an idealized geometry [40].

Prabhu and his friends explored the effect of substrate roughness on spreading of coconut, sunflower, palm and mineral oils on stainless steel substrates. All the oils took longer period of time on rough surfaces than on smooth surfaces to reach the same degree of wetting. Contact angle decreased with increase in roughness. Low viscosity liquids exhibit improved wetting characteristics during spreading on rough surfaces [41].

## 2.9 Stuttgart University of Applied Sciences Studies

In Stuttgart University of Applied Sciences, Sustainable Energy Competence (SENCE), Tina Päßler and her friends are studying on a liquid desiccant cooling system. Salt solutions of  $\text{CaCl}_2$  and  $\text{LiCl}$  are used as a liquid desiccant for absorption process. For improving the absorption efficiency, different paddings are tested such as plexiglass, polypropylene, and normal glass. This study is still going on for achieving the efficiency cooling. The absorption process box, its dimensions and the inlet conditions for air and salt solutions are shown in Figure 2.19 and Table 2.4 [42].



**Figure 2.20 :** The absorption process studied in Stuttgart University of Applied Sciences [42].

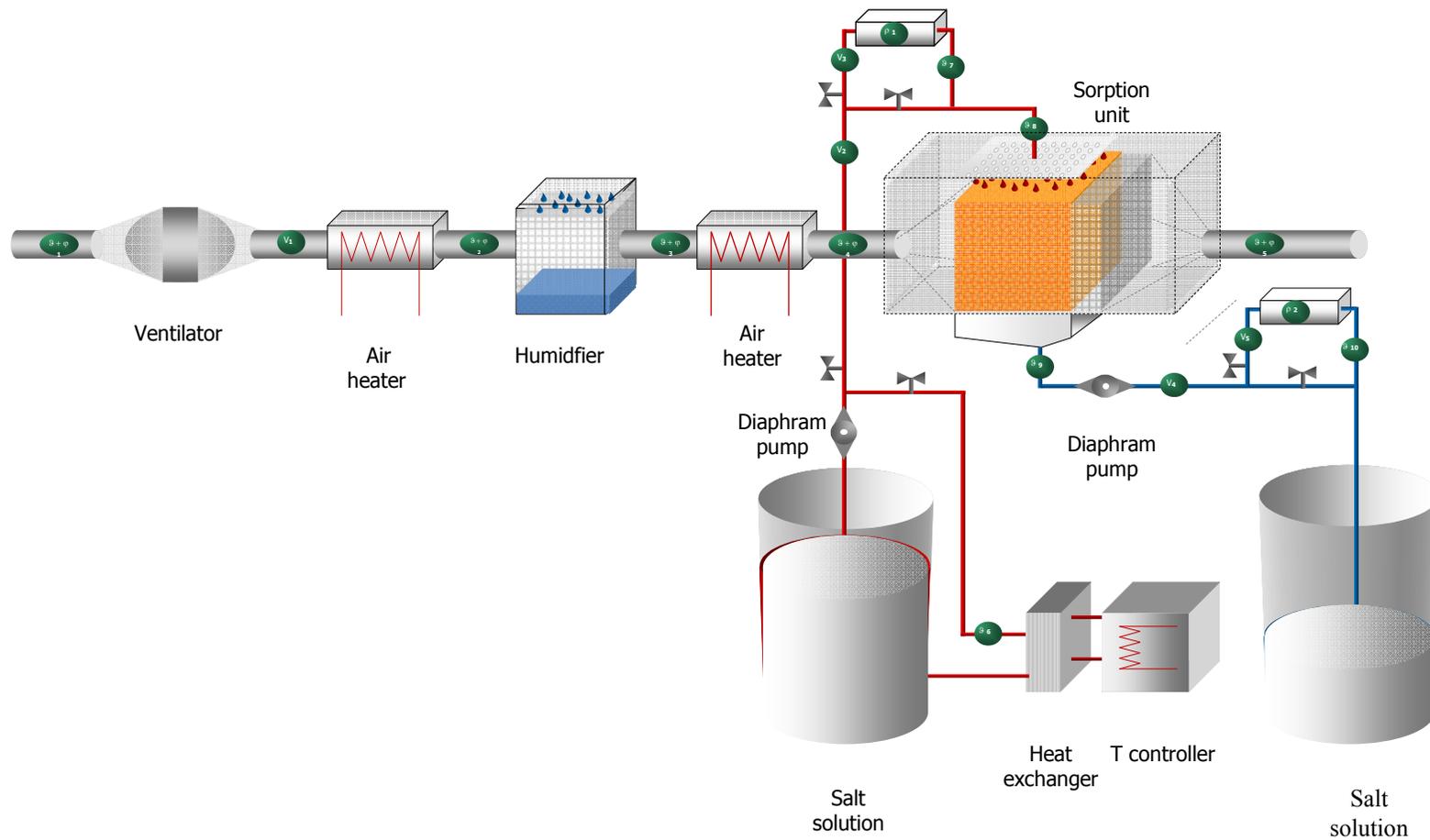
Firstly, air is cleaned in ventilator and enters the heater. It is heated for increasing the humidity capacity. The air is humidified in humidifier and enters the heater again for the constant conditions of the air before the sorption unit. While humidifying the air, the temperature decrease because of the absorption of the water (under  $30^\circ\text{C}$ ). For the measurements it is need to have constant conditions of  $30^\circ\text{C}$ , so because of this the air is heated again after the humidifier. All the measurements are done with the same temperature and humidity ( $30^\circ\text{C}$  and 75% R.H.). The red line in Figure 2.20 is the salt solution which enters the sorption unit. The blue one is the liquid that flows out of the

sorption unit into another tank. Air is brought into contact with the liquid desiccant coming from the red tank in the sorption unit. The humidity is absorbed from air by direct contact to the liquid desiccant. The air cools and leaves the process. The liquid desiccant leaves the sorption unit to the blue tank as a dilute desiccant and goes to the regeneration unit to become regenerated again. For the regeneration the same unit is used. For this only the tank of salt solution is changed [42].

**Table 2.4 :** The inlet conditions of air and salt solutions [42].

Parameter	Size
Supply air temperature	30°C
Relative humidity	75 %
Absolute humidity	20 g/kg
Air flow rate	0.5; 0.7; 0.9 m/s
Solution concentration	~ 41 %
Solution temperature	30 - 40 °C
Solution density	3; 4; 5 m <sup>3</sup> /m <sup>2</sup> h
Solution flow rate	270; 360; 450 l/h

The tank of salt solution that is for absorption process is 41%. The other tank has a concentration of 35% salt solution [42].



**Figure 2.21** : The liquid desiccant cooling system studied in Stuttgart University of Applied Sciences [42].

### 3. EXPERIMENTAL STUDY

#### 3.1 Aim of the Experiments

In this study, the aim of the project that is studied in HfT Stuttgart is to improve the absorption efficiency in air conditioning system. The aim of the experiments that i made in HfT Stuttgart and ITU is to find the convenient solution and paddings for air conditioning system.

The experiments that are made for purposes are offered:

- Surface tensions of LiCl, CaCl<sub>2</sub> and CELD solutions by “Drop Volume/Weight Method” in Building Chemistry Laboratory in HfT Stuttgart.
- Comparison the wettability of CaCl<sub>2</sub>, LiCl and CELD solutions on rough glass surface in Building Physics Laboratory in HfT Stuttgart.
- Contact angles of CaCl<sub>2</sub>, LiCl and CELD solutions on different paddings by goniometer in Surface Chemistry Laboratory in the department of Mineral Processing Engineering in ITU.

As a liquid desiccant, LiCl, CaCl<sub>2</sub> and three different weight concentration of CELD solutions are used. According to the changed LiCl/CaCl<sub>2</sub> ratio: 100% CaCl<sub>2</sub> (100C), 70% CaCl<sub>2</sub>+30% LiCl (70C+30L), 50% CaCl<sub>2</sub>+50% LiCl (50C+50L), 30% CaCl<sub>2</sub>+70% LiCl (30C+70L) and 100% LiCl (100L).%35 weight of overall concentration of solutions are used in the experiments.

The room temperature is 25°C and the solutions' temperature are approximately 20±0.5 °C.

Surface tension measurements are considered by “Drop Volume/Weight Method”. Pure water is tested as a referens firstly. CaCl<sub>2</sub> has the lowest, LiCl has the highest surface tension. CELD solutions has the surface tension values between LiCl's and CaCl<sub>2</sub>'s. When the concentration of CaCl<sub>2</sub> in the solution increase, the surface tension decrease. The literature information of surface tensions of 40% weight LiCl and 40% weight CaCl<sub>2</sub> is known. As known, when the concentration of the solution

decreases, the surface tension decreases. 35% weight of LiCl and CaCl<sub>2</sub>'s surface tension values are less than 40% weight of LiCl and CaCl<sub>2</sub>. The results are acceptable and concordant with the literature values. "Drop Volume/Weight Method" is convenient for measuring the surface tension.

Wettability is measured by the method developed by Mr. Dietrich SCHNEIDER. The solutions are flowed on the glass rough plate and compared the wettability area of the solutions. Pure water is experimented for a reference. The measurements are tested using the solutions with an overall concentration 35 wt%. In the experiments concentration 35 wt% was used because of the usage in the project of HfT Stuttgart and the lower cost than the others.

### 3.2 Surface Tension Measurements

"Drop Volume/Weight Method" is used for measuring the surface tensions. Surface tension measurements are made in the laboratory of Building Chemistry in Stuttgart University of Applied Sciences. To set up the system; a syringe, a thermometer, a beaker and Sortirius Universal digital balance are used. The solutions temperature is readed as 20°C±0.5 on the termometer. Counting the droplets and collecting them in the beaker are used to calculate the surface tension in the "DropVolume/Weight Method" equation.



**Figure 3.1 :** The setup of the drop volume/weight method



**Figure 3.2 :** The breaking-off the droplet

All of the liquid groups and pure water are tested for surface tension. Pure water is tested firstly for a reference. The measurements are repeated 20 times for each liquid group. Then the acceleration of these 20 results are calculated.

### **3.3 Wettability Measurements**

Surface wetting is important for absorption system. The method, developed by Mr. Dietrich Schneider from HfT Stuttgart, is run in Building Physics Laboratory in Stuttgart University of Applied Sciences. The surface wetting of 100C, 70C+30L, 50C+50L, 30C+70L and 100L were compared in a rough glass made system. The liquids are filled in a funnel at the same level for each liquid. The adjustable gauge was used to hold and fall the liquids down to the glass plate. The liquid, has the best wetting, spreads at most. The liquid coming from the glass, collected in 8 cups at the below of the glass plate. The liquid that has the best surface wetting capacity, spreads to the all cups. If the surface wetting is not good enough, it does not disperse on the glass so much, so only the cups on the middle should have liquid inside. The scheme of the wettability system is indicated in Figure 3.3 and 3.4 below.



**Figure 3.3 :** The glass made surface wetting system



**Figure 3.4 :** The wettability of liquids on the glass

### **3.4 Contact Angle Measurements**

Pure water and all different weight of solutions are tested on different paddings. The paddings that are used in the experiments are

- Polypropylene
- Normal glass
- Plexiglass (Bayer Plastics TechCenter)

The measurements are made in Surface Chemistry Laboratory of Mineral Processing Engineering Department in ITU. The contact angles are read on different paddings by contact angle measurement device, goniometer (NRL C.A. 100-00-230). Owing to

this, the liquids' wettability capacity is compared on different paddings. The setup of the experiment system is shown in the Figure 3.5



**Figure 3.5 :** Contact angle measurement device, goniometer

If the contact angle of the liquid is small, that means the liquid wets the surface better.



#### 4. RESULTS AND DISCUSSION

In this part of the study, the results of the experiments are examined. Evaluation and explanation of the experiments can be found below.

Surface tension is calculated and the average results of the groups at 20°C is shown below in Table 4.1. Detailed surface tension results are listed in the Appendix A.1.

**Table 4.1** : Average surface tension results of pure water and groups at 20°C

Samples	Surface tension (N/m)
Pure water	0.07302
100C	0.08866
70C+30L	0.08894
50C+50L	0.08908
30C+70L	0.08917
100L	0.08922

In Figure 4.1, it is seen that surface tension of water is the lowest one and when the concentration of the LiCl in the solution increases, the surface tension increases.

The liquids surface wetting capabilities were compared with water. The detailed datas of table of liquid levels collected in the cups and the figures of the comparison of the wettability of solutions and water on glass plate are exhibited in Appendix A.2. The areas under the curve shown in the Figure 4.1 were calculated with an integral calculus. The liquid that has the best wetting capability, spreads the most. So that, the area between this liquid's curve and the water's curve should be the smallest one. The point that is intersection between liquid and water and the point that cuts the water's x axis are used to measure the area with the formulation of  $\int y.dx$ . The areas between the water trendline, the areas of the solutions and the wettability proximity of the solutions to the wettability of water are listed in the Table 4.2.

**Table 4.2 :** The liquids compared with the pure water's wettability

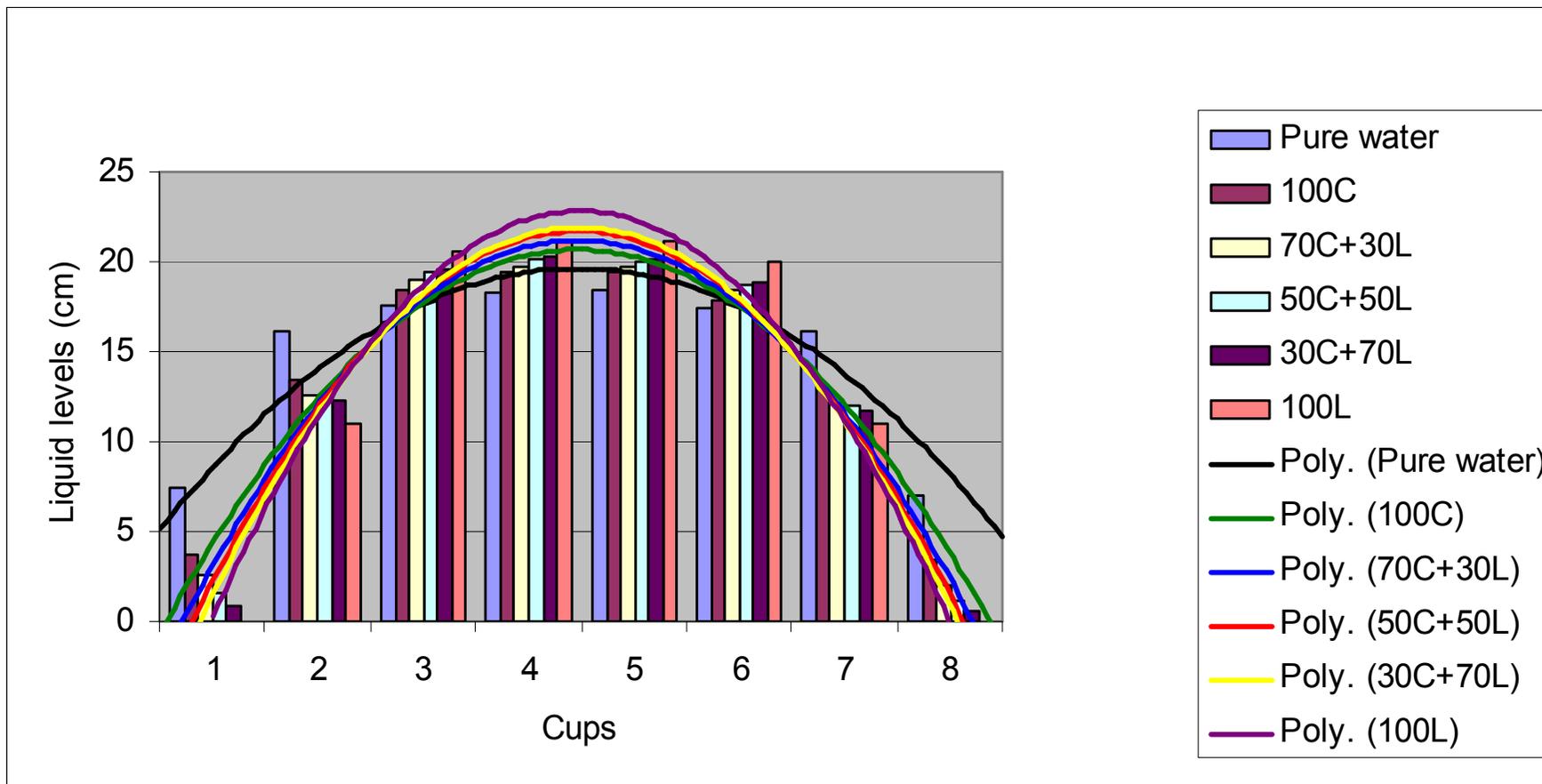
Samples	Areas between the water	Samples areas	Wettability proximity to the water (%)
100C	7.693649467	105.8609456	0.873
70C+30L	9.135496824	102.9772509	0.849
50C+50L	9.863584426	101.5210756	0.837
30C+70L	10.62546435	99.9973158	0.825
100L	11.36198721	98.52427008	0.813

In table 4.2, the sample areas are shown.  $\text{CaCl}_2$ 's sample area is the highest one so  $\text{CaCl}_2$  wets the surface more than the other liquids. When the solutions are compared with the water, water has the best wettability capability. If it is thought that water wets the surface as a 100%, it is considered how much proximity of the other liquids wets the surface to the water. The best wettability proximity to the water is  $\text{CaCl}_2$  and got 87.3%. That means if the water wets the surface as a 100%,  $\text{CaCl}_2$  wets 87.3%. The best sorption capability liquid,  $\text{LiCl}$ , has the worst surface wetting capacity when compared to the others.

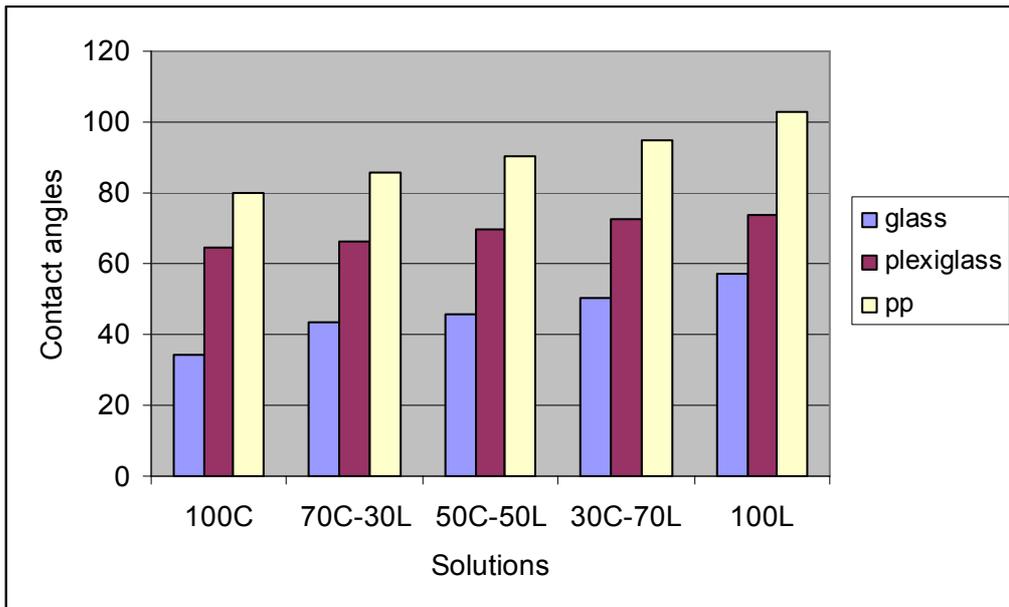
The wettability capacity of the liquids on different surfaces were compared with using goniometer. Glass, plexiglass and polypropylene were used to compare the wettability. Table 4.3 and Figure 4.2 below, are seen the comparison between the liquids and paddings. The detailed contact angle values and figures are displayed in Appendix A.3.

**Table 4.3 :** Average contact angle values of solutions on different paddings

	100C	70C+30L	50C+50L	30C+70L	100L
Glass	34.25	43.69	45.70	50.50	56.88
Plexiglass	64.44	66.20	69.75	72.44	73.67
Polypropylene	80.00	86.00	90.06	94.69	103.13



**Figure 4.1** : Comparison of surface wetting values of groups and pure water at 20°C



**Figure 4.2 :** The solutions' contact angles on different paddings

As a result, increasing  $\text{CaCl}_2$  percentage in the solution causes to decrease the contact angles. So it is proved that the wettability capability of  $\text{CaCl}_2$  is the best one and  $\text{LiCl}$  wets the surface at least. Increasing CELD solutions' wettability capacity is proportional to increasing the  $\text{CaCl}_2$  percentage in the solution.

The paddings such as glass, plexiglass and polypropylene are compared in their wettability capacity. On the glass surface contact angles of the liquids are smaller than the others. It causes to spread the liquids most on glass surface. Glass is followed by plexiglass and polypropylene, respectively as shown in the figure.

## 5. CONCLUSION AND RECOMMENDATION

The project about liquid desiccant cooling system is continuing in SENCE of Stuttgart University of Applied Sciences. The absorption efficiency is intended to be improved. In this system, LiCl and CaCl<sub>2</sub> are used as a liquid desiccant and the air is cooled. The inlet concentration of liquids to the absorption process is 41% weight and outlet is 35% weight. Different paddings are used in the absorption process as glass, plexiglass and polypropylene.

- It is found that CaCl<sub>2</sub> wets the rough glass surface area more than LiCl. CELD solutions' wettability capacity is between LiCl's and CaCl<sub>2</sub>'s. Increasing the weight concentration of CaCl<sub>2</sub> in the solution increases the wettability area on the glass surface. Pure water wets the surface better than all of the liquids which are tested. Wettability proximity of the liquids to the water are considered and the closest value is CaCl<sub>2</sub>'s. So CaCl<sub>2</sub>'s wettability capacity is the best for absorption system in liquid desiccant air conditioning systems.
- It is realised that surface tension is inversely proportional to wettability. Because surface tension wants to pull all the liquid molecules together. If the pulling force (surface tension force) is stronger, the liquid can not spread so much, so the wettability does not occur.
- It is deduced that CaCl<sub>2</sub>'s contact angle is smaller than the other liquids' contact angles on different paddings. When CaCl<sub>2</sub>'s weight concentration increase, the contact angles decrease. So LiCl, which has best sorption capability, has worse wettability. When compared the paddings, the liquids wettability increases in the order of pp, plexiglass, glass, respectively. Glass material is convenient for wettability in sorption systems.
- For liquid desiccant cooling systems, CELD solutions wettability capacity is better than LiCl, which has the highest cost. As a padding, on glass material the liquids have the best wettability. In a conclusion; CELD solutions and

glass material are preferred for the efficiency, low cost liquid desiccant cooling systems.

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## **APPENDICES**

**APPENDIX A.1** : The experimental surface tension datas

**APPENDIX A.2** : The experimental wettability datas

**APPENDIX A.3** : Contact angle values on different paddings

## APPENDIX A.1

**Table A.1:** The surface tension values for CaCl<sub>2</sub>, LiCl and different concentrations of CELD solutions

Sample	Composition	r (mm)	g (N/kg)	Density (g/cm <sup>3</sup> )	m total (g)	drop	m drop (g)	V drop (ml)	r/V <sup>1/3</sup>	correc<0.7	S.T. (N/m)
1	100C	0.75	9.80665	1.352	0.12708	4	0.031770	0.023499	0.261847	0.76087887	0.086936362
2	100C	0.75	9.80665	1.352	0.09119	3	0.030397	0.022483	0.265733	0.75835170	0.083455520
3	100C	0.75	9.80665	1.352	0.26343	8	0.032929	0.024356	0.258739	0.76291970	0.089866160
4	100C	0.75	9.80665	1.352	0.59516	14	0.042511	0.031443	0.237621	0.77724446	0.113880098
5	100C	0.75	9.80665	1.352	0.48295	12	0.040246	0.029768	0.241999	0.77420864	0.108233743
6	100C	0.75	9.80665	1.352	0.52337	13	0.040259	0.029778	0.241972	0.77422715	0.108267184
7	100C	0.75	9.80665	1.352	0.70368	16	0.043980	0.032530	0.234946	0.77911664	0.117531023
8	100C	0.75	9.80665	1.352	0.15912	5	0.031824	0.023538	0.261699	0.76097578	0.087073039
9	100C	0.75	9.80665	1.352	0.19218	6	0.032030	0.023691	0.261137	0.76134382	0.087594306
10	100C	0.75	9.80665	1.352	0.15950	5	0.031900	0.023595	0.261491	0.76111186	0.087265375
11	100C	0.75	9.80665	1.352	0.16382	5	0.032764	0.024234	0.259172	0.76263439	0.089449990
12	100C	0.75	9.80665	1.352	0.26202	8	0.032753	0.024225	0.259202	0.76261442	0.089420936
13	100C	0.75	9.80665	1.352	0.16015	5	0.032030	0.023691	0.261137	0.76134382	0.087594306
14	100C	0.75	9.80665	1.352	0.22810	7	0.032586	0.024102	0.259644	0.76232386	0.088999486
15	100C	0.75	9.80665	1.352	0.16274	5	0.032548	0.024074	0.259744	0.76225793	0.088904168
16	100C	0.75	9.80665	1.352	0.22941	7	0.032773	0.024240	0.259149	0.76264977	0.089472367
17	100C	0.75	9.80665	1.352	0.19140	6	0.031900	0.023595	0.261491	0.76111186	0.087265375
18	100C	0.75	9.80665	1.352	0.29462	9	0.032736	0.024213	0.259247	0.76258497	0.089378125
19	100C	0.75	9.80665	1.352	0.29604	9	0.032893	0.024329	0.258832	0.76285850	0.089776706
20	100C	0.75	9.80665	1.352	0.12625	4	0.031563	0.023345	0.26242	0.76050479	0.086411036

**Table A.1:** The surface tension values for CaCl<sub>2</sub>, LiCl and different concentrations of CELD solutions (continued)

21	100L	0.75	9.80665	1.2108	0.60924	16	0.038078	0.031448	0.237609	0.77725298	0.102001322
22	100L	0.75	9.80665	1.2108	0.15900	5	0.031800	0.026264	0.252315	0.76719221	0.086302366
23	100L	0.75	9.80665	1.2108	0.32829	10	0.032829	0.027113	0.249651	0.76898586	0.088887167
24	100L	0.75	9.80665	1.2108	0.39008	11	0.035462	0.029288	0.243313	0.77330418	0.095479560
25	100L	0.75	9.80665	1.2108	0.09321	3	0.031070	0.025661	0.254276	0.76588028	0.084465652
26	100L	0.75	9.80665	1.2108	0.16206	5	0.032412	0.026769	0.250717	0.76826661	0.087840265
27	100L	0.75	9.80665	1.2108	0.16155	5	0.032310	0.026685	0.250980	0.76808912	0.087584068
28	100L	0.75	9.80665	1.2108	0.22956	7	0.032794	0.027085	0.249739	0.76892638	0.088800045
29	100L	0.75	9.80665	1.2108	0.26358	8	0.032948	0.027211	0.249351	0.76918840	0.089184526
30	100L	0.75	9.80665	1.2108	0.29212	9	0.032458	0.026807	0.250599	0.76834607	0.087955231
31	100L	0.75	9.80665	1.2108	0.32942	10	0.032942	0.027207	0.249365	0.76917902	0.089170726
32	100L	0.75	9.80665	1.2108	0.22789	7	0.032556	0.026888	0.250347	0.76851565	0.088201157
33	100L	0.75	9.80665	1.2108	0.26639	8	0.033299	0.027501	0.248471	0.76978403	0.090065570
34	100L	0.75	9.80665	1.2108	0.16233	5	0.032466	0.026814	0.250578	0.76836033	0.087975880
35	100L	0.75	9.80665	1.2108	0.15714	5	0.031428	0.025956	0.253307	0.76652788	0.085366713
36	100L	0.75	9.80665	1.2108	0.22581	7	0.032259	0.026642	0.251114	0.76799939	0.087454875
37	100L	0.75	9.80665	1.2108	0.26337	8	0.032921	0.027190	0.249417	0.76914361	0.089118661
38	100L	0.75	9.80665	1.2108	0.29571	9	0.032857	0.027136	0.249581	0.76903322	0.088956598
39	100L	0.75	9.80665	1.2108	0.15833	5	0.031666	0.026153	0.252670	0.76695390	0.085965405
40	100L	0.75	9.80665	1.2108	0.33428	10	0.033428	0.027608	0.248151	0.77000145	0.090389632
41	50C+50L	0.75	9.80665	1.2814	0.42815	13	0.032935	0.025702	0.254139	0.76597131	0.089524079
42	50C+50L	0.75	9.80665	1.2814	0.29378	9	0.032642	0.025474	0.254896	0.76546676	0.088787770
43	50C+50L	0.75	9.80665	1.2814	0.43571	13	0.033516	0.026156	0.252661	0.76696023	0.090987367
44	50C+50L	0.75	9.80665	1.2814	0.36586	11	0.033260	0.025956	0.253308	0.76652699	0.090343011
45	50C+50L	0.75	9.80665	1.2814	0.26564	8	0.033205	0.025913	0.253448	0.76643349	0.090204620

**Table A.1:** The surface tension values for CaCl<sub>2</sub>, LiCl and different concentrations of CELD solutions (continued)

46	50C+50L	0.75	9.80665	1.2814	0.26620	8	0.033275	0.025968	0.253270	0.76655246	0.090380752
47	50C+50L	0.75	9.80665	1.2814	0.26465	8	0.033081	0.025816	0.253763	0.76622248	0.089893190
48	50C+50L	0.75	9.80665	1.2814	0.15948	5	0.031896	0.024892	0.256868	0.76415613	0.086906827
49	50C+50L	0.75	9.80665	1.2814	0.19127	6	0.031878	0.024878	0.256916	0.76412469	0.086862264
50	50C+50L	0.75	9.80665	1.2814	0.22696	7	0.032423	0.025303	0.255470	0.76508494	0.088235103
51	50C+50L	0.75	9.80665	1.2814	0.15788	5	0.031576	0.024642	0.257733	0.76358369	0.086099423
52	50C+50L	0.75	9.80665	1.2814	0.22845	7	0.032636	0.025469	0.254913	0.76545547	0.088771377
53	50C+50L	0.75	9.80665	1.2814	0.29327	9	0.032586	0.025430	0.255044	0.76536840	0.088645026
54	50C+50L	0.75	9.80665	1.2814	0.33236	10	0.033236	0.025937	0.253369	0.76648621	0.090282624
55	50C+50L	0.75	9.80665	1.2814	0.25926	8	0.032408	0.025291	0.255510	0.76505810	0.088196404
56	50C+50L	0.75	9.80665	1.2814	0.22928	7	0.032754	0.025561	0.254605	0.76566072	0.089070016
57	50C+50L	0.75	9.80665	1.2814	0.35906	11	0.032642	0.025474	0.254897	0.76546606	0.088786752
58	50C+50L	0.75	9.80665	1.2814	0.29579	9	0.032866	0.025648	0.254317	0.76585259	0.089350207
59	50C+50L	0.75	9.80665	1.2814	0.36576	11	0.033251	0.025949	0.253331	0.76651155	0.090320137
60	50C+50L	0.75	9.80665	1.2814	0.26509	8	0.033136	0.025859	0.253623	0.76631637	0.090031612
61	30C+70L	0.75	9.80665	1.25316	0.36281	11	0.032983	0.026320	0.252136	0.76731241	0.089498161
62	30C+70L	0.75	9.80665	1.25316	0.29783	9	0.033092	0.026407	0.251857	0.76749933	0.089773405
63	30C+70L	0.75	9.80665	1.25316	0.23039	7	0.032913	0.026264	0.252314	0.76719278	0.089322496
64	30C+70L	0.75	9.80665	1.25316	0.43447	13	0.033421	0.026669	0.251029	0.76805609	0.090598972
65	30C+70L	0.75	9.80665	1.25316	0.29871	9	0.033190	0.026485	0.251610	0.76766566	0.090019149
66	30C+70L	0.75	9.80665	1.25316	0.29393	9	0.032659	0.026061	0.252966	0.76675554	0.088683791
67	30C+70L	0.75	9.80665	1.25316	0.33087	10	0.033087	0.026403	0.251871	0.76749043	0.089760279
68	30C+70L	0.75	9.80665	1.25316	0.39716	12	0.033097	0.026411	0.251846	0.76750690	0.089784576
69	30C+70L	0.75	9.80665	1.25316	0.35717	11	0.032470	0.025910	0.253456	0.76642789	0.088208564
70	30C+70L	0.75	9.80665	1.25316	0.32868	10	0.032868	0.026228	0.252429	0.76711582	0.089209706
71	30C+70L	0.75	9.80665	1.25316	0.46625	14	0.033304	0.026576	0.251324	0.76785819	0.090304535
72	30C+70L	0.75	9.80665	1.25316	0.32390	10	0.032390	0.025847	0.253665	0.76628849	0.088007242
73	30C+70L	0.75	9.80665	1.25316	0.39389	12	0.032824	0.026193	0.252541	0.76704051	0.089099481

**Table A.1:** The surface tension values for CaCl<sub>2</sub>, LiCl and different concentrations of CELD solutions (continued)

74	30C+70L	0.75	9.80665	1.25316	0.39451	12	0.032876	0.026234	0.252409	0.76712927	0.089229403
75	30C+70L	0.75	9.80665	1.25316	0.29603	9	0.032892	0.026247	0.252367	0.76715739	0.089270612
76	30C+70L	0.75	9.80665	1.25316	0.32450	10	0.032450	0.025895	0.253508	0.76639308	0.088158237
77	30C+70L	0.75	9.80665	1.25316	0.42686	13	0.032835	0.026202	0.252512	0.76705979	0.089127691
78	30C+70L	0.75	9.80665	1.25316	0.35821	11	0.032565	0.025986	0.253211	0.76659215	0.088446453
79	30C+70L	0.75	9.80665	1.25316	0.32634	10	0.032634	0.026041	0.253031	0.76671249	0.088621183
80	30C+70L	0.75	9.80665	1.25316	0.39033	12	0.032528	0.025956	0.253307	0.76652786	0.088353246
81	70C+30L	0.75	9.80665	1.30964	0.26278	8	0.032848	0.025081	0.256219	0.76458696	0.089448940
82	70C+30L	0.75	9.80665	1.30964	0.26161	8	0.032701	0.024970	0.256600	0.76433390	0.089080162
83	70C+30L	0.75	9.80665	1.30964	0.39413	12	0.032844	0.025079	0.256228	0.76458121	0.089440536
84	70C+30L	0.75	9.80665	1.30964	0.22596	7	0.032280	0.024648	0.257712	0.76359797	0.088017399
85	70C+30L	0.75	9.80665	1.30964	0.19375	6	0.032292	0.024657	0.257681	0.76361849	0.088046844
86	70C+30L	0.75	9.80665	1.30964	0.29332	9	0.032591	0.024886	0.256889	0.76414250	0.088802375
87	70C+30L	0.75	9.80665	1.30964	0.25882	8	0.032353	0.024703	0.257519	0.76372538	0.088200367
88	70C+30L	0.75	9.80665	1.30964	0.42111	13	0.032393	0.024734	0.257411	0.76379655	0.088302760
89	70C+30L	0.75	9.80665	1.30964	0.32712	10	0.032712	0.024978	0.256572	0.76435255	0.089107272
90	70C+30L	0.75	9.80665	1.30964	0.29453	9	0.032726	0.024988	0.256537	0.76437605	0.089141457
91	70C+30L	0.75	9.80665	1.30964	0.32392	10	0.032392	0.024734	0.257414	0.76379467	0.088300042
92	70C+30L	0.75	9.80665	1.30964	0.22887	7	0.032696	0.024965	0.256615	0.76432430	0.089066201
93	70C+30L	0.75	9.80665	1.30964	0.29318	9	0.032576	0.024874	0.256930	0.76411541	0.088763136
94	70C+30L	0.75	9.80665	1.30964	0.36194	11	0.032904	0.025124	0.256073	0.76468377	0.089590466
95	70C+30L	0.75	9.80665	1.30964	0.26349	8	0.032936	0.025149	0.255989	0.76473993	0.089672681
96	70C+30L	0.75	9.80665	1.30964	0.32567	10	0.032567	0.024867	0.256952	0.76410051	0.088741555
97	70C+30L	0.75	9.80665	1.30964	0.32519	10	0.032519	0.024830	0.257079	0.76401680	0.088620469
98	70C+30L	0.75	9.80665	1.30964	0.29599	9	0.032888	0.025112	0.256114	0.76465644	0.089550486

**Table A.1:** The surface tension values for CaCl<sub>2</sub>, LiCl and different concentrations of CELD solutions (continued)

99	70C+30L	0.75	9.80665	1.30964	0.36101	11	0.032819	0.025060	0.256293	0.76453791	0.089377313
100	70C+30L	0.75	9.80665	1.30964	0.23042	7	0.032917	0.025134	0.256038	0.76470703	0.089624515
101	Pure water	0.75	9.80665	1	0.05092	2	0.025460	0.025460	0.254942	0.76543592	0.069254712
102	Pure water	0.75	9.80665	1	0.13737	5	0.027474	0.027474	0.248554	0.76972798	0.074316353
103	Pure water	0.75	9.80665	1	0.05232	2	0.026160	0.026160	0.252648	0.76696910	0.071016561
104	Pure water	0.75	9.80665	1	0.20227	7	0.028896	0.028896	0.244409	0.77255229	0.077876302
105	Pure water	0.75	9.80665	1	0.12628	5	0.025256	0.025256	0.255627	0.76498032	0.068740719
106	Pure water	0.75	9.80665	1	0.14225	5	0.028450	0.028450	0.245679	0.77168384	0.076761355
107	Pure water	0.75	9.80665	1	0.09147	3	0.030490	0.030490	0.240072	0.77554027	0.081856438
108	Pure water	0.75	9.80665	1	0.05028	2	0.025140	0.025140	0.256019	0.76471944	0.068448338
109	Pure water	0.75	9.80665	1	0.13656	5	0.027312	0.027312	0.249044	0.76939586	0.073910038
110	Pure water	0.75	9.80665	1	0.09988	4	0.024970	0.024970	0.256599	0.76433470	0.068019703

**APPENDIX A.2:**

**Table A.2.1 :** The collected liquid levels in the cups

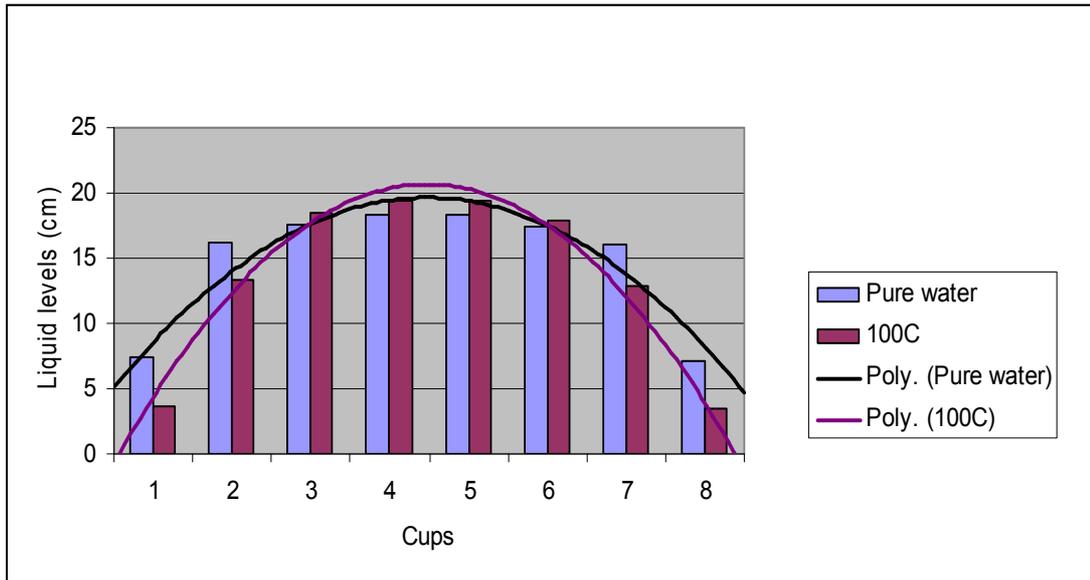
Samples with glass	1st cup	2nd cup	3rd cup	4th cup	5th cup	6th cup	7th cup	8th cup
Pure H <sub>2</sub> O	0.1200	0.2000	0.2600	0.2750	0.2800	0.2700	0.1900	0.1000
	0.1000	0.1900	0.2700	0.2750	0.2800	0.2600	0.1800	0.1100
	0.1200	0.2000	0.2700	0.2800	0.2750	0.2600	0.2000	0.1100
Average	0.1133	0.2450	0.2667	0.2767	0.2783	0.2633	0.2433	0.1067
100C	0.0500	0.1700	0.2500	0.3000	0.3000	0.2400	0.1500	0
	0	0.1600	0.2500	0.3100	0.2900	0.2400	0.1600	0
	0.0500	0.1600	0.2600	0.3000	0.3100	0.2300	0.1500	0
Average	0.0530	0.1933	0.2667	0.2800	0.2800	0.2567	0.1867	0.0500
70C+30L	0.0500	0.1600	0.2600	0.3050	0.3100	0.2500	0.1500	0
	0	0.1550	0.2600	0.3100	0.3100	0.2500	0.1600	0
	0	0.1600	0.2550	0.3100	0.3050	0.2450	0.1500	0
Average	0.0367	0.1833	0.2767	0.2867	0.2867	0.2667	0.1767	0.0300
50C+50L	0	0.1550	0.2600	0.3100	0.3050	0.2500	0.1500	0
	0	0.1550	0.2650	0.3100	0.3100	0.2550	0.1500	0
	0	0.1600	0.2550	0.3100	0.3150	0.2500	0.1550	0
Average	0.0233	0.1800	0.2800	0.2900	0.2883	0.2700	0.1733	0.0167
70L+30C	0	0.1600	0.2650	0.3100	0.3150	0.2550	0.1500	0
	0	0.1550	0.2650	0.3150	0.3100	0.2550	0.1500	0

**Table A.2.1 :** The collected liquid levels in the cups (continued)

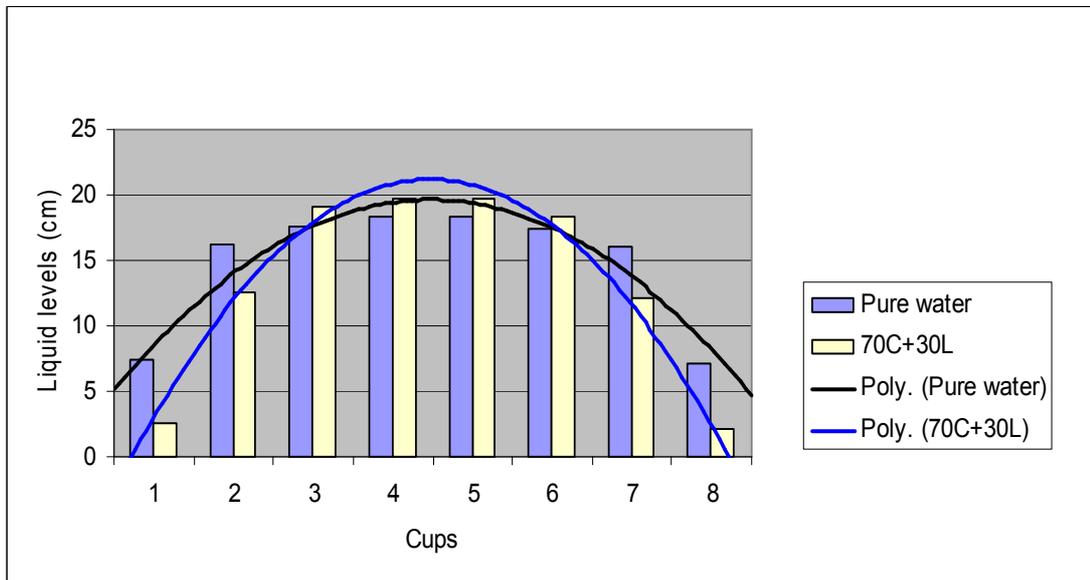
	0	0.1550	0.2600	0.3100	0.3100	0.2500	0.1500	0
Average	0.01167	0.1767	0.2833	0.2933	0.29167	0.2733	0.1700	0.0083
100L	0	0.1400	0.2650	0.3150	0.3200	0.2550	0.1400	0
	0	0.1500	0.2600	0.3200	0.3150	0.2600	0.1500	0
	0	0.1500	0.2650	0.3150	0.3150	0.2600	0.1450	0
Average	0	0.1600	0.2967	0.3067	0.3050	0.2900	0.1583	0

**Table A.2.2 :** The approximation of the average liquid levels to 100 percentage

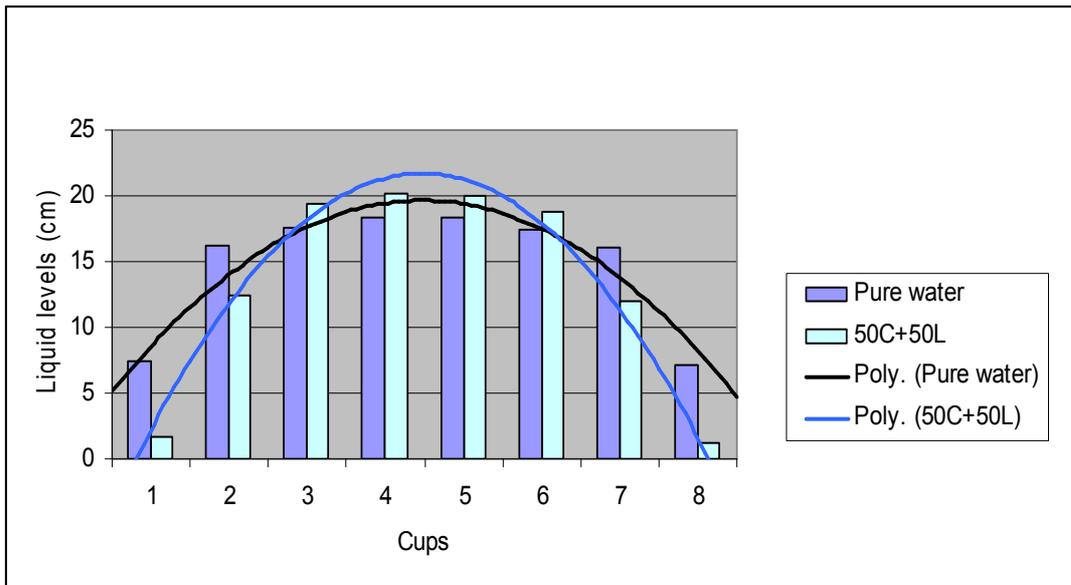
	Pure water	100C	70C+30L	50C+50L	30C+70L	100L	Average
1st cup	7.487938669	3.676215579	2.528941566	1.617943198	0.806998133	0	1.487527199
2nd cup	16.19192386	13.40778248	12.63092613	12.49913200	12.21907199	11.06194690	11.17896067
3rd cup	17.62606569	18.49899424	19.06697905	19.44309423	19.59062306	20.51299779	17.41832907
4th cup	18.28696054	19.42151627	19.75606395	20.13749045	20.28213816	21.20436947	21.03095874
5th cup	18.39270372	19.42151627	19.75606395	20.01944309	20.16942120	21.08683628	20.77928246
6th cup	17.40136144	17.80536866	18.37789416	18.74869801	18.89910795	20.04977876	16.70638353
7th cup	16.07957174	12.94998960	12.17613010	12.03388654	11.75575686	10.94441372	10.73766450
8th cup	7.051748067	3.468127905	2.067254686	1.159641692	0.573957541	0	0.660894833
Total	100	100	100	100	100	100	100



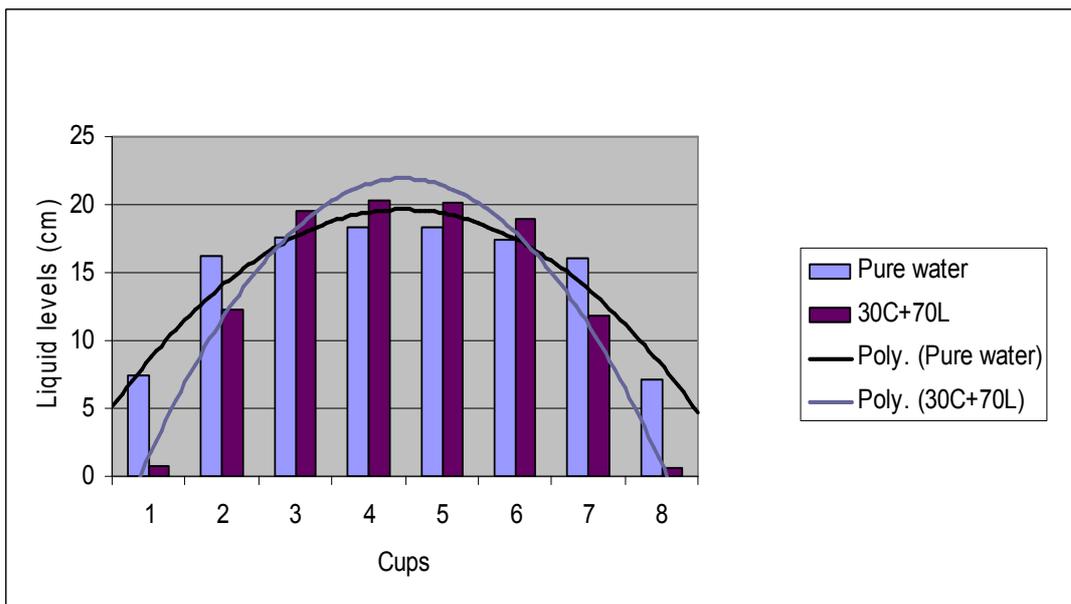
**Figure A.2.1 :** Comparison of wettability of 100C and pure H<sub>2</sub>O on glass plate



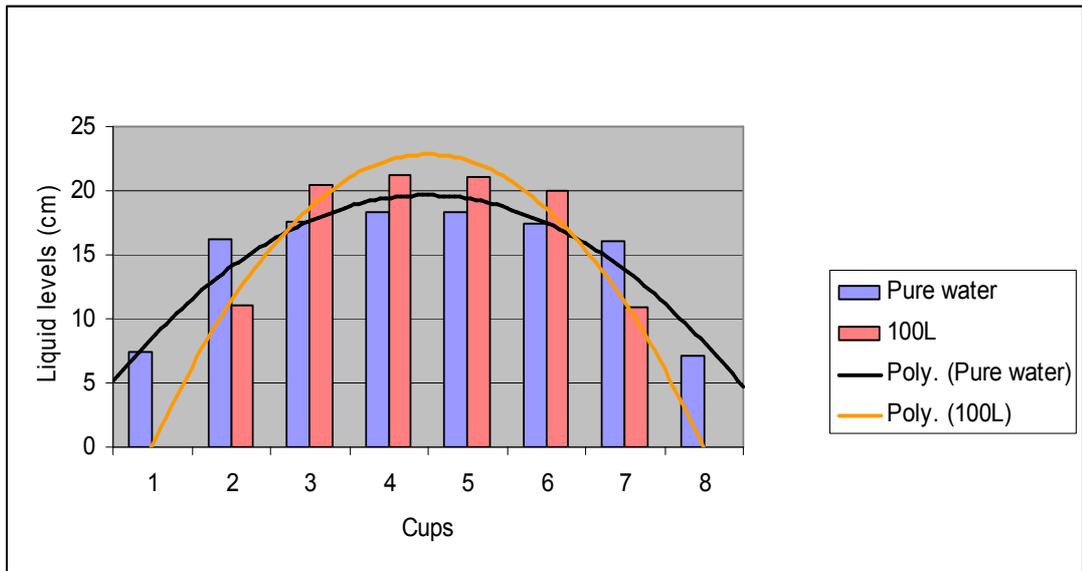
**Figure A.2.2 :** Comparison of wettability of 70C+30L and pure H<sub>2</sub>O on glass plate



**Figure A.2.3 :** Comparison of wettability of 50C+50L and pure H<sub>2</sub>O on glass plate



**Figure A.2.4 :** Comparison of wettability of 30C+70L and pure H<sub>2</sub>O on glass plate



**Figure A.2.5** : Comparison of wettability of 100L and pure H<sub>2</sub>O on glass plate

### APPENDIX A.3 :

**Table A.3.1 :** Contact angle values on plexiglass plate

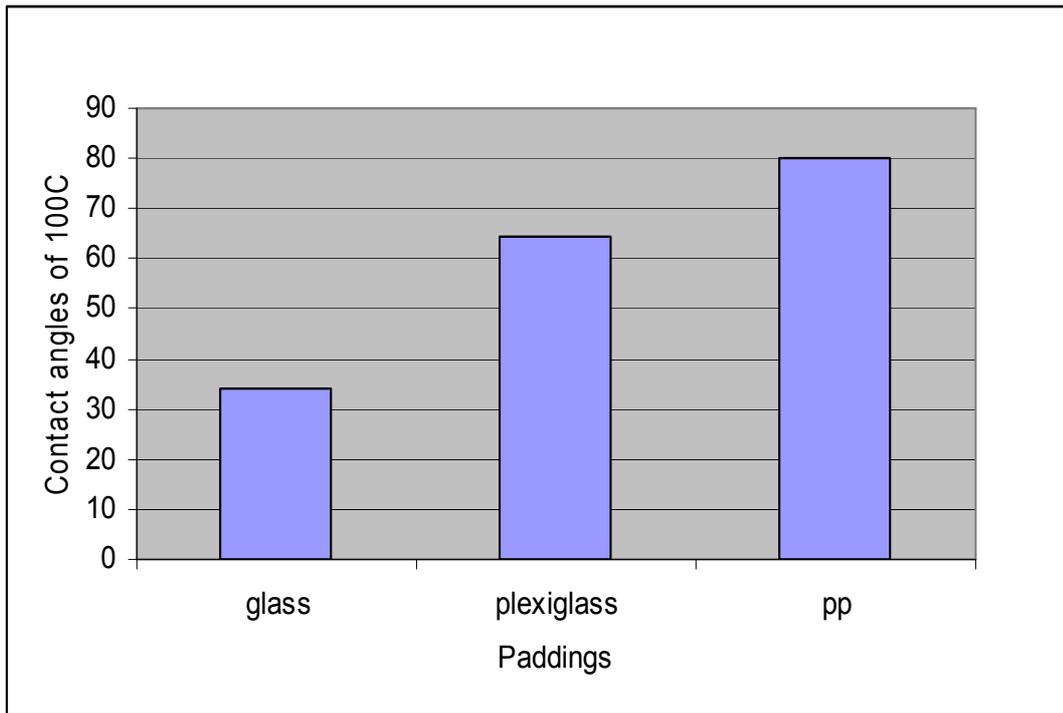
Plexiglass	1st angle	2nd angle	Average
Pure H <sub>2</sub> O	60.0	59.0	59.5
	60.0	58.0	59.0
	62.0	58.0	60.0
	61.0	58.0	59.5
100C	64.0	62.0	63.0
	68.5	66.0	67.3
	68.0	64.0	66.0
	67.0	64.0	65.5
70C+30L	66.0	68.0	67.0
	65.0	65.0	65.0
	66.0	68.0	67.0
	67.0	66.0	66.5
	65.0	66.0	65.5
50C+50L	70.0	68.0	69.0
	68.5	73.0	70.8
	69.0	69.0	69.0
	71.0	69.5	70.3
30C+70L	72.0	72.0	72.0
	74.0	74.0	74.0
	72.0	71.0	71.5
	71.5	73.0	72.3
100L	76.0	70.0	73.0
	77.0	71.0	74.0
	76.0	72.0	74.0
	73.0	74.0	73.5

**Table A.3.2 : Contact angle values on polypropylene plate**

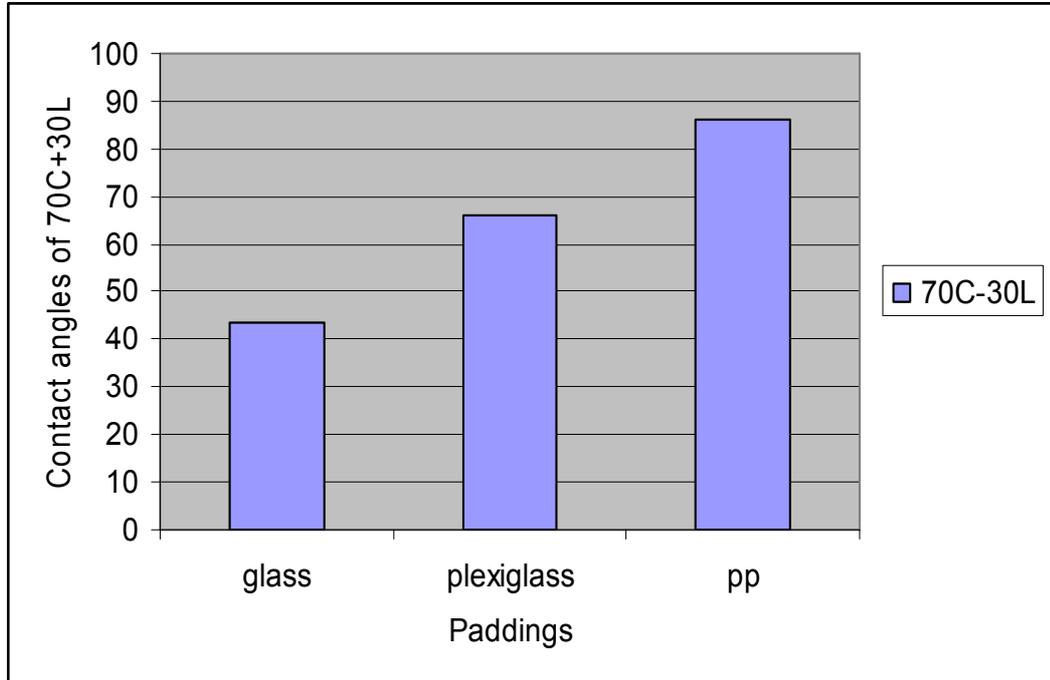
Polypropylene	1st angle	2nd angle	Average
Pure H <sub>2</sub> O	83.0	82.0	82.5
	84.0	84.0	84.0
	83.0	82.0	82.5
	81.0	79.0	80.0
	78.0	81.0	79.5
100C	76.0	86.0	81.0
	80.0	81.0	80.5
	83.0	78.0	80.5
	80.5	75.5	78.0
70C+30L	87.0	83.5	85.3
	84.0	87.0	85.5
	80.5	86.0	83.3
	91.0	89.0	90.0
50C+50L	95.5	98.0	96.8
	92.0	95.0	93.5
	76.0	90.0	83.0
	84.0	90.0	87.0
70L+30C	94.0	95.5	94.8
	95.0	94.0	94.5
	94.0	95.0	94.5
	94.0	96.0	95.0
100L	107.0	98.5	102.8
	120.0	101.0	110.5
	105.0	101.0	103.0
	95.5	97.0	96.3

**Table A.3.3** : Contact angle values on glass plate

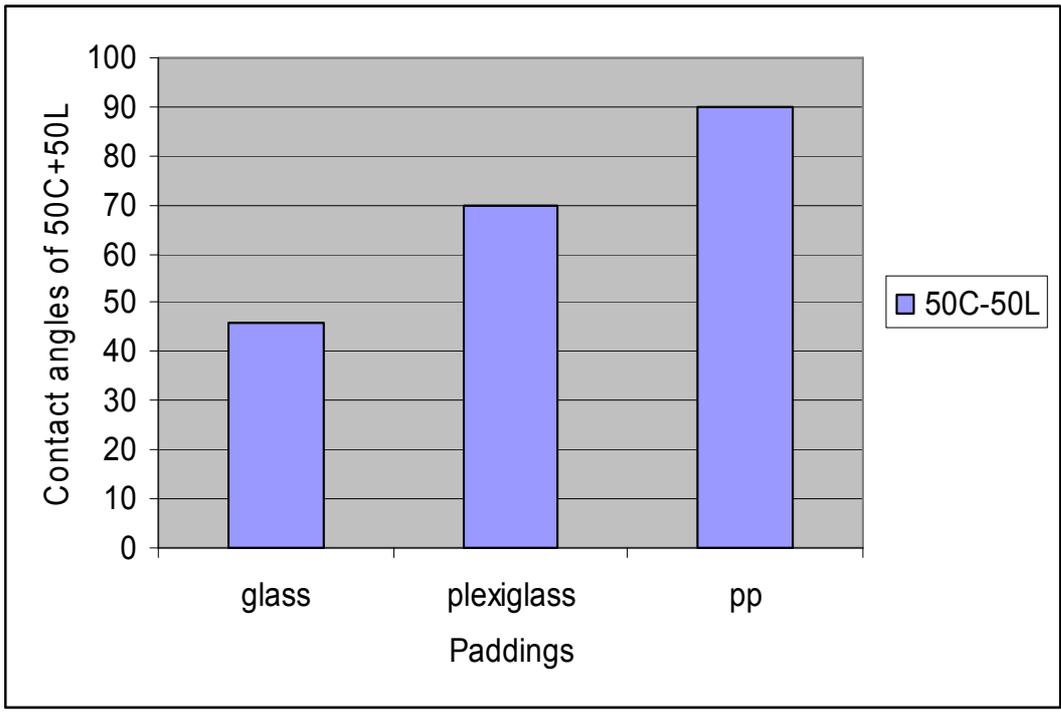
Glass	1st angle	2nd angle	Average
Pure H <sub>2</sub> O	28.0	27.0	27.5
	23.0	26.0	24.5
	19.0	18.0	18.5
100C	18.5	27.0	22.8
	30.0	34.0	32.0
	44.0	35.0	39.5
	28.0	32.0	30.0
70C+30L	42.0	29.0	35.5
	43.0	50.0	46.5
	51.0	41.0	46.0
	37.0	43.0	40.0
50C+50L	48.0	36.5	42.3
	41.0	48.5	44.8
	51.0	37.0	44.0
	35.0	46.5	40.8
30C+70L	47.0	58.0	52.5
	40.0	53.0	46.5
	43.0	55.0	49.0
	46.0	58.0	52.0
100L	57.0	47.0	52.0
	44.0	54.0	49.0
	67.0	58.5	62.8
	56.0	59.0	57.5
	56.0	48.0	52.0
	58.5	52.0	55.3



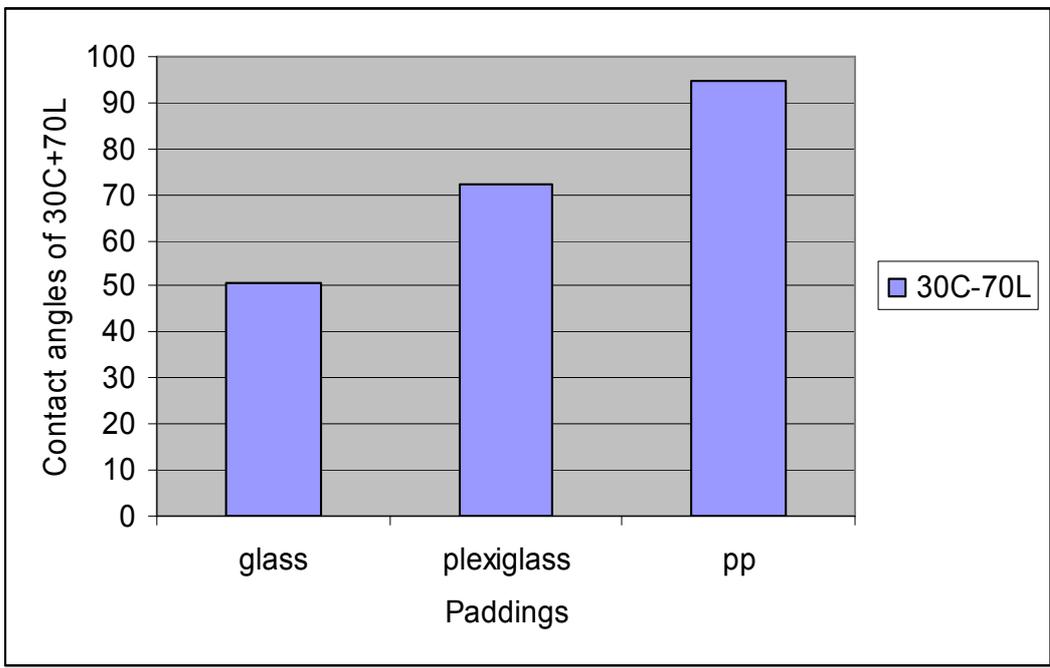
**Figure A.3.1** : 100C's contact angles on different packings



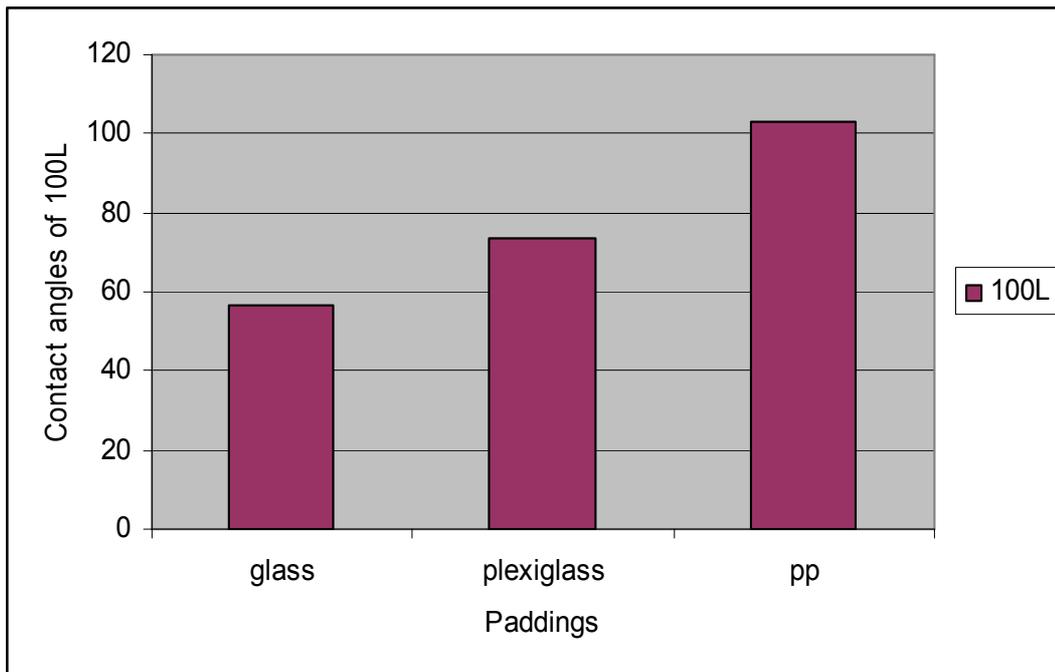
**Figure A.3.2** : 70C-30L's contact angles on different paddings



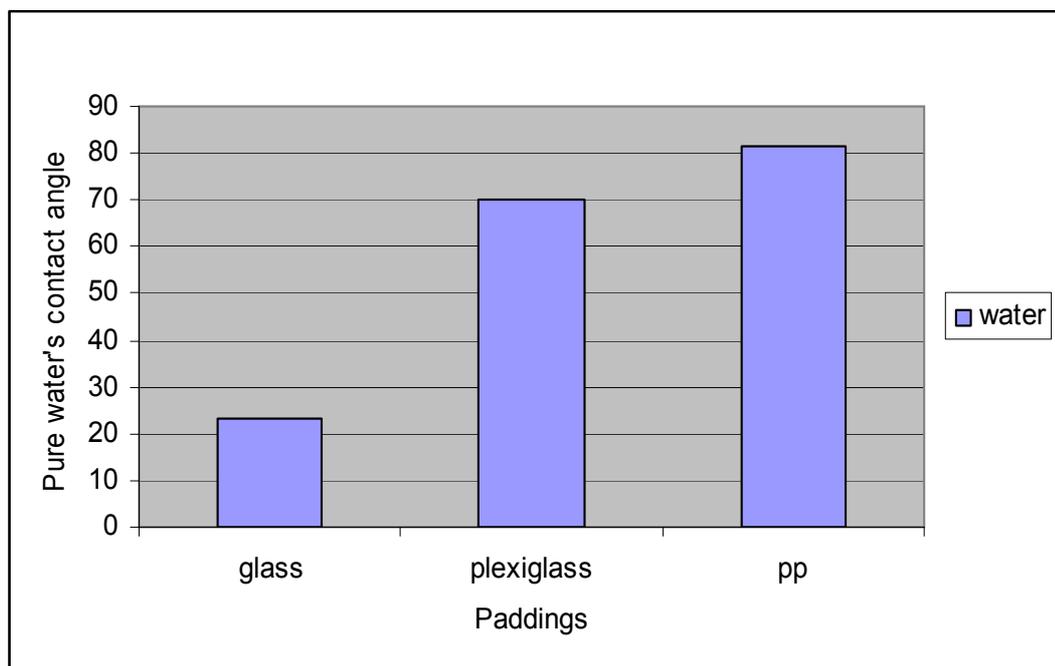
**Figure A.3.3** : 50C-50L's contact angles on different paddings



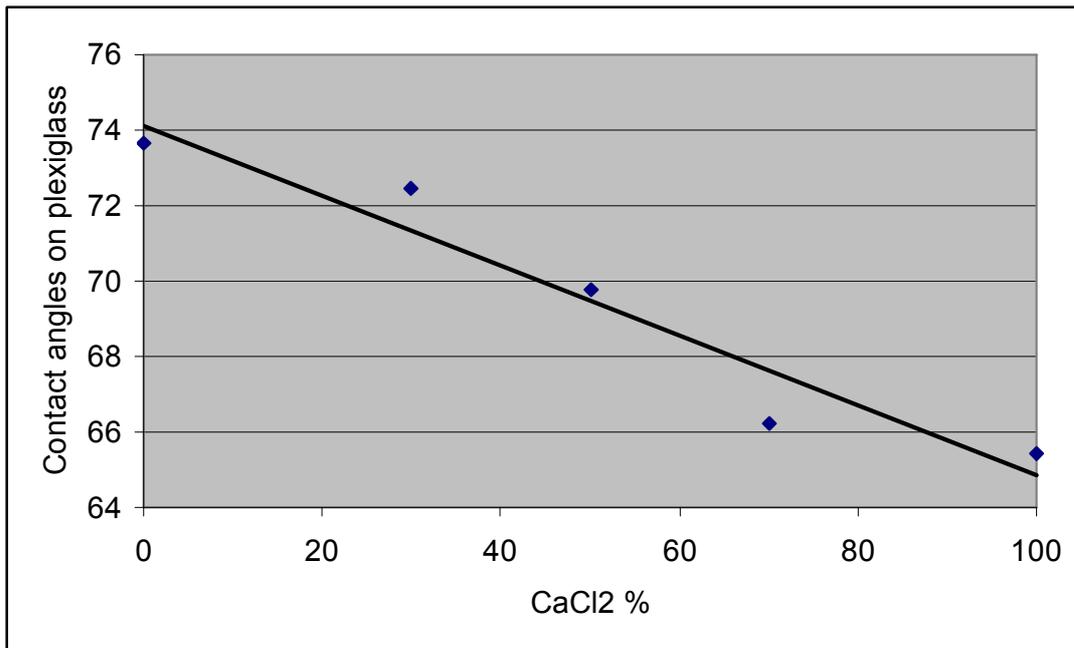
**Figure A.3.4** : 30C-70L's contact angles on different paddings



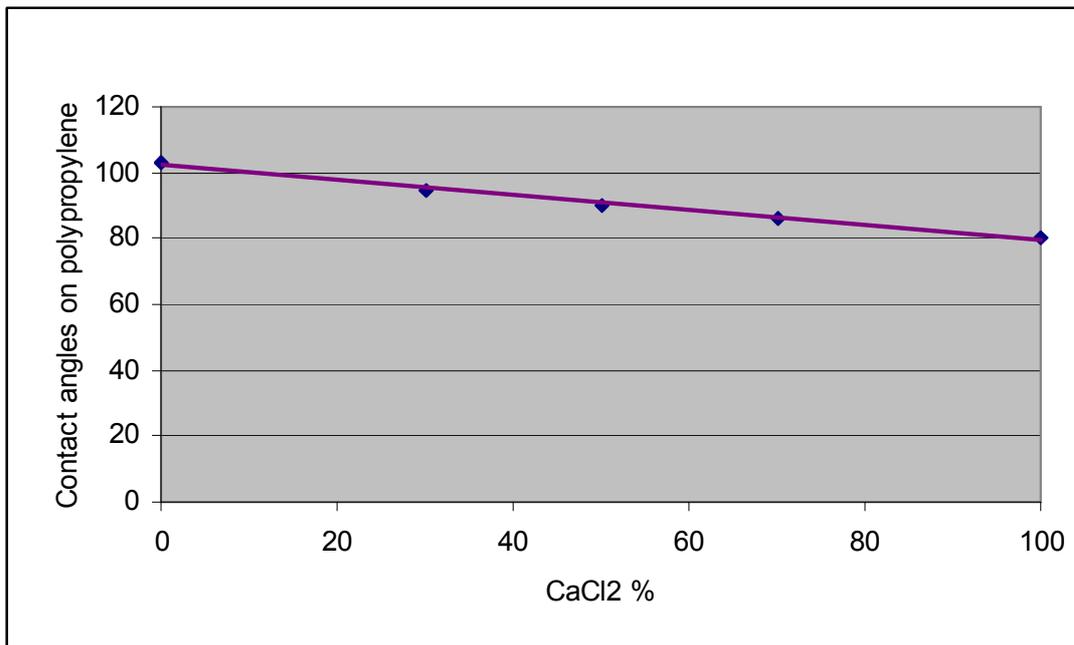
**Figure A.3.5 :** LiCl's contact angles on different paddings



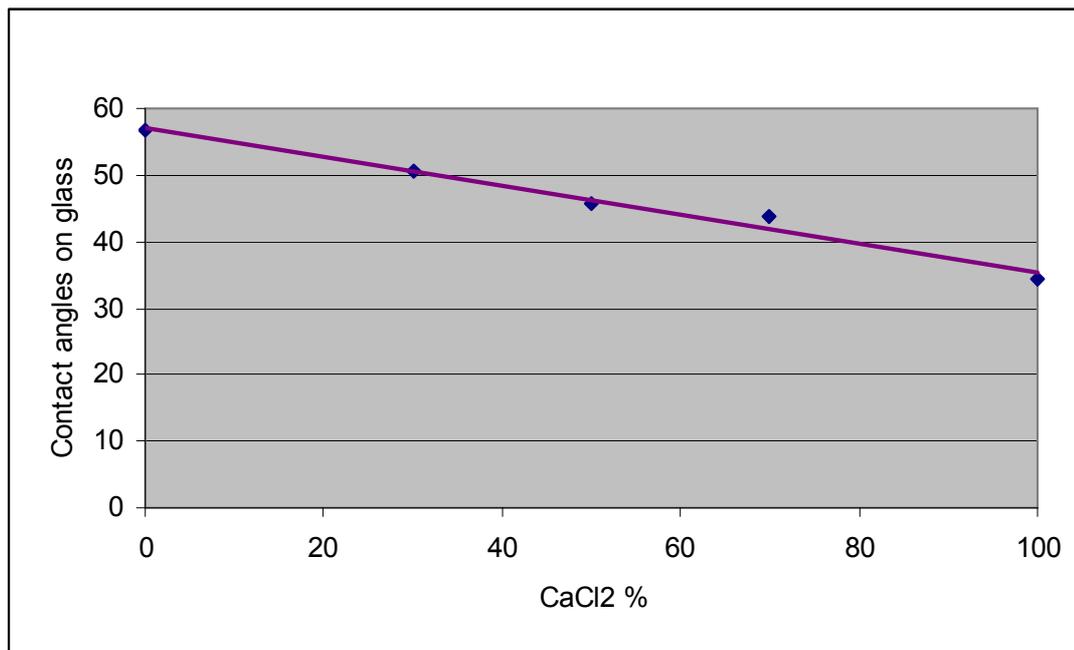
**Figure A.3.6 :** Pure water's contact angles on different paddings



**Figure A.3.7 :** CaCl<sub>2</sub>% in the solution vs. contact angles on plexiglass



**Figure A.3.8 :** CaCl<sub>2</sub>% in the solution vs. contact angles on polypropylen



**Figure A.3.9 :** CaCl<sub>2</sub>% in the solution vs. contact angles on glass





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