

BIHE



**Chemical Engineering Department
Dissertation for Bachelor's Degree**

Modeling and Feasibility study for Humidification- Dehumidification (HDH) Desalination

**By: Vafa Hoveydai
Supervisor: Dr. Kamran Keynejad**

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Abstract

As we know, having fresh water is an essential human concern. In the past, humans have sought to find freshwater resources or purify and desalinate salt water. However, the Earth's freshwater resources are limited, and with increasing drought, the need for saltwater desalination is more urgent than before. There are several methods to desalinate water. Each of these methods has its advantages and disadvantages. In this article, we review different methods and technologies of water desalination. Then, we study the HDH or Humidification and Dehumidification methods and how they work. We also learn the different types of approaches used in this method. Then we explore the advantages and disadvantages of water desalination in this method. Finally, we do a feasibility study for building an HDH plant in southern Iran in Bandar Abbas city, which works with solar water heating collectors. Finally, we come to the results that show the conditions for building an HDH plant in Iran and the analysis and study of this plant in terms of engineering and economics.

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Section 1

Introduction

1-1: General Topic and Background

As said before, one of the most important concerns of human societies is supplying treated water. The problem which this article has a solution for that is water scarcity and drought, which is of substantial importance.

1-2: Outline the Methodology

This article reviews different water treatment methods and technologies and the advantages and disadvantages associated with each method. HDH method has been studied specifically by simulation of a plant with ASPRN HYSYS and COMSOL software, feasibility study to ensure economic viability, and reviewing previous works done by pioneer researchers. The HDH is simulated by the assumption that the real work is done in Bandar Abbas, Iran, and the Persian Gulf seawater is considered raw water for treatment. The plant is assumed to operate 24 hours a day and 335 days a year. In an economic study, capital cost, operating cost, and net income are investigated. This article consists of 7 case studies which will be discussed in detail in the following sections. Also, a hazard study is conducted for the HDH plant, and solutions are suggested for safe operation. A brief description of the entire process would be:

Sea water with a mass flow rate of $5000 \frac{\text{kg}}{\text{h}}$ is pumped through solar water heating collectors to be heated before entering the top of the absorption tower, where moist air with a mass flow rate of $5000 \frac{\text{kg}}{\text{h}}$ is entered from the bottom of the absorption tower after being compressed in the compressor for the humidification process to be operated. The bottom product of the absorption tower, which contains a large concentration of NaOH, is considered wastewater. The overhead product of absorption water which is the air with an enriched concentration of water, enters the bottom of the stripper tower. Distilled water, i.e., water with zero TDS, is entered at the top of the stripper column for the dehumidification process. Overhead product, which is dried air, leaves to the atmosphere. The bottom product, which is the initial distilled water and added dehumidified water, is pumped to a PVC pipe placed in a certain depth of seawater, where the process of cooling

is operated by making use of the lower temperature of sea water compared to the bottom product of desorption tower. After the cooling process, the initial amount of distilled water is taken from the cooled water and recycled back to the desorption column, and the rest is the final product.

At the end of this article, the amount of product from $5000 \frac{\text{kg}}{\text{h}}$ of seawater is calculated. The investment cash return payback period is determined, and some suggestions are made for future works.

Section 2

Water Desalination Different Methods

2-1: introduction of water desalination different methods

In the desalination process, fresh water is created by isolating soluble salts from salt water. Desalination technology may be used for several reasons, but it is most often employed to provide drinking water for urban and home consumption. Agricultural and industrial wastewater sweetened using desalination methods may also be employed. Thermal processes and membrane processes are the two main types of conventional procedures. A new approach called hybrid is produced by combining these two types. These sorts of processes will be briefly discussed in this study. [1]

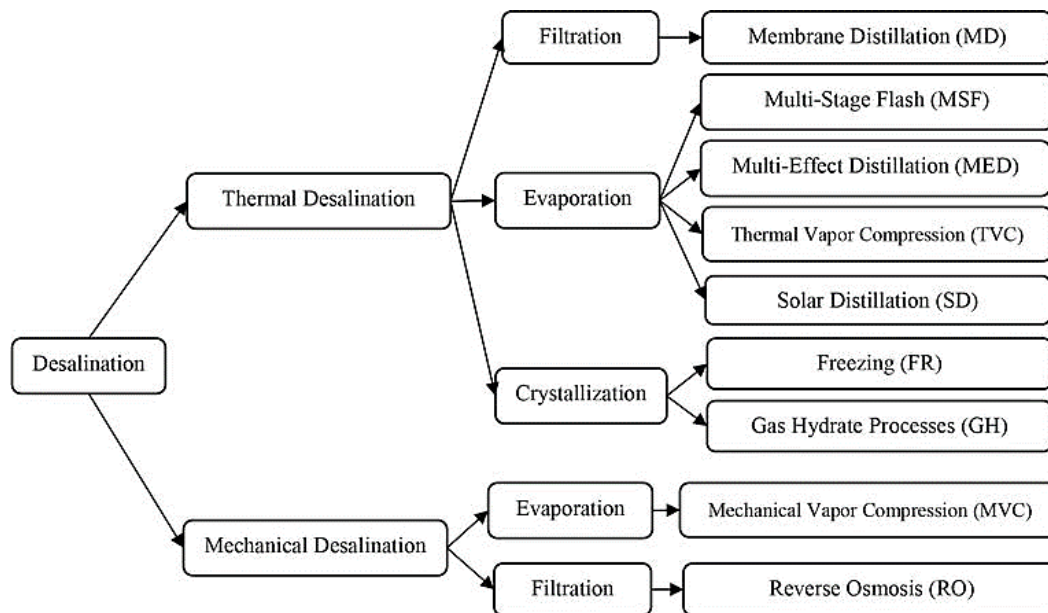


Figure 1: Flowchart of various desalination systems [1]

2-2: Five Leading Technologies of Water Desalination

There are five leading technologies to remove salt and other insoluble solids from water:

- Reverse osmosis
- Electro dialysis

- Distillation
- Ion-exchange
- Freezing desalination

Distillation and freezing involve extracting pure water from salt water in the form of water vapor or ice. During water passage through a chemical chamber in electrodialysis and reverse osmosis technologies, an excellent membrane separates salts and lighter and more favorable salts. In addition to separating and eliminating salts and other insoluble particles from water, some desalination equipment also eliminates suspended particulates, organic molecules, bacteria, and viruses. These technologies have developed through time to cleanse large quantities of water on a large scale. However, some of them are only used in small quantities and the home. Boiling and evaporation are the most frequent methods of desalination.

Water may boil in a distillation machine and generate steam, which is created by the condensation of this pure water vapor. Some distillation units may be linked together to build a high-performance system. By heating salt water to its boiling point or lowering the vapor pressure above saline water, the evaporation of water molecules may be hastened. The heat created during the condensation step is utilized to warm the feeding water or reheat unheated salt water to improve the efficiency of the distillation process [2].

Processes in which water sweetening is done without changing the phase:

- Reverse osmosis (RO)
- Electro dialysis (ED)

Processes in which phase change takes place:

- Multi-effect desalination (MED)
- Multi-stage flash desalination (MSF)
- Vapor compression desalination (VCD)
- Humidification-dehumidification desalination (HDH)

The efficiency of each of these processes is determined by the amount of salt in the water supply as well as the cost of water. To accomplish the separation process, each desalination technique requires energy, which may be provided in the form of thermal, mechanical, or electrical energy.

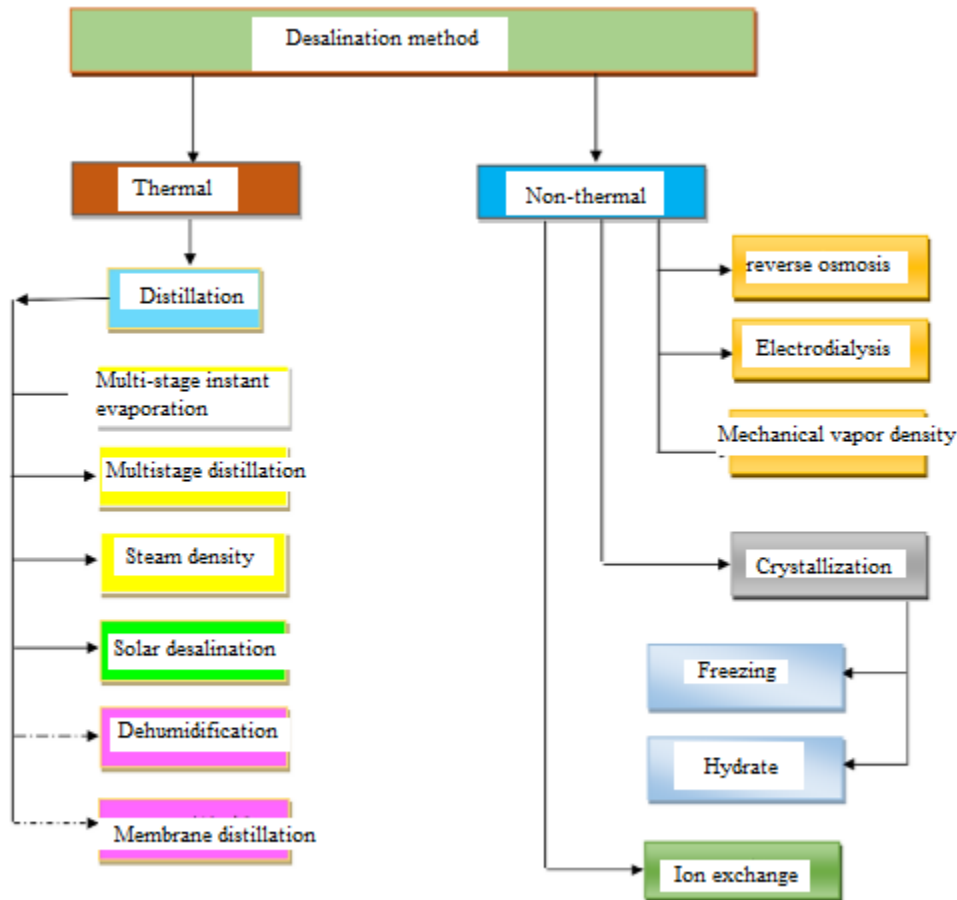


Figure 2: Division of desalination processes [3]

2-3: Membrane Processes

2-3-1: Description of Membrane Process

By exerting pressure on nanoscale membranes, saltwater water is transported through them. These membranes work as a filter, sweetening the water by separating the impurity particles. The moisture generated in this procedure is of drinking water grade. Membrane separation is described as the use of semi-permeable membranes to separate solvents from soluble plants using physical

techniques. In recent years, these processes have made significant development. Membranes have been used for straightening since the early twentieth century. Membranes were first utilized in the third decade of the twentieth century for the separation, purification, and thickening of solutions, particularly fluids containing microorganisms. Desalination, like other separation processes, needs energy input. Currently, more than two-thirds of the world's population is impacted, and this number is growing. As worldwide trust in alternate water sources grows, reducing desalination energy usage is critical to ensuring a long-term future [4].

This phenomenon evolved throughout time due to a study into the creation of various kinds of membranes and the identification of the process, to the point where it is now one of the most common ways of water desalination. The following names are given to membrane processes depending on the size of the smallest particle that passes through the membrane under the effect of compressive force.

- Microfiltration
- Ultrafiltration
- Nanofiltration
- Reverse osmosis

Two stages of a membrane process are generally separated by the membrane, which is the third phase. The membrane determines the mass transfer phenomena. Each of the two stages is a mixture of several ingredients.

The two major specifications in the transmission applied by the membrane are:

- A) Permeability
- B) Ectivitysel

The membrane process has various advantages:

- Reduction of required space in terms of the low volume of membrane modules
- Fast process due to membrane cuteness and high mass transfer rate
- Low pain ability, which is a high advantage for heat-sensitive solutions.

- Low investment costs compared to other methods at the global level
- Ease of expanding the system

Membranes may last for a long time. Ultrafiltration membranes have a shelf life of more than two years, whereas osmosis membranes have a shelf life of more than five years. The osmotic characteristics must be identified to recognize the reverse osmosis phenomena. In general, chemical potential differences are superior at causing mass transfer from one environment to another. Consider a water container in which a piece of salt crystal has been tossed. The salt concentration is high, and the water concentration is minimal in the section of the container with salt crystals, while the salt concentration is nil and the water concentration is relatively high in the other half of the container. Because of the concentration difference, salt crystal molecules begin to permeate the other portion, which is water, while water molecules, on the other hand, penetrate the salt crystal. This process is repeated until the concentration of water and salt in two sections is equal. A pipe is submerged in water on the left side of the form.

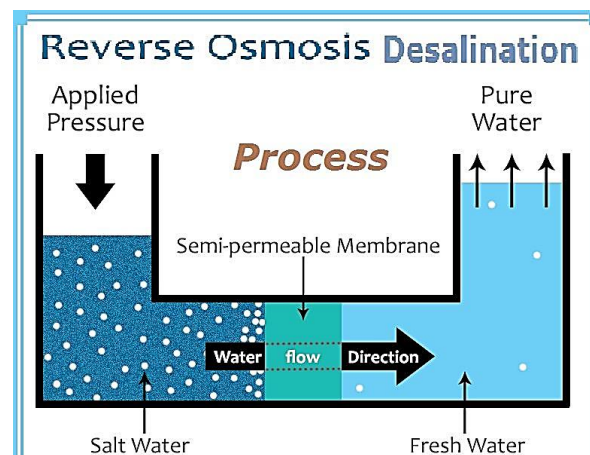


Figure 3: Osmotic water sweetening [5]

Figure 8 shows that the water surface inside and outside the pipe is the same. By applying artificial pressure to saline water, reverse osmosis reverses the flow of water (which is usually from the sweet to the salt), allowing clean water to pass through the membrane while the salts remain on the other side [5].

2-3-2: Reverse Osmotic Method

The most popular desalination technology in the world is reverse osmosis, which is a kind of membrane desalination. The reverse osmosis system is a process in which the osmotic flow of water is reversed under pressure, and water passes through a semi-permeable membrane, where all ions and larger particles of water, nitrate and minerals, chemicals, and microorganisms, mostly bacteria, are removed. The output product is water free of impurities. Compared to thermal techniques, this approach has the benefit of not using heat energy to sweeten water. However, it does use more power. Another advantage of this approach is that it does not need the use of additional salts. Salts are lost and changed into fresh water after passing through the membrane that stops salts from moving through it. Solar energy will provide the required force for this process by converting it to mechanical energy [5].

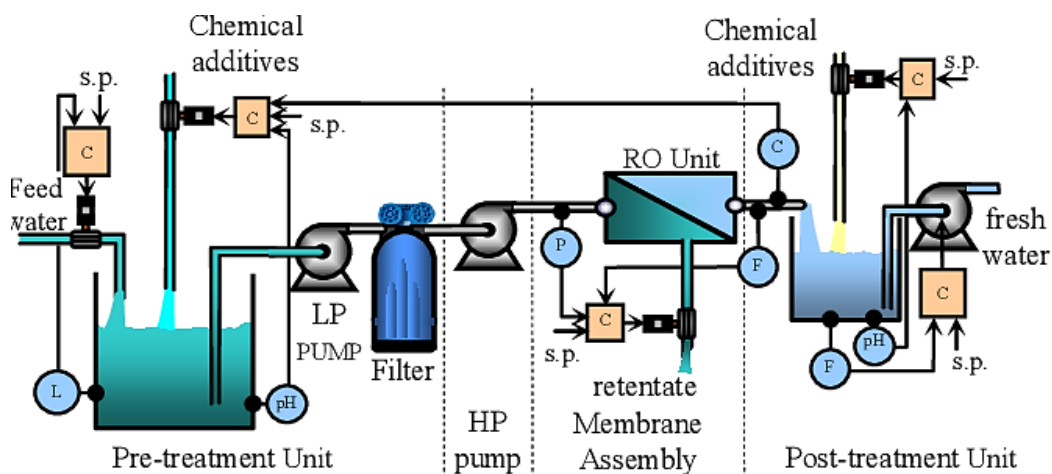


Figure 4: Schematic Diagram of Reverse Osmosis Desalination [5]

Fresh water is separated from soluble substances by a membrane in reverse osmosis, which uses higher pressure than the osmotic pressure of a saline water solution. There is no need for heating or phase change in this method of separation, and the majority of the needed energy is spent on pressurizing water. Saltwater is forced towards the membrane in a closed container during the osmosis process. A portion of the water passes through the membrane, increasing the salt content in the remaining solution. As a result, some water with a high salt content should be left, while the rest should be drained and replaced with salt water with a reduced salinity percentage. The quantity of salt discharged (water with a high salt percentage) will range from 35 percent to 100 percent of the freshwater generated, depending on the feeding circumstances. Using energy recovery devices

and developing membranes that perform effectively at low pressures have decreased the running expenses of reverse osmosis units during the last decade.

Advantages of reverse osmosis method

The choice of the best desalination method depends on the location, geographical conditions of the area, and the available initial cost. The reverse osmosis method is used in more than 50% of desalination plants worldwide, which shows its importance. Of course, in addition to the production of effluents with very high concentrations and very little space occupied by reverse osmosis, the following are also among the advantages of this method: [6]

1. The procedure is simple; the only problem is finding or producing a source of incoming water without foreign matter, which makes the less membrane need to be washed.
2. Low installation cost.
3. The production capacity of reverse osmosis devices is very high and is from 6000 to $25000 \frac{\text{m}^3}{\text{day}}$.
4. Non-metallic materials that require less maintenance are used in the construction of the devices.
5. Reverse osmosis technologies can use unlimited water resources like the sea.
6. Except for draining salt water, reverse osmosis has little environmental impact.
7. This technology minimizes the use of chemical materials.

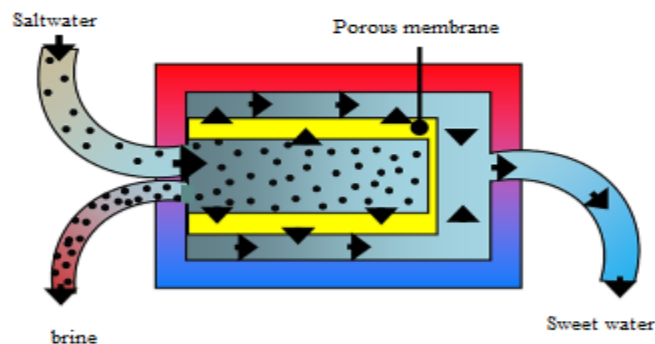


Figure 5: Schematic Diagram of Reverse Osmosis Desalination [5]

2-3-3: Electro Dialyze

Electrodialysis, also known as reverse electrodialysis, is an electrochemical separation method that involves moving salt ions across a membrane using electrical energy. In the mid-1950s, commercial electrodialysis became available. Low-salinity water is typically desalinated using these technologies. In the form of parallel channels, the electrodes are linked to an external direct current source in a container containing brine and an ionic membrane. When the salt is connected to electricity, positive ions flow to the negative electrode via the membrane of the permeable cation, and negative ions travel to the positive electrode through the membrane of the permeable anion. As a consequence, the water's salinity drops. This results in the formation of two channels: a concentrated channel for saltwater and a dilute channel for creating fresh water. An electrodialysis system's capacity ranges from 2 to 145,000 cubic meters per day. The poles of the electrodes occasionally shift in reverse electrodialysis. To decrease scaling and deposition in the membrane, switching the polarity of electricity is employed to reverse the ion flow direction. Reversing the current extends the life of the electrodes and aids in membrane cleaning. A deposit accumulates on the thick side when the membranes shift in one direction over time. Solar electrodialysis desalination systems are appropriate for a) places with little or no power, b) areas without access to low-cost fuel, and c) areas with plenty of sunlight [7]. A schematic of solar electrodialysis desalination water is shown in the following figure [8].

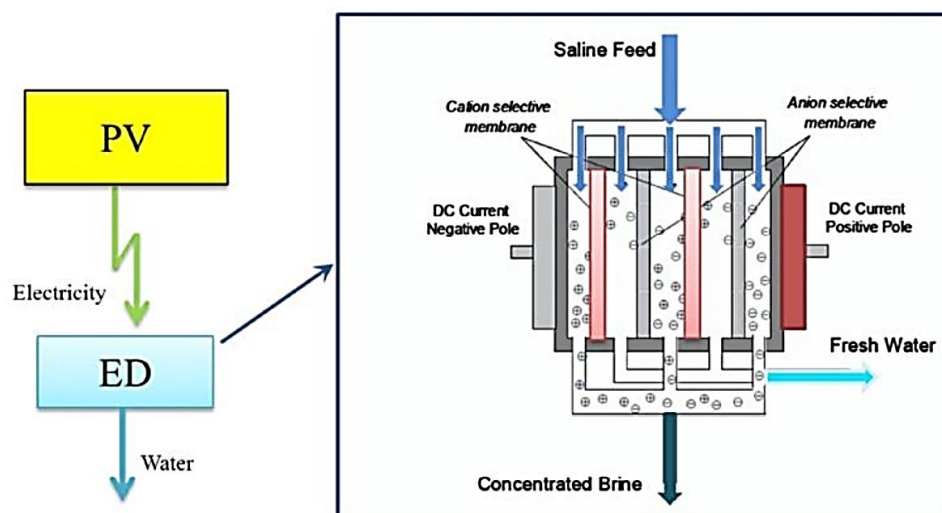


Figure 6: Solar electrodialysis desalination water [8]

The electrodialysis process is according to the following general principles:

- A) Many salts dissolve in water and produce positive and negative ions.
- B) These ions tend to move to unidentified poles by applying an electric current in the solution.
- C) Membranes can be applied to pass cations or anions.

Hundreds of cells were used in early electro dialysis devices. Reverse electro dialysis is a more sophisticated version of this technique, in which the positive and negative poles are continually switched. Chemical use in the pre-treatment industry is reduced as a result. The accumulation of silt on the membrane and blockage of its cavities is also avoided owing to the regular changing of electric poles. This method is widely used to extract salts from saline fluids [9].

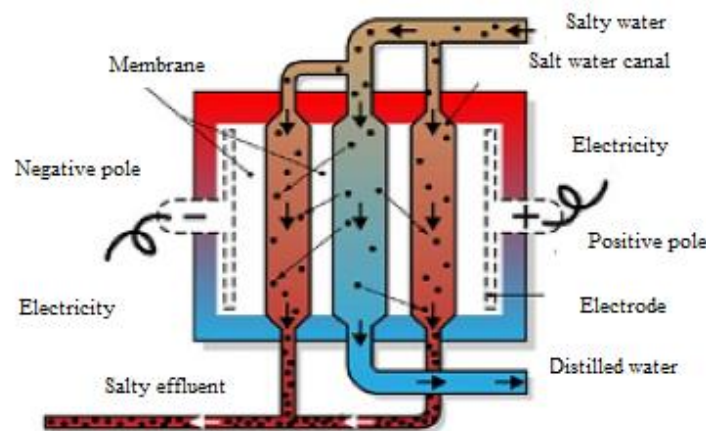


Figure 7: Schematic of the electro dialysis method [10]

2-3-4: Ion Exchange Resins

Ion exchangers are organic or inorganic materials that can absorb one kind of cation (or anion) and replace it with another (or anion). For example, a cation exchanger may replace Na^+ ions with H^+ , or an anion exchanger can replace Cl^- ions with OH^- ions, and the solution is salted. Acids recovered cation exchangers, whereas bases recycled anion exchangers. Five milliequivalents of ions may be exchanged per gram of solid in an ion exchanger [11]. Resins are employed in the ion exchange process to remove undesirable ions. This procedure is used to purify water after other desalination technologies have removed a considerable portion of the salt content.

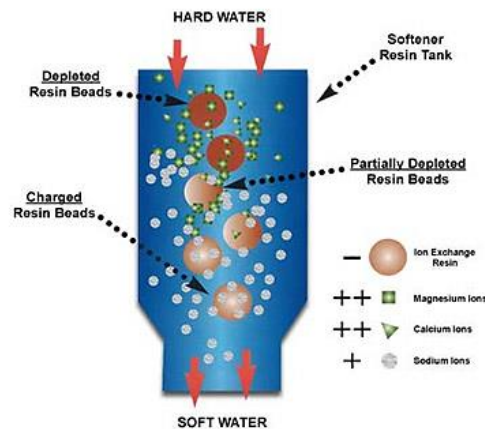


Figure 8: Ion exchange resin desalination water [11]

At both the laboratory and industrial levels, ion exchange resins are employed as resin columns. Water containing ionic contaminants enters at the top of the column and slowly passes through the resin grains before exiting. This procedure is schematically shown in the diagram below. Water progressively travels through the resin column containing ion exchange grains, as indicated in the diagram, and the resins lose their mobile ions and saturate from top to bottom. Most of the resins are saturated after a time (figure on the right), and ion-containing water emerges from the opposite side. The procedure must be halted in this situation, and the impregnated resin must be replaced with new resin.

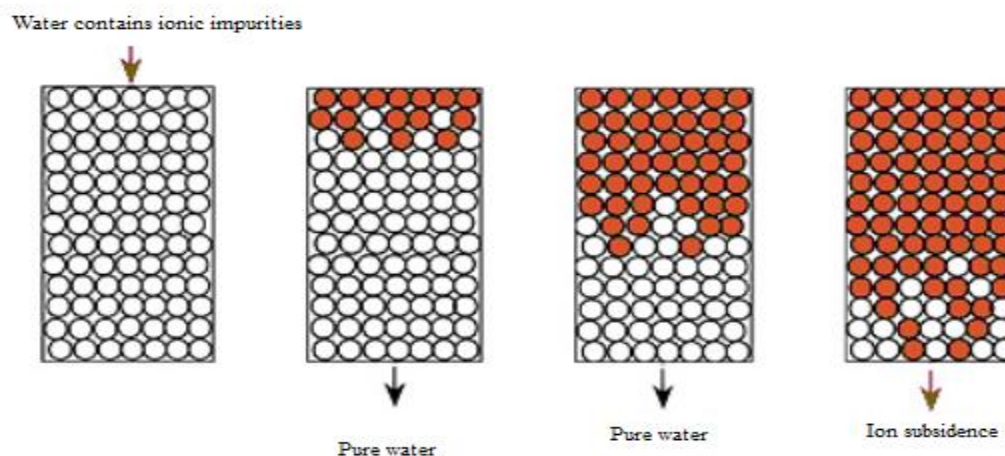


Figure 9: Ion exchange [11]

Water desalination applying ion exchange resins is a compelling and acceptable method that was widely considered. Among the typical applications of this method, the following can be noted:

- Hardening of water at the entrance of houses
- Water hardening for use in boilers and cooling towers
- Water purification for laboratories
- Water purification in nuclear and thermal power plants
- Water purification in the industries of toxic production of conductors and computer chips
- Removal of undesirable impurities from drinking water

In addition to water treatment, using resin in other industries like food, chemical, and wastewater treatment also has a wide variety of applications.

In water treatment with ion exchange resins, there are three significant limitations and conditions:

- For the ion exchange process to be efficient, the resin's affinity to absorb the ion in water must be greater than the tendency to retain the mobile ion in the resin structure.

When the concentration of the solution containing the impurity ion is low, the ion exchange procedure is effective. The time necessary to saturate the resin column in this situation will be sufficient to justify its usage. When the concentration of soluble ions is large, the resin column's saturation period is short, and the usage of reducing agents grows to the point where this technology loses its economic basis. The utilization of reverse osmosis (RO) procedures and subsequent distillation of ion exchange resins will be employed under the aforementioned situations.

Ion exchange cannot eliminate non-ionic contaminants from water that are water-soluble. Filtration materials such as activated carbon, polymeric adsorbents, or molecular sieves may be used to separate these contaminants according to their kind [12].

2-4: Electric Desalination

Electrical desalination is potentially a viable alternative to RO and thermal procedures since it does not need high pressures or temperatures. The salt ions are separated from the saline water using an

electric current, and the saline water is taken by passing it through a solvent adsorbent. The electrical energy gained from solar energy may be utilized in this process [13].

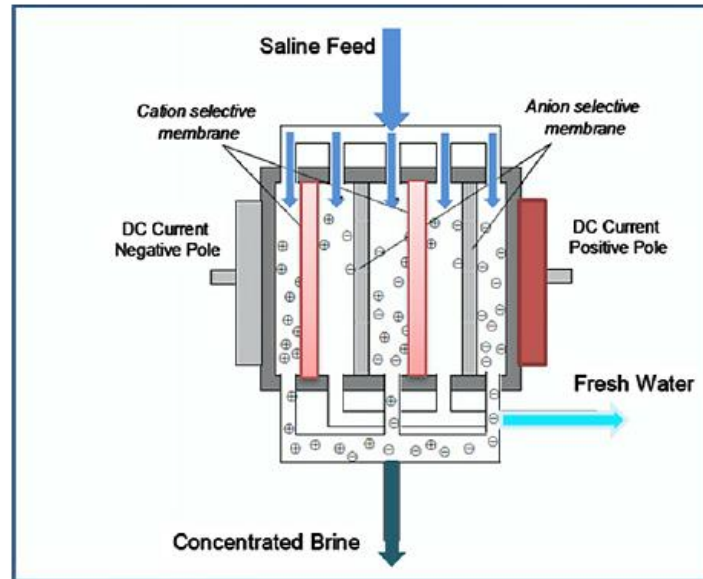


Figure 10: Schematic of water desalination by electrolysis [13]

2-5: Freezing Desalination

Fresh water can be provided by freezing salt water. After freezing, the solute water is isolated from it, and freshwater is prepared by melting the ice. Solar energy can be applied for both cooling and melting steps.

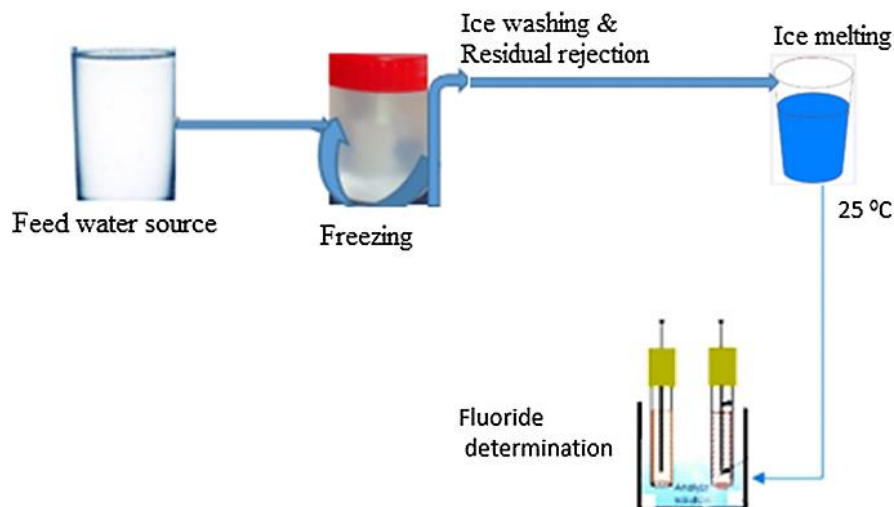


Figure 11: Schematic of water desalination by freezing [14]

2-6: Thermal water desalination processes

2-6-1: Thermal Water Desalination

Saline water is evaporated using thermal energy in these procedures, and the resulting steam is distilled and turned into almost pure water. Because distilled water is created this way, salts are added to it if required during the supplementary purification process. It may be transformed into drinking water or water that can be utilized in other applications.

Heat procedures use greater thermal energy but use less power than membrane processes. Water vapor, which may be created directly by burning fuel or by utilizing surplus heat from power plants, is the source of this heat. One of the benefits of installing thermal water desalinators close to power plants is that the heat lost in the power plants may be utilized to evaporate water, a process known as simultaneous production of energy and water. Because there is no need for fresh thermal energy in this circumstance, thermal efficiency improves, and desalination costs are drastically lowered. [15]

2-6-2: One-stage Distillers

One-stage desalination plants come in various shapes and sizes, and they're named that because fresh water is generated in only one step. Depending on the form and kind of coating, this sort of desalination plant comes in various shapes and sizes. The most well-known form in this category is multi-pool desalination with a horizon deviation. Water sweeteners in the shape of pools have been created in many places around the globe.

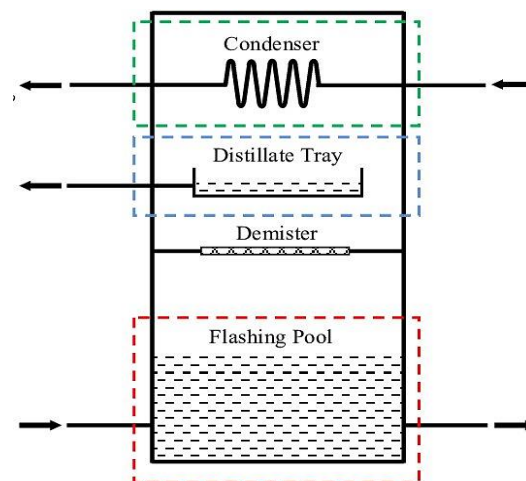


Figure 12: Schematic of water desalination by one-step distillation method [15]

2-6-3: Multi-Effect Desalination (MED)

The feed water is sprayed on these tubes, and part of it evaporates, and the boiler hot water vapor enters the first chamber via the evaporator tube. The leftover saline water is sprayed by the pump on a pipe with a secondary steam flow, and the created steam enters the second chamber. The water evaporates more quickly as the pressure in the chamber lowers at each level. Multi-stage distillation desalination facilities that utilize petroleum or petroleum fuel solar energy cannot compete economically with high-capacity pond-type desalination plants because multi-stage desalination plants for producing 30 kcal are required to produce one kilogram of fresh water. Pond desalination systems need 1000 kcal to generate the same quantity of fresh water, and the reason for this large discrepancy is because distillation heat is lost in a pond desalination plant, and salty and fresh water is withdrawn from the device at a greater temperature. To exist. So that the greatest amount of fresh water generated per square meter of device surface is about 7 kilogram per day, and a multi-stage distillation system with a capacity of 600 to 30,000 cubic meters per day is commonly used. [15]

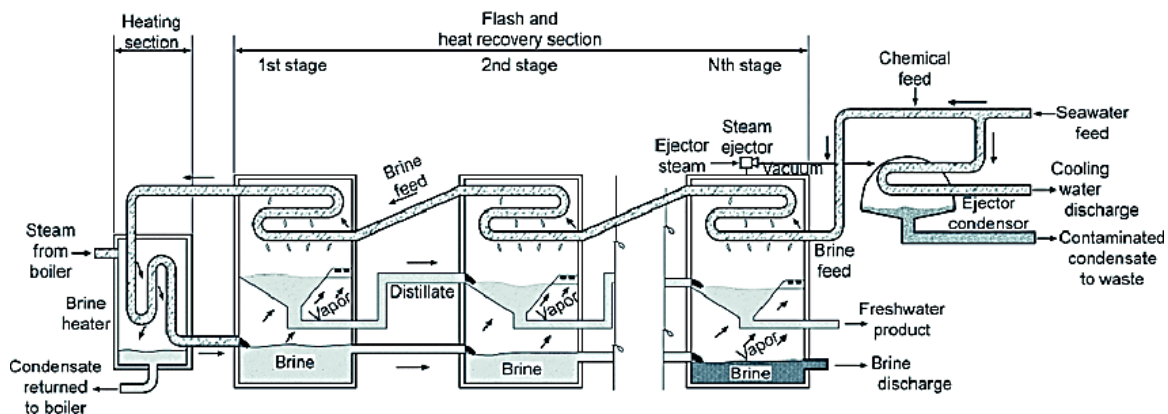


Figure 13: Schematic of water desalination by multi-stage distillation method [15]

An evaporating string generates water in stages as the pressure steadily lowers in multi-stage distillation. As the pressure drops and the water boils at a lower temperature, the water vapor created in the first evaporator serves as a secondary heating medium, and the process continues. The performance factor increases as the number of steps increases. [16]

Advantages of MED Method:

- Less energy consumption compared to other thermal methods; [16]

- Work at lower temperatures (less than 70 degrees Celsius) and lower concentrations (less than 1.5) to prevent corrosion and fouling;
- No need for pre-treatment of seawater;
- Straightforward process and operation.
- Low maintenance costs;
- Ability to work 24 hours a day;
- Ability to adapt to different sources such as hot water, fossil fuels, industrial evaporation processes, etc.

Disadvantages of MED Method:

- Incompatibility with higher temperature sources due to problems with deposition during the process;
- Small-scale construction problems in terms of the complexity of the equipment and a large number of components.

2-6-4: Multi Stage flash Distillers (MSF)

This approach is now one of the most extensively utilized and has been employed in the industry for many years. This system works by pumping saltwater into closed pipelines, which are then heated and heated by steam from the top levels. It's then heated using built-in burners or steam, and since it's coupled to a vacuum system within the chambers, the water evaporates quickly under vacuum. It's worth noting that the quantity of vacuum in each chamber grows. After going through a removal system, the vapor from this evaporation collides with the condensate pipes and warms the incoming feed. The collecting trays send the liquefied water to the outside, where it is mixed with the unit input sufficiently to achieve a proper solute concentration. Due to the high salt concentration in the by-product, it is often combined with water to minimize its corrosiveness. Finally, the created saline water is discarded as waste due to its high salt content. To recover the water, some of the brine may be re-mixed with feed. These machines typically have 4 to 40 stages with a capacity of 5 to 60 thousand cubic meters per day [17].

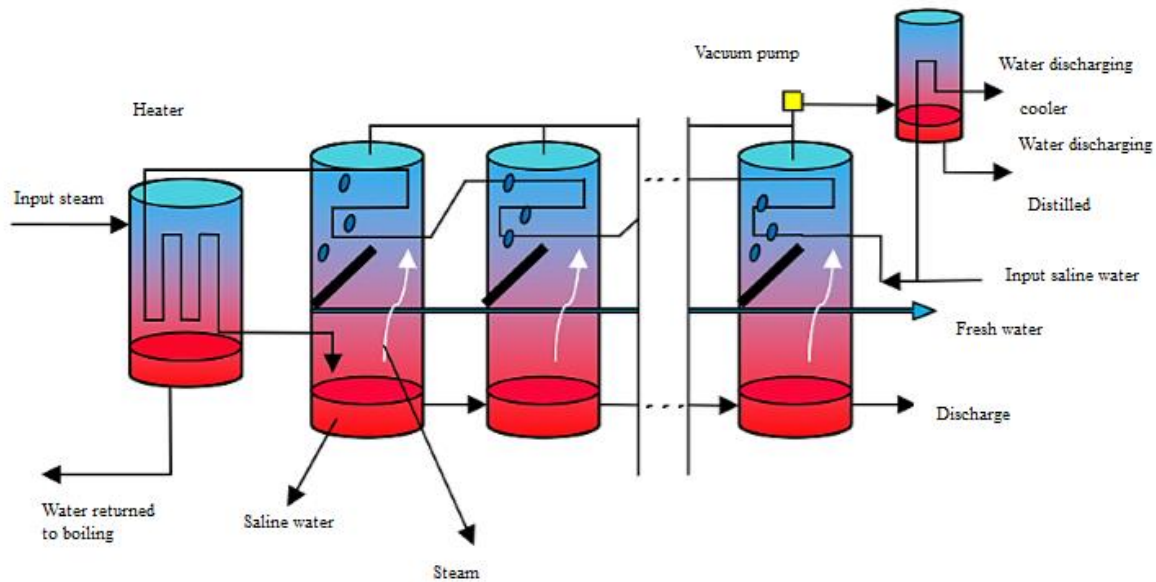


Figure 14: Multi stage abrupt distillation process [17]

In a multi-stage sudden distillation unit, each stage runs at a lower pressure than the one before it. Water is heated to prevent it from boiling and enters the first abrupt distillation chamber at reasonably high pressure. The pressure drops in the first flash chamber, causing rapid evaporation. The evaporation process continues in phases as the pressure drops with each one. This process, unlike multi-stage distillation, generates and condenses steam in the same phase.

The multi-stage flash distillation method may include four to forty chambers, although most are between 18 and 25. [18]

2-6-5: Vapor Compression Desalination

Compressed steam distillation involves evaporating saltwater or brackish water by exchanging heat with condensed steam. This procedure may be utilized in combination with other processes or on its own, depending on the scenario. The pressure and temperature of steam rise as it condenses. Evaporation may be aided by the heat energy stored in thick steam [19].

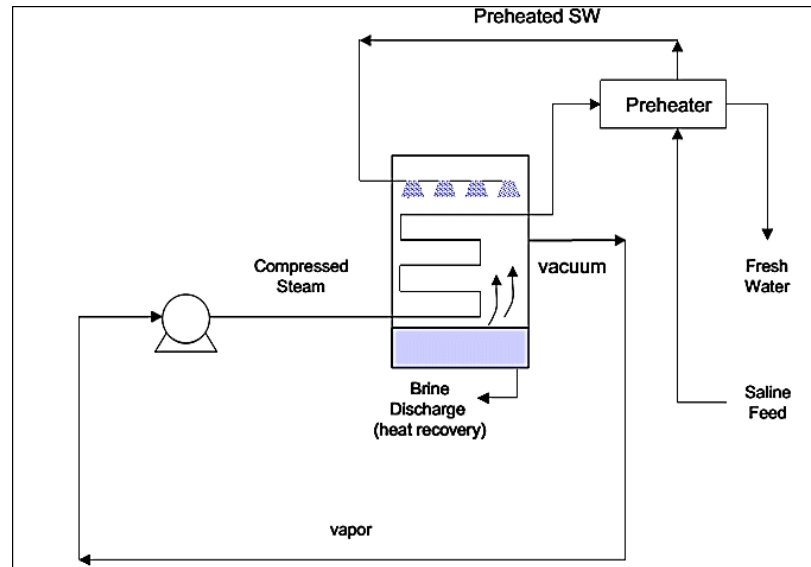


Figure 15: Schematic of water desalination by steam compression method [19]

Mechanical or electrical technologies may be used to condense the steam. Mechanical vapor compression, or MVC for short, was developed as a result of the usage of mechanical systems. There are two models in the MVC method: vapor density (VC) and vacuum vapor density (VVD) (VVC). The procedure is carried out at atmospheric pressure in the VC technique, whereas evaporation occurs at sub-atmospheric pressure in the VVC method.

In mechanical techniques, a turbine or compressor is used to compact the material. This method is now one of the most often employed in power plants and other sectors. Steam vapor distillation is a small-scale method that produces very little fresh water and is often used in hotels, resorts, and even industrial settings.

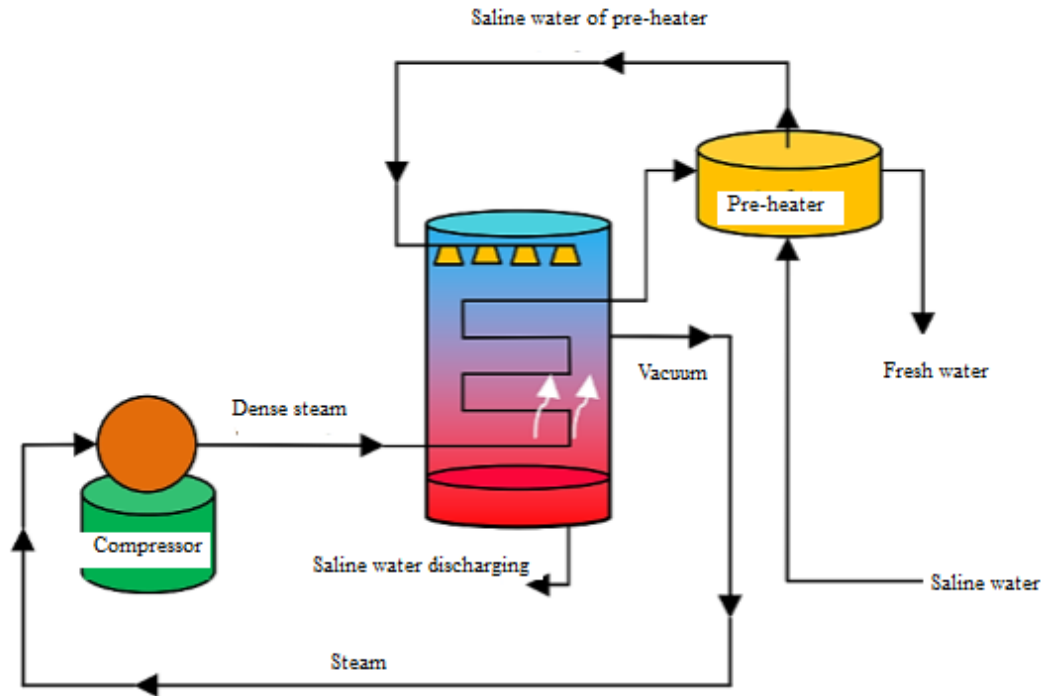


Figure 16: Fresh water production process by steam density method [19]

Evaporative compressive distillation is a method of extracting external thermal energy by compressing a portion of the steam generated. Electricity is used to condense mechanical vapor density. Evaporation density techniques, in general, are utilized in conjunction with other technologies, particularly the efficient multi-stage distillation process. Compared to the multi-stage abrupt evaporation approach, the evaporation density method uses less energy. Although the capacity of compression evaporation units is smaller, the amount of pure water produced per unit of evaporation density is higher than that of sudden multi-stage distillation units and effective multi-stage distillation.[20]

2-6-6: Production of Fresh Water by Distillation Method

The salty water is placed into a shallow container that is entirely sealed and has no contact with the outside air in the distillation system. A transparent cover, such as a sheet of glass or plastic, is also used to cover the solar desalination plant, similar to a flat solar collector. The rays entering the desalination plant clash with the water within it and heat it, and this coating layer passes all of the sun's wavelengths, save the infrared ones. Furthermore, heat loss by displacement is

considerably reduced by the transparent layer. The desalination plant traps solar energy, which causes the water to evaporate and increases the quantity of water vapor in the desalination water. Consequently, the salt in the water settles in the pond, and the water vapor is progressively distilled on the transparent cover as the relative humidity increases. The water collecting point at the end of the cover collects fresh water.

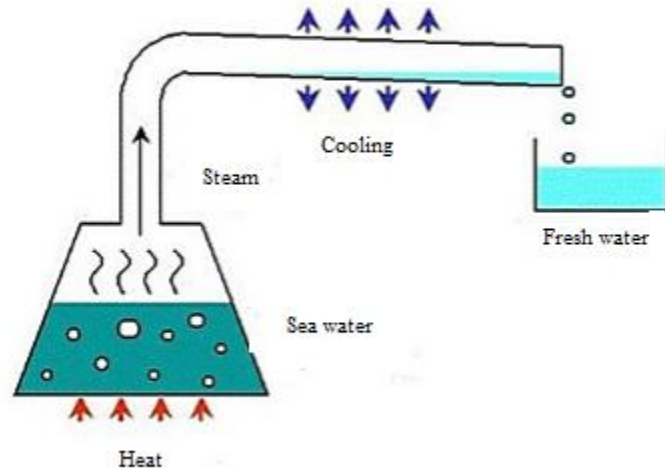


Figure 17: Distillation desalination cycle [21]

Section 3

Humidification–Dehumidification (HDH) Process for Desalination

3-1: HDH Method Description

From ancient times to today, people have been fascinated by the mechanisms that control the creation of freshwater. Because of the Industrial Revolution and continued population increase, the production of freshwater has taken on greater significance than it ever has before. The most fundamental type of these systems makes use of solar energy to drive the evaporation and distillation of salty water within a chamber. The processes of distillation, reverse osmosis, electrodialysis, ion exchange, desalination, and freezing are only a few of the several significant technologies that fall under this category [22][23]. Examples of distillation-based desalination systems that are extensively utilized include multi-stage spray distillation, multi-effect distillation, vapor condensation, solar distillation, and humidification-dehumidification methods [24][25]. In the process known as humidification-dehumidification desalination or HDH in abbreviation, the air is allowed to enter the dehumidifier chamber only after it has been moistened while circulating within the hot salt water dehumidifier chamber. After that, the chamber will begin to create fresh water as the temperature starts to fall and the humidity level will decrease [26]. The ability to operate at atmospheric pressure, a reduced maximum system temperature, simple and inexpensive equipment used, low maintenance costs, applicability for extremely salty water, and the exclusion of boiling salted water and very little sedimentation are some of the advantages of this system in comparison to other distillation-based systems [27],[28]. In the current investigation, following an analysis of the various techniques for desalinating water, as well as a comparison of the benefits and drawbacks associated with each method, a simulation of the HDH solar water desalination system using Aspen HYSYS software was carried out.

3-2: Research purpose

One of the essential requirements for the continued existence of human societies is the availability of freshwater resources. The lack of access to freshwater resources combined with the ever-increasing global population has become one of the most significant difficulties that scholars face in the modern era. The salty water found in the world's oceans accounts for approximately 96.5 percent of the total amount of water on Earth. As freshwater sources, polar ice, groundwater, and

the water that exists in the earth's atmosphere collectively make up only 3.5 percent of the total water on the planet. To put it into perspective, just 0.0014 percent of the freshwater resources on the planet are directly accessible to humans and other living creatures [29]. As a result, respected companies and educational institutions worldwide devote a large amount of their time and resources to research in the field of saline water desalination systems. As part of this investigation, an effort is made to devise a system that combines a solar water heater with a humidification-dehumidification desalination system to address the problem of decreasing supplies of freshwater resources. In addition to reducing energy consumption, this system also reduces environmental damage. In addition, we have made an effort to get the highest possible performance for this system by carefully analyzing its critical parameters.

3-3: Problem statement

Drought and a lack of available freshwater resources have emerged as one of today's most significant problems. This problem is particularly obvious in regions with hot, dry climates and nations with a history of dealing with drought crises. For this reason, in recent years, countries that are connected to seawater and oceans have endeavored to satisfy a considerable portion of their demands through the process of desalination of seawater. This is because the desalination process removes salt from the water, making it suitable for human consumption. When it comes to the production of fresh water, however, it is of the utmost importance to give careful consideration to economic calculations. This is because the cost of creating one cubic meter of fresh water is relatively high [30]. The high energy consumption and high expense of these devices are the most significant new obstacles that have emerged in the production of freshwater. Consumption is increased because of the many different types of equipment that are put into this system, such as cooling and water heating equipment. Because of this, it is no longer practicable for any part of society to utilize this expensive and time-consuming method. On the other hand, traditional devices used in the production of freshwater typically lack the capability to desalinate and purify moderately contaminated and salty water at high concentrations. This is because conventional devices are not designed to deal with such challenges. In addition, these devices are unable to function in normal climatic circumstances and require unique equipment to achieve the desired temperature and pressure within the chamber. It is difficult for people in isolated places to acquire this equipment and construct the necessary chambers.

Given the difficulties that have been brought up, one may have faith that the device that has been presented in this study will be able to desalinate water with a high salt concentration and pollution, reduce energy consumption, be self-cooling, have water heating ability, and lead to the overcoming of obstacles in manufacturing, commissioning, and public consumption.

3-4: Research background

The thermodynamic behavior and performance of HDH desalination systems based on multi-chamber cycles, multistage pressure, and vapor concentration have been the subject of theoretical research conducted by Narian and colleagues [31]. The cycles of heated air or water, open or closed air cycles, open or closed water cycles, and open or closed air cycles are the foundations of the systems that are under study. The following factors determine the effectiveness of the system: the cycle of heated water; the ratio of heat capacity; the effective component of the dehumidifier and dehumidifier; the maximum and minimum temperature and relative humidity of the output of the dehumidifier and dehumidifier chambers; The thermodynamic behavior of closed-air and closed-water systems is analogous to one another. Within the context of heated water cycles, humidification performance is prioritized above dehumidification performance. Additionally, HDH systems based on multistage pressure and vapor concentration were evaluated and tested. Even though this improves the system's overall performance, it does so at the expense of increasing the system's overall cost.

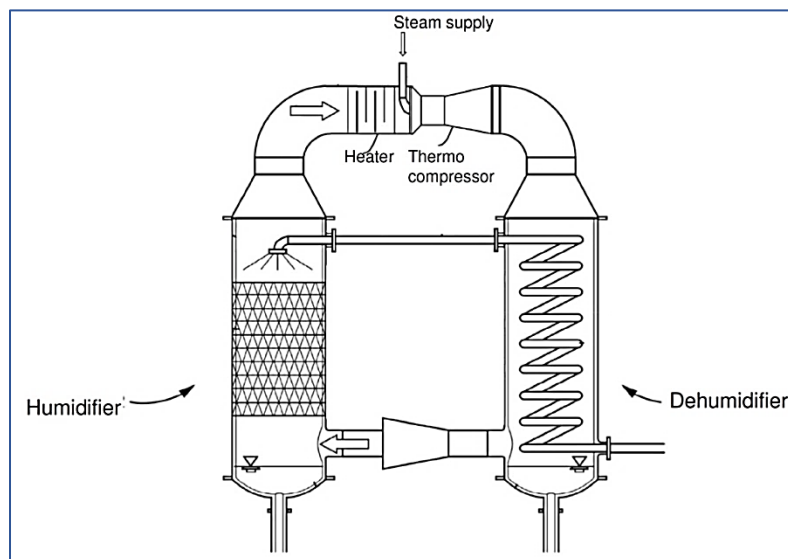


Figure 18: An HDH desalination system [31].

Khalil et al. [32] created a solar HDH desalination system by employing a dehumidification bubble column in their design. The application of the bubble column approach, as demonstrated by the findings, is a very successful strategy for enhancing the functionality of the apparatus. In addition, the performance of the system is not improved by having a water height that is greater than 5 cm; instead, this just results in an increase in the pressure drop and total saturation of the exhaust air.

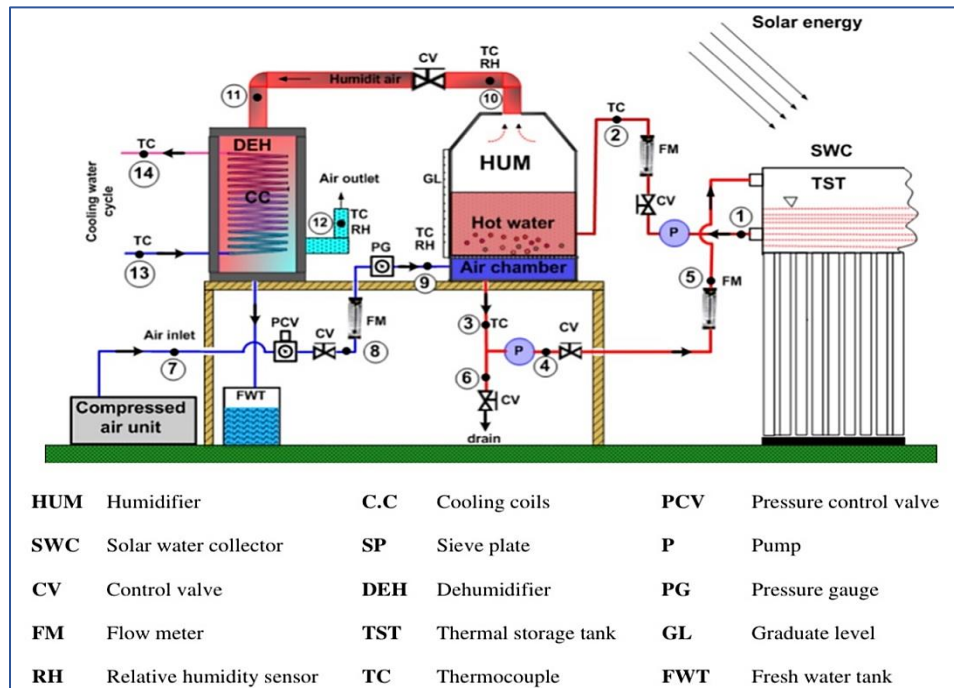


Figure 19: A schematic representation of HDH solar desalination system [32]

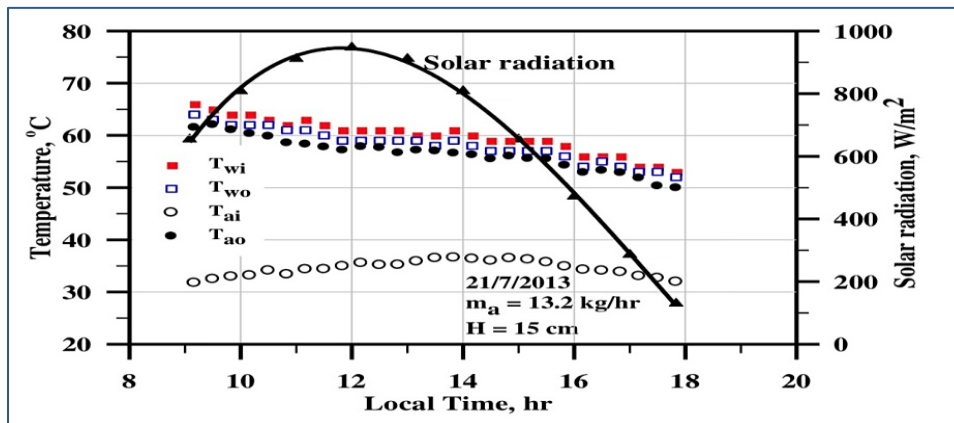


Figure 20: Sunlight, entrance water temperature, and output air at a $13.2 \frac{\text{kg}}{\text{h}}$ air mass flow in the research by Khalil et al. [32].

Using a bubble column approach, Majid Khan et al. [33] have developed an HDH water desalination system with a two-stage humidifier and a single-stage dehumidifier. They studied the impact of water-to-air flow ratio, air temperature, and water depth on the parameters of the desalination system. According to their findings, the two-stage dehumidification system increases the amount of water generated and the ratio of water produced to heat received.

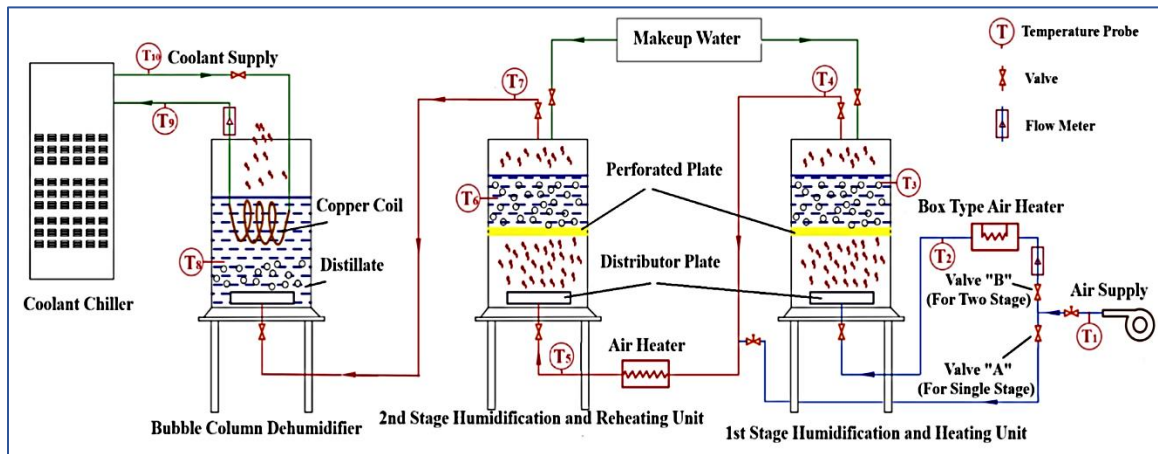


Figure 21: A schematic representation of the HDH two-stage desalination system [33].

Chahayeb et al. [34] have investigated the thermodynamic analysis of the two-stage HDH desalination system. In this investigation, two techniques were employed: bubble column and moistening substrates with water recovery. The effects of the water-to-air mass ratio on entropy generation as well as heat and mass transfer potential in a system of fixed dimensions have also been examined. The results indicate that when the ratio of each dehumidifier floor's heat capacity equals one, entropy generation is at its lowest level while heat and mass transfer is optimal. Furthermore, the relative heat capacity of the humidifier does not affect the HDH system. On the other hand, thermodynamic equilibrium affects system behavior far more than energy efficiency and water recovery.

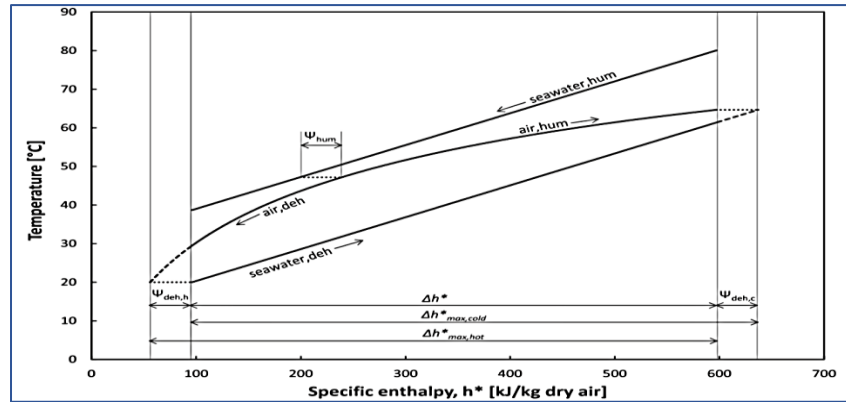


Figure 22: Diagram of temperature changes in terms of enthalpy in the research of Chahaib et al. [34].

In addition, Narayan et al. [35] compared the results of a mathematical model with an experimental model for injecting air into cold water. To use a bubble column for the HDH desalination system, the effects of superficial velocity, the molar ratio of the air inlet, bubble diameter, and liquid height on heat transfer rate were studied. According to the data collected, the performance of the bubble column increases as the superficial velocity and bubble diameter decrease. Furthermore, the molar ratio of the entering air does not affect the performance of the bubble column.

3-5: Desalination technologies and current updates

According to climate classification, our country is classified as dry and receives little precipitation. In recent years, the government has faced the effects of freshwater shortages, including the drying up of lakes and harm to agriculture, as a result of improper management and planning. With steps such as lowering transmission losses and conserving freshwater, consumption can be reduced to an acceptable level. However, given the country's economic and population expansion, this is insufficient, and the need for new resources is felt. One of the effective measures is the desalination of water by the HDH method.

Geographically, freshwater resources are not uniformly distributed. Overall, 96.54 percent of the water on earth is salty. While 2.53 percent of accessible sources of water are freshwater.

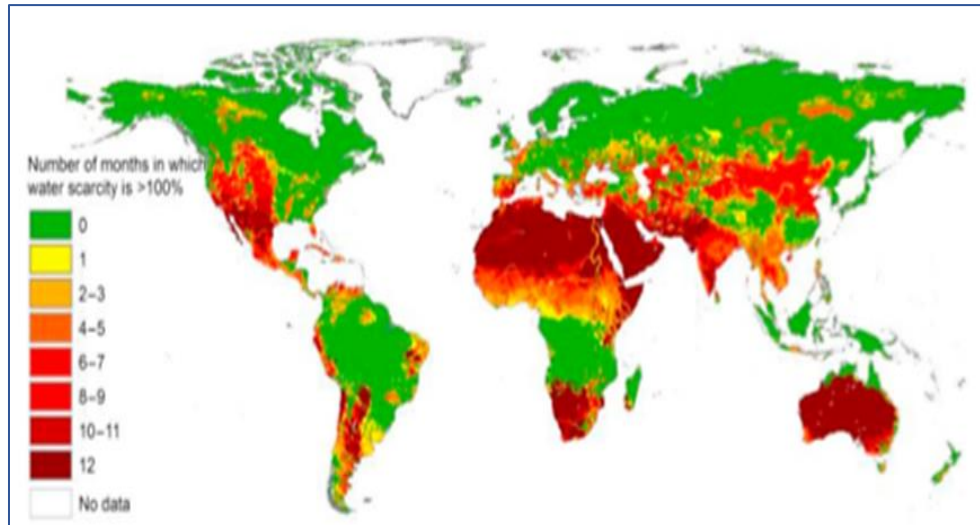


Figure 23: Suitable areas for thermal desalination (distillation systems) [36].

3-6: HDH desalination system

In a dehumidifiers-dehumidifiers desalination system, the air humidity increases with hot air circulation in the saltwater of the humidifier chamber. As the temperature inside the dehumidifier chamber decreases, the air loses its moisture, resulting in the production of fresh water. In recent years, several researchers have studied the behavior of desalination systems, which, among other benefits compared to conventional distillation systems, can be operated at atmospheric pressure, with a low maximum system temperature, and with minimal equipment requirements. These systems are also simple and inexpensive to operate, have low system maintenance expenses, are appropriate for highly salty water, avoid the boiling of salt water, and have minimal sedimentation [37].

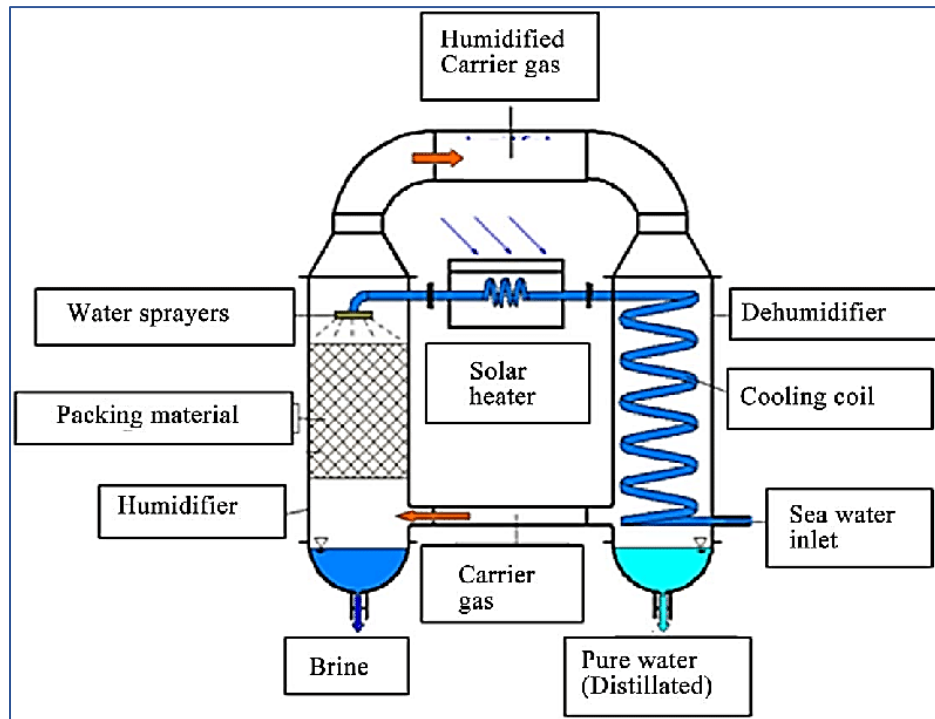


Figure 24: A schematic representation of the HDH process [37].

3-6-1: Description of HDH solar desalination system and its Types

An HDH desalination system consists of three subsets:

- 1) heater (solar, electrical, etc.) for heating water or air
- 2) humidifier or evaporator chamber
- 3) dehumidifier or condenser chamber.

Depending on the arrangement of these components and the heating of each stream, desalination systems are divided into different categories.[38]

HDH is classified into different types, which are divided into four main categories in terms of open or closed systems:

- 1) Open Air-Closed Water (OACW)
- 2) Closed Air-Open Water (CAOW)
- 3) Open Air- Open Water (OAOW)

4) Closed Air-Closed Water (CACW).

Also, from the point of view of heating, these systems are divided into two categories: water heating and air heating.

3-6-2: Advantages of HDH Desalination Systems

The following are some of the advantages of this system [38]:

- Reduced sedimentation
- Performance of the system under atmospheric pressure
- Biodegradable
- Compatible with extremely saline waters
- Low expenses for system maintenance
- Used simple and inexpensive equipment
- Lower maximum system temperature
- Low-temperature heating sources

3-6-3: Introduction of Essential Parameters of HDH Desalination System

Efficacy parameter or ε [39]:

$$\varepsilon_H = \frac{\Delta \dot{H}_{H,actual}}{\Delta \dot{H}_{H,max}}$$

$$\varepsilon_D = \frac{\Delta \dot{H}_{D,actual}}{\Delta \dot{H}_{D,max}}$$

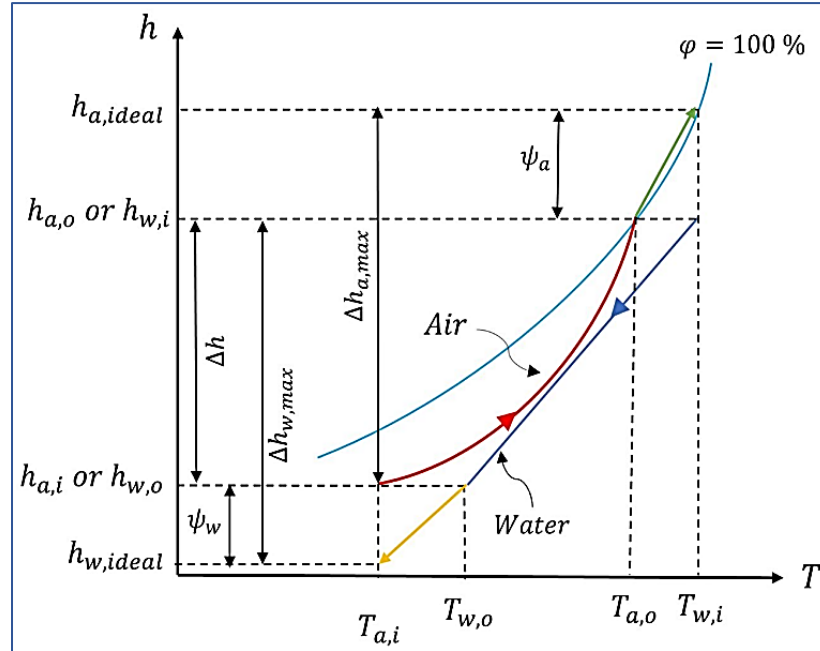


Figure 25: Diagram of heat capacity in terms of temperature [39].

Heat capacity Ratio

Heat capacity ratio is defined as the ratio of maximum change in cold flow enthalpy to maximum change in hot flow enthalpy for heat exchangers and mass heat exchangers, as well as heat capacity ratios for dehumidifier and humidifier chambers.

$$HCR_H = \frac{\Delta \dot{H}_{\max,H,a}}{\Delta \dot{H}_{\max,H,w}}$$

$$HCR_D = \frac{\Delta \dot{H}_{\max,D,a}}{\Delta \dot{H}_{\max,D,w}}$$

Desalination systems output

The resulting output ratio is equal to the product of the ratio of the latent heat of vaporization in the mass flow rate of the produced pure water divided by the rate of heat input to the system. In fact, this characteristic expresses the efficiency of the system and is also a good indicator to determine the amount of energy recovered.

$$\text{GOR} = \frac{\dot{m}_{\text{fw}} h_{\text{fg}}}{\dot{Q}_{\text{in}}}$$

h_{fg} is the latent heat of vaporization at an ambient temperature. If the value of GOR is equal to one, it means that the energy required by the system is exactly equal to the energy required to evaporate the amount of water produced, which is therefore not recovered in the energy system. So, the goal for the GOR value is to be a number greater than one, which means less energy per unit of water produced is needed. [40]

Technical and economic evaluation of HDH desalination systems:

Due to the dry climates in several regions of Iran, the limited availability of potable water, and the absence of fresh water, it is conceivable to provide water by developing extremely deep wells. In addition to the expensive expenses, there are health concerns and groundwater salinity. On the other hand, the supply of drinking water through the transfer of water from big cities to impoverished areas has additional challenges, such as expensive transmission and network development costs. Therefore, the most prevalent technique for supplying water in dry climates is the employment of extensive heating systems, such as abrupt multi-stage distillation or multi-effect distillation, which are often unsuitable in terms of size, expense, and pollution levels and areas with little precipitation. Due to the absence of electricity, remote osmosis systems are also unworkable in distant regions. In addition to the economics of the desalination plant, maintenance expenses must be considered to provide potable water. Solar desalination systems appear to be the only method that can fulfill all of the parameters listed above. Because the working temperature of traditional units is relatively high, more energy must be invested to achieve this temperature. But the new method of humidification and dehumidification does not require high temperatures, and all the thermal energy necessary can be supplied by solar energy. This type of desalination system has three significant benefits. First, the HDH desalination system's needed equipment is simple and can be fabricated with readily accessible components. Second, as a low-temperature thermal desalination technology, HDH is readily run by solar heating; hence, it requires no fuel and minimal electrical input. As a result, the HDH desalination system has attracted great interest during the past few years. [41]

The efficiency of the HDH desalination system

In general, increasing the efficiency of the HDH solar desalination system can be accomplished through the following steps:[42]

1. Air heaters and solar water heaters are two methods that can be used to raise the temperature before it enters the humidifiers. The amount of humidification that takes place is directly proportional to the temperature. Because of this, the quantity of solar energy that can be absorbed can be enhanced by selecting dark colors for the absorber plate and the pipes that transport air and water fluid. It is possible to transport more daylight or sunlight and, as a result, more energy into the collection by installing a reflector at both the beginning and the end of the collectors. Utilizing an adsorbent plate with a rough surface also results in increased heat transfer.
2. Loss of heat through the humidifier and dehumidifier chambers decreases the working temperature, which in turn brings about a decrease in production efficiency. As a result, these two compartments have been insulated with the assistance of various insulations such as elastomeric, ionolithic, fiberglass, and so on. To avoid a drop in temperature, it is also preferable for air heaters and solar water heaters to have walls and floors that are insulated.
3. The amount of freshwater that is generated can be increased by lowering the temperature of the water that is going into the dehumidifier. This can be accomplished by increasing the amount of heat exchange that occurs within the dehumidifier unit.
4. Increasing the flow rate of water entering the dehumidifier will result in an increase in the amount of freshwater produced. However, because the dimensions of the dehumidifier unit remain the same, this increase in flow rate will result in an increase in the amount of fresh water and, after that, the amount of desalinated water is relatively the same [42].



Figure 26: An illustration of the Iranian-made humidification-dehumidification desalination system [42].

3-7: Classification of HDH systems

The HDH systems were categorized by Narayan according to one of three categories: the kind of energy consumption, the cycle configuration, or the type of flow heating. HDH systems can be categorized according to the source of their energy consumption, such as solar, thermal, geothermal, or a mix of these three, which falls under the energy consumption category. This categorization is relevant for several reasons, one of which is that HDH desalination can be carried out using minimal heat, which helps conserve the environment. In accordance with the configuration of the cycle, these kinds of systems are categorized as closed-air open-water (CAOW), closed-air open-water (CAOW), or open-water open-air (OWOA). In every one of these scenarios, the fluid flow might be either natural or forced. This division is illustrated in the following figure. There are two distinct types of HDH systems, each designated by the medium used to heat the fluid: hot air systems and hot water systems. The heating of either the air or the water has a considerable impact on the functioning of these systems, as will be demonstrated in the following section [43].

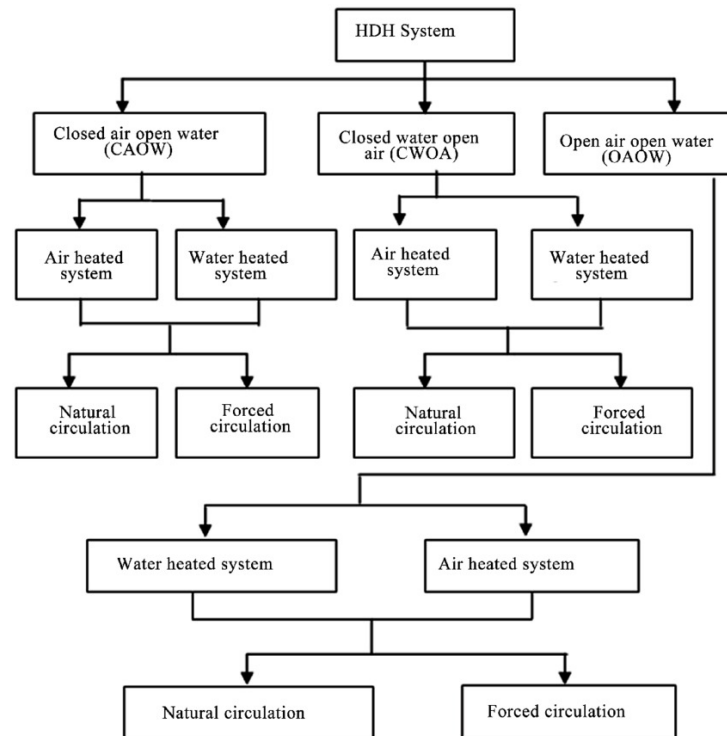


Figure 27: Classification of HDH systems [43].

3-7-1: Closed-Air Open-Water (CAOW) water-heated Cycle

The following diagram illustrates how the air that enters the humidifier is heated and turned more humid by spraying hot seawater as it passes through. The hot and moist air is then directed into the second piece of equipment known as a dehumidifier. This equipment decreases the air's temperature by cooling it with a stream of cold water, causes the air to condense, and generates desalinated water.

In these systems, saltwater is pumped into the section of the system responsible for dehumidification to simultaneously cool and dehumidify the flow of hot, humid air. During this step of the process, the system's efficiency of evaporation from the moist air is used to preheat the seawater (condensation process). The water that was generated by the condensation process is what gets expelled from the system. The heated seawater is then introduced into the humidifier, where it serves the purpose of removing moisture from the cold air stream. The seawater is heated either in a solar collector or water heater. Evaporation is the process by which mass and heat are transferred from the warm seawater to the stream of humid air, and the process is followed by the

discharge of any seawater that is still present in the system. In this system, the air is continually circulated in a closed cycle between the humidifier and the dehumidifier [44].

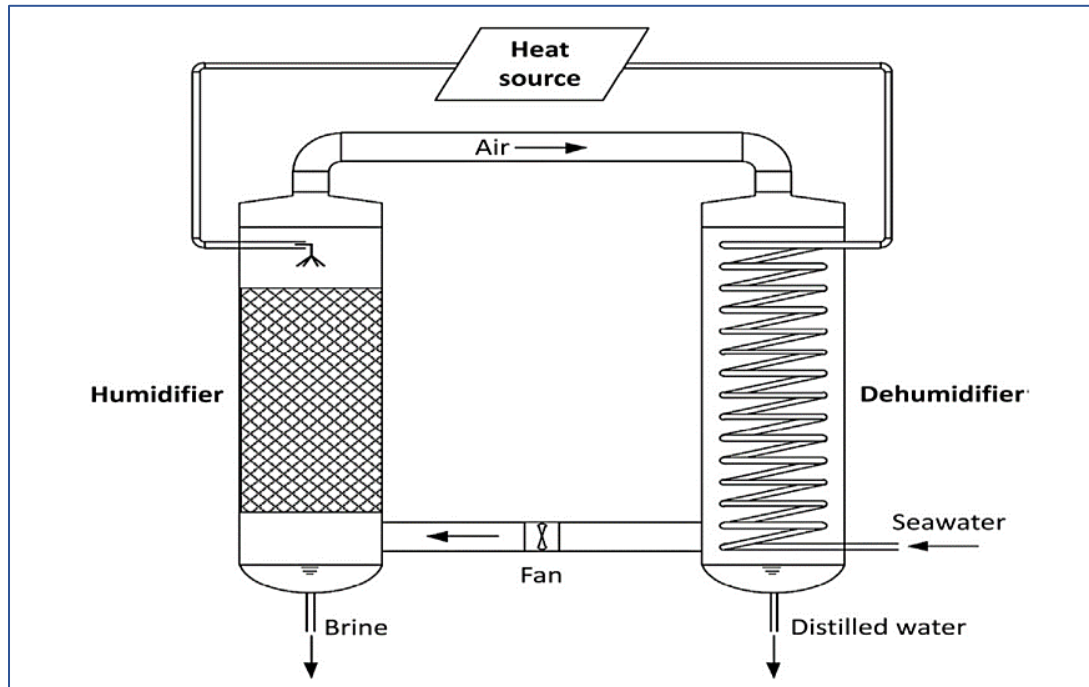


Figure 28: Closed-Air Open-Water (CAOW) water-heated cycle [44]

3-7-2: Multi-effect Closed-Air Open-Water (CAOW) water heated Cycle

Utilizing a multi-extraction air system that is fed by a single humidifier is one method that may be used to increase the effectiveness of the HDH cycle. The HDH cycle of multiple extractions is depicted in the following figure. In this cycle, hot and humid air can be extracted from different portions of a humidifier and sent to a dehumidifier, respectively. However, this system is more complex in design and construction. In this system, the moisture that comes from the dehumidifier is also converted into seawater that passes through the dehumidifier coil so that the process can increase the heat recovery in the humidifier. This method continues to lead to a small temperature gap between the air. This particular kind of HDH cycle is utilized by TinoxGmbH, commercial water and wastewater treatment company. It is possible that this is the first time the idea of the HDH cycle has been applied to a commercial setting [44].

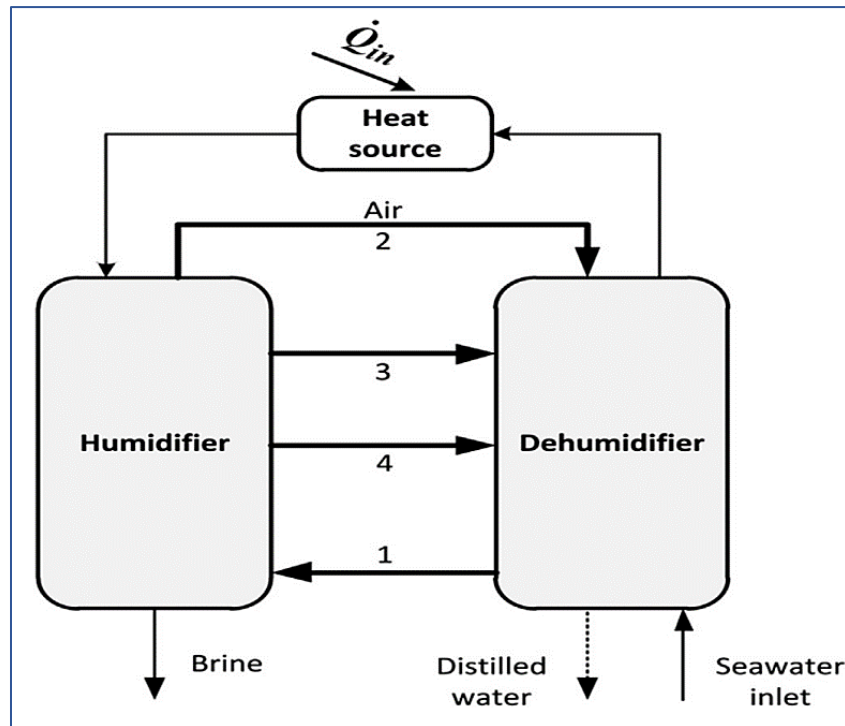


Figure 29: Multi-effect Closed-Air Open-Water (CAOW) water heated cycle [44].

3-7-3: Closed-Air Open-Water (CAOW) air heated Cycle

The next type of cycle is the HDH cycle (CAOW) with air heating. The diagram below illustrates its schematic. The air circulates throughout the cycle and heats up before entering the humidifier. Using a solar air collector, the air temperature can be raised to 80 to 90 C. In a humidifier, humidification of the air both saturates the air and reduces its temperature. Then this hot air and the low degree of humidity prevent it from getting wet at high temperatures when leaving the humidifier. The air is sent through a dehumidifier as part of the subsequent procedure once it has been humidified. The most significant drawback of using this approach is that it is unable to transport the heat capacity of the steam in an efficient manner, which results in a lower rate of water distillation in the dehumidifier. Utilizing a heating and humidification cycle that is comprised of many stages is one possible approach to resolving this issue. At each stage, the air is first heated, and then it is sent through a series of independent humidifiers to achieve the desired level of saturation. It is important to note that the procedure with many steps results in simultaneously increased levels of both water production and the need for heat energy [44].

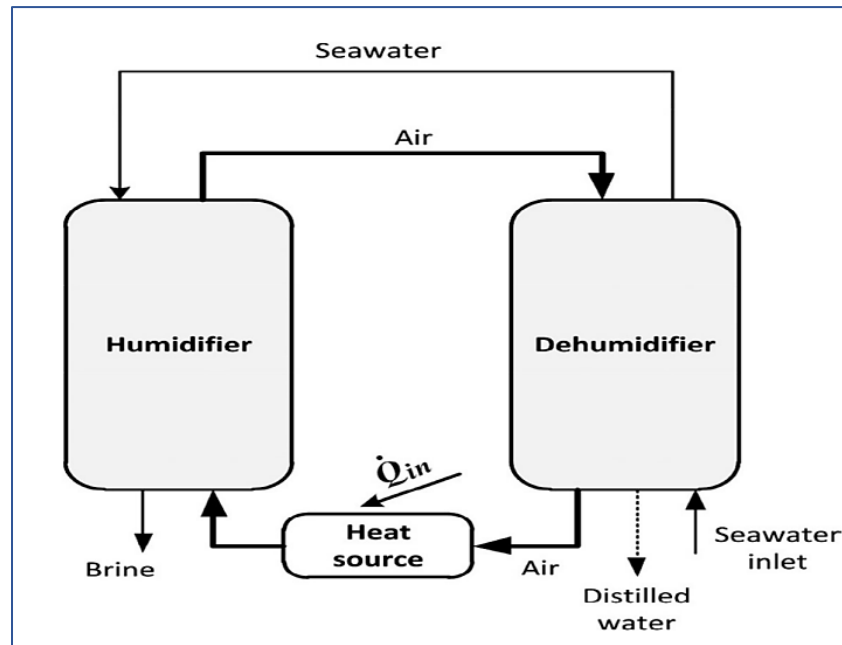


Figure 30: Closed-Air Open-Water (CAOW) air heated cycle [44].

3-7-4: Closed-Water Open-Air (CWOA) water-heated Cycle

In this cycle, air from the surrounding environment is pulled into the humidifier, where it is then humidified by being sprayed with warm seawater. After being preheated in the dehumidifier, the seawater is then transported to a humidifier, where it is heated further by an external source (such as a solar collector). After that, it goes back into the dehumidifier. After the humidification, compensation water is used to adjust the concentration of the seawater to a more appropriate level. After dehumidification, the air is discharged to the outside environment. The disadvantage of this cycle is that the output temperature of the seawater in the humidifier will rise if the temperature and humidity of the ambient air at the humidifier intake are not sufficiently low enough. As a consequence of this, the humid air contained within the dehumidifier is unable to be adequately cooled to have more pure water than it does during open cycles. Utilization might result in an increase in the cycle interval. The cycle interval can be improved with an efficient humidifier that brings the temperature of the seawater exiting the system down to a level that is more comparable to the temperature of the surrounding air [44].

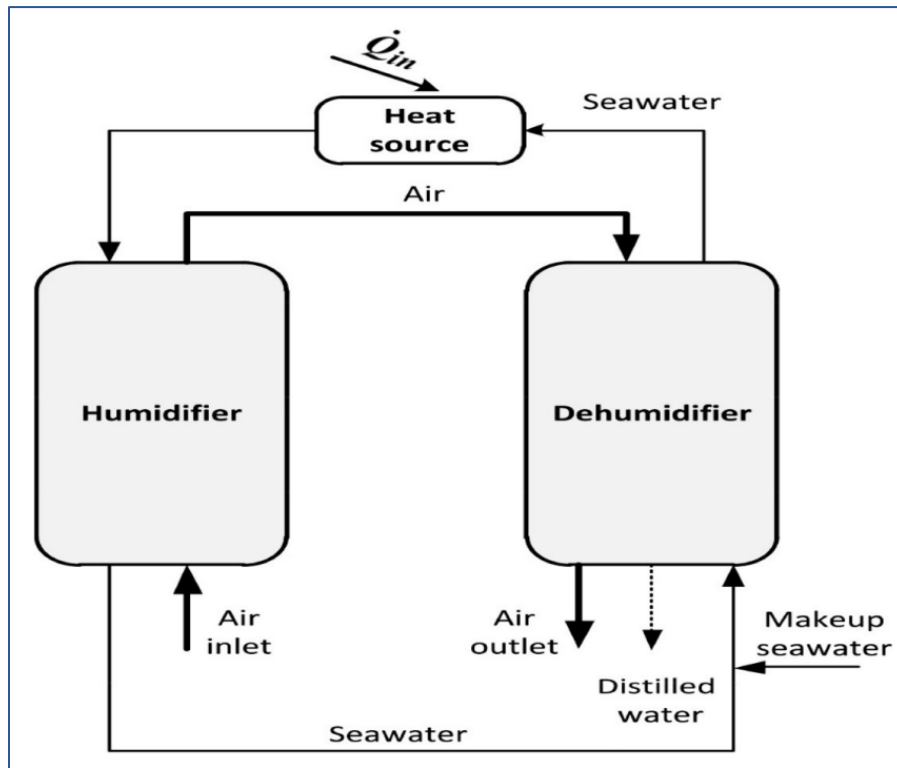


Figure 31: Closed-Water Open-Air (CWOA) water-heated cycle [44]

3-7-5 :Closed-Water Open-Air (CWOA) air-heated Cycle

As shown in the figure below, there is another type of HDH (CWOA) cycle that heats the air instead of the water. In this cycle, ambient air passes through a hot source (such as a solar air heater) and is then humidified by a humidifier. Humidification significantly reduces the air temperature, which strongly affects the efficiency of the cycle. The disadvantage of this cycle is that the low specific heat capacity of the air compared to water causes the air temperature to rise quickly. This reduces the amount of moist air vapor transferred to the dehumidifier and thus reduces water production. The multi-stage heating and humidifier process can improve this. When the ambient air is too hot, it increases the efficiency of the cycle. A more efficient humidifier can reduce the saline water temperature at the humidifier outlet and increase cycle efficiency [44].

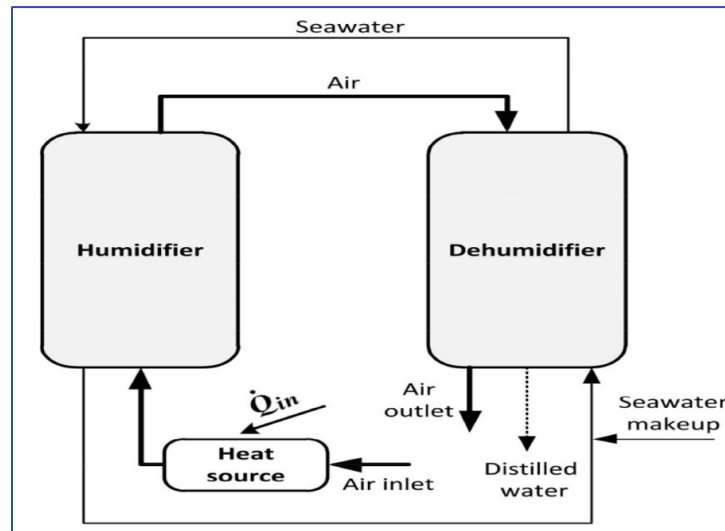


Figure 32: Closed-Water Open-Air (CWOA) cycle with air heating [44]

3-7-6: Open-Air Open-Water (OAOW) air-heated Cycle

In an Open-Air Open-Water air-heated (OAOW-AH) system, air flows in an open cycle between the humidifier and the dehumidifier, as shown below. Humid air enters the air heater after leaving the humidifier and before entering the dehumidifier and is discharged after leaving the dehumidifier. Excess water in the humidifier is also drained into the environment. These cycles behave very similarly to their air-closed counterparts. However, it is essential to note that open-air cycles are highly dependent on environmental conditions because the airflow is taken directly from the environment. As a result, it is reasonable to anticipate that the performance of OAOW cycles will shift in response to changes in the relative humidity and temperature of the surrounding environment.[45]

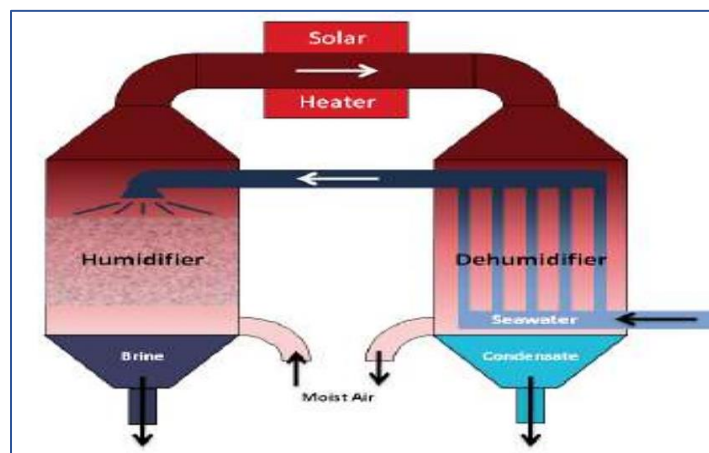


Figure 33: Open-Air Open-Water (OAOA) air-heated cycle.[45]

3-7-7: Open-Air Open-Water (OAOW) water-heated Cycle

This cycle is similar to the Open-Air Open-Water air-heated cycle. Climate currents follow the same flow patterns between humidifier and dehumidifier, but instead of heating the air, the heater is in the water flow path. The following figure shows this cycle [43].

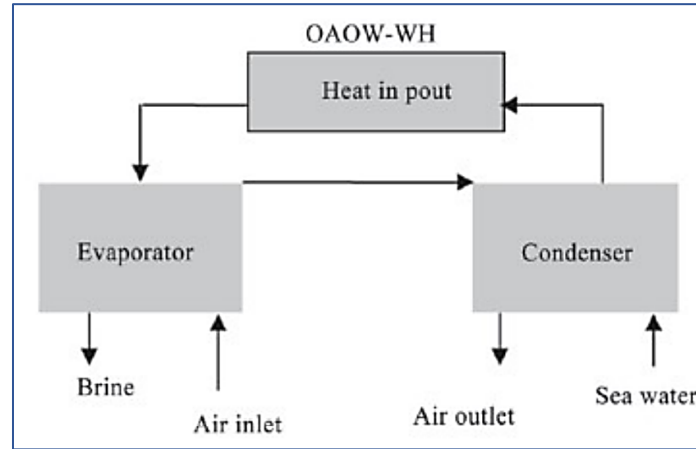


Figure 34: Open-Air Open-Water water-heated (OAOW-WH) cycle [43].

Air-heated systems use more heat energy than water-heated systems. This is because the air in the humidifier heats the water, and this energy is subsequently not recovered from the water. In a water-heated cycle, the water flow in the humidifier cools, and part of the thermal energy (carried by the air) is recovered in the dehumidifier [43].

3-8: Governing Equations

In this research, a computational model based on thermodynamic laws of mass and energy conservation in each part of the desalination system has been written. Desalination efficiency: The output ratio obtained from the product of the ratio of the latent heat of vaporization in the mass flow rate of produced pure water to the rate of heat input to the system, which expresses the efficiency of the system:

$$\text{GOR} = \frac{\dot{m}_{\text{FW}} \times h_{\text{fg}}}{\dot{Q}_{\text{H}}}$$

High system temperature (HDH): The temperature of the fluid (or water or air) heated at the heater outlet.

Low system temperature (HDH): Describes the temperature of the seawater inlet to the dehumidifier.

$$Q_{\text{heater}} = \dot{m}_2(h_3 - h_2)$$

$$\dot{m}_3 h_3 + \dot{m}_6 h_6 = \dot{m}_4 h_4 + \dot{m}_7 h_7$$

$$\varepsilon_{\text{Hum}} = \max\left(\frac{h_7 - h_6}{h_{7,\text{ideal}} - h_6}, \frac{h_3 - h_4}{h_3 - h_{4,\text{ideal}}}\right)$$

$$\dot{m}_1 h_1 + \dot{m}_7 h_7 = \dot{m}_2 h_2 + \dot{m}_5 h_5 + \dot{m}_6 h_6$$

$$\varepsilon_{\text{Dhum}} = \max\left(\frac{h_7 - h_6}{h_7 - h_{6,\text{ideal}}}, \frac{h_3 - h_2}{h_{3,\text{ideal}} - h_2}\right)$$

RR includes the recovery ratio of the amount of distilled water to the gross water entering the cycle, which is a measure of water production efficiency in the cycle. This parameter is about 7% for the HDH system in the single-pass algorithm and can be increased to a higher value (up to 7% depending on the incoming salty water). RR is an indirect parameter and is presented as a percentage. It should be noted that for a low recovery ratio, the desalination process is not required.

$$\text{RR} = \frac{\dot{m}_{\text{fwp}}}{\dot{m}_{\text{sw}}} \times 100$$

Also, one of the key parameters in the HDH desalination system, which appears mainly about other cycle performance parameters, is the mass flow rate ratio, which is defined as the ratio of liquid to gas flow rate [46]:

$$\text{MR} = \frac{\dot{m}_{\text{sw}}}{\dot{m}_{\text{da}}}$$

Regarding specific energy consumption, the total electrical energy used to produce 1 kg of freshwater can be presented as follows [47]:

$$SEC = \frac{\dot{E}_{in}}{\dot{V}_{fwp}}$$

Which $\dot{V}_{fwp}$ is the flow of produced freshwater ($\frac{m^3}{h}$).

The smaller the SEC, the more efficient the system will be. This can be explained by the fact that the quantity of energy consumption was lower for a particular volume of fresh water generated, which in turn will save expenses and energy.

The specific water production parameter can be used mainly for the HDH cycle based on solar energy. This parameter indicates the efficiency of solar energy in the HDH cycle and the capital cost of solar collectors [48]:

$$SWP = \frac{\dot{m}_{fwp}}{A_{se}}$$

3-9: Solar Energy Potential in Iran

Iran is one of the nations that is most likely to utilize solar energy due to its location on the solar belt and the fact that the quantity of daily sunshine that is received in the country reaches 4.5 to 5.5 kWh per square meter. This can be seen in the figure that is provided below. Iran is located in an area that is among the top in terms of solar energy among many regions of the world. Its latitude ranges from 25 to 40 degrees north, making it one of the most solar-rich regions on the planet. The amount of solar radiation in Iran is estimated to be between 1800 and 2200 kWh per square meter per year, which is higher than the average for the entire world. This is because Iran is geographically located in the northern hemisphere, and our country is also in the world solar belt. According to this point, the amount of solar radiation in Iran is higher than the average worldwide. Iran is one of the nations that has sunshine with desirable power and is one of the locations that are most prone to utilizing solar energy. It is also one of the countries that appreciate sunlight. Therefore, the average daily sunshine is 4 kWh per square meter, and the average number of sunny hours is more than 2800 hours per year. This figure is much higher in the desert towns of our country, such as Yazd and Kerman, where it may reach up to 3200. In the southern parts of Iran, getting access to clean drinking water has long been one of the most difficult challenges. On the other hand, the majority of these regions have access to salty water and an acceptable amount of

sunshine. Desalination of water by the use of solar energy, therefore, has the potential to be one of the good and environmentally friendly solutions to this problem.[49]

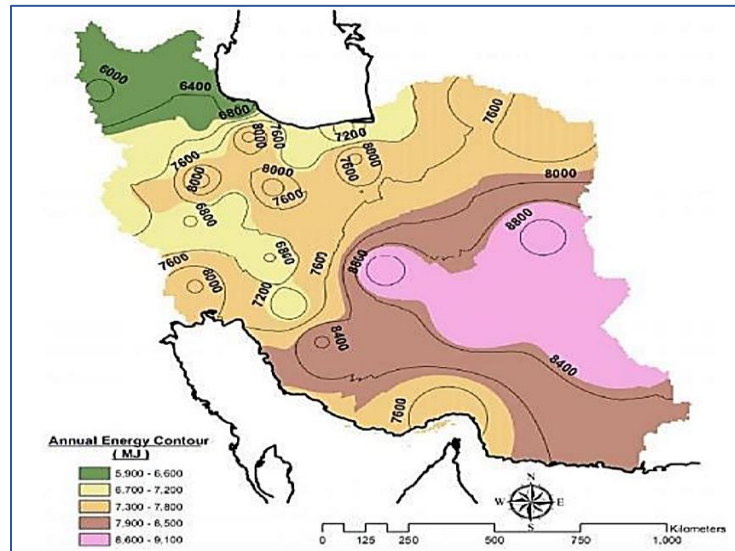


Figure 35: The solar energy input contour for the whole year in Iran [49].

Section 4

Simulation and Methodology of Process

4-1: Simulation and methodology for HDH plant in Iran:

The gap we identify and cover is designing an HDH plant in Iran with Iran's conditions.

To cover that gap, we choose Bandar-e 'Abbās as the place of our plant. We use environmental information of Bandar-e 'Abbās like temperature and pressure. We use water from the Persian Gulf with a TDS of 40,000 ppm and try to produce water with almost zero ppm with the HDH method.[50]

4-2: Physical Conditions of the Place

4-2-1: Location of the Plant

Bandar-e 'Abbās, Hormozgān province, Iran. Latitude and longitude coordinates are 27.183708 and 56.277447. [50]

Bandar-e 'Abbās, port city and capital of Hormozgān province, on the Strait of Hormuz, the main maritime outlet for much of southern Iran. It lies on the northern shore of Hormuz Bay opposite the islands of Qeshm, Lārak, and Hormuz. The inhabitants are mainly Arabs and African blacks. The summer climate is oppressively hot and humid, and many inhabitants then move to cooler places; however, winter is pleasant.[51]

4-2-2: Temperature of Bandar-e 'Abbās:

We use an average temperature of Bandar-e 'Abbās for the simulation.

Average	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
High	23°C	24°C	27°C	31°C	36°C	38°C	37°C	37°C	36°C	34°C	29°C	25°C
Temp.	17°C	19°C	22°C	27°C	31°C	33°C	34°C	34°C	32°C	29°C	24°C	19°C
Low	12°C	14°C	17°C	21°C	25°C	29°C	31°C	30°C	28°C	24°C	18°C	14°C

Figure 36: The average temperature of Bandar Abbas [52]

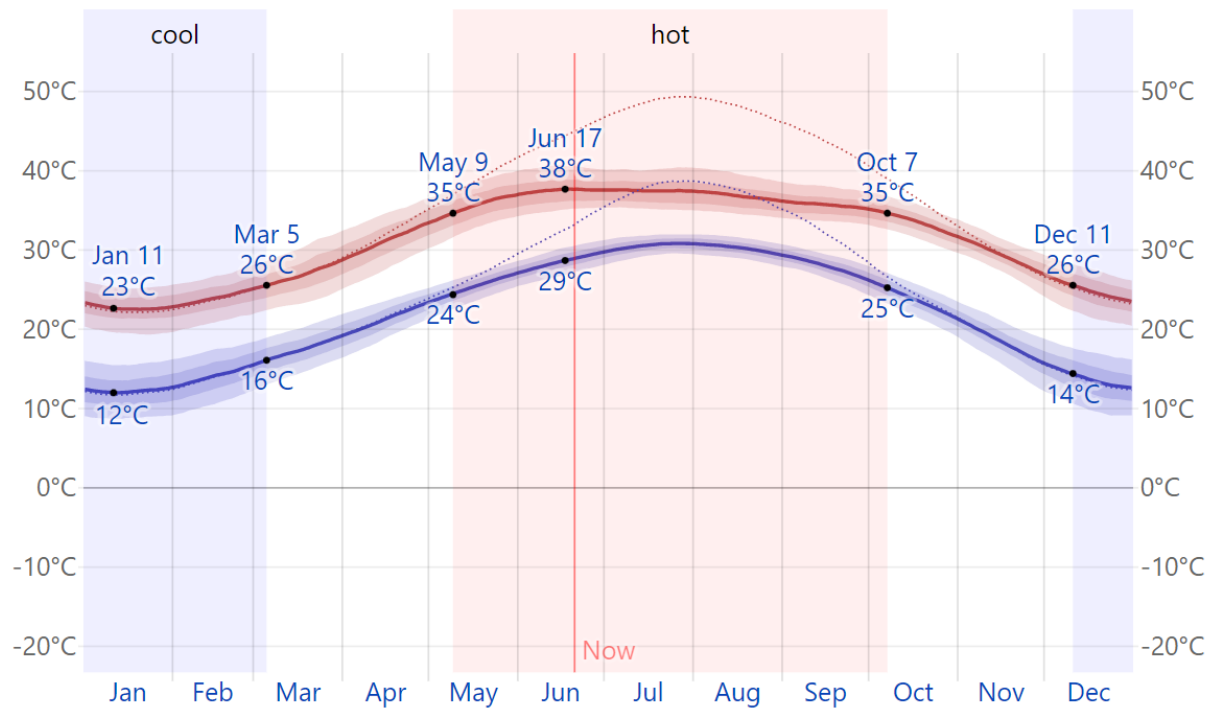


Figure 37: average high and low temperature in Bandar Abbas [52]

Based on information in figure 36, the average Temperature of Bandar-e ‘Abbās is 26.7°C.

4-2-3: The humidity of Bandar-e ‘Abbās:

We use an average relative humidity of Bandar-e ‘Abbās for the simulation.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Relative Humidity (%)	64	68	67	64	61	64	68	69	67	64	61	63	65
Average Dew Point Temperature °C (°F)	11.2 (52.1)	13.3 (56)	16.6 (62)	19.4 (67)	22.8 (73)	25.9 (78.7)	27.6 (81.7)	27.5 (81.5)	25.6 (78)	22.1 (71.7)	16.3 (61.3)	12.5 (54.4)	20.1 (68.1)
Interpretation	Very comfortable	Comfortable	Ok	Humid	Very humid	Muggy	Severely high	Severely high	Muggy	Very humid	Ok	Comfortable	Humid

Figure 38: average humidity in Bandar Abbas [53]

Based on the information in figure38, the average relative humidity of Bandar-e 'Abbās is 65%. We must calculate absolute humidity. We use figure 39 to calculate the absolute humidity.

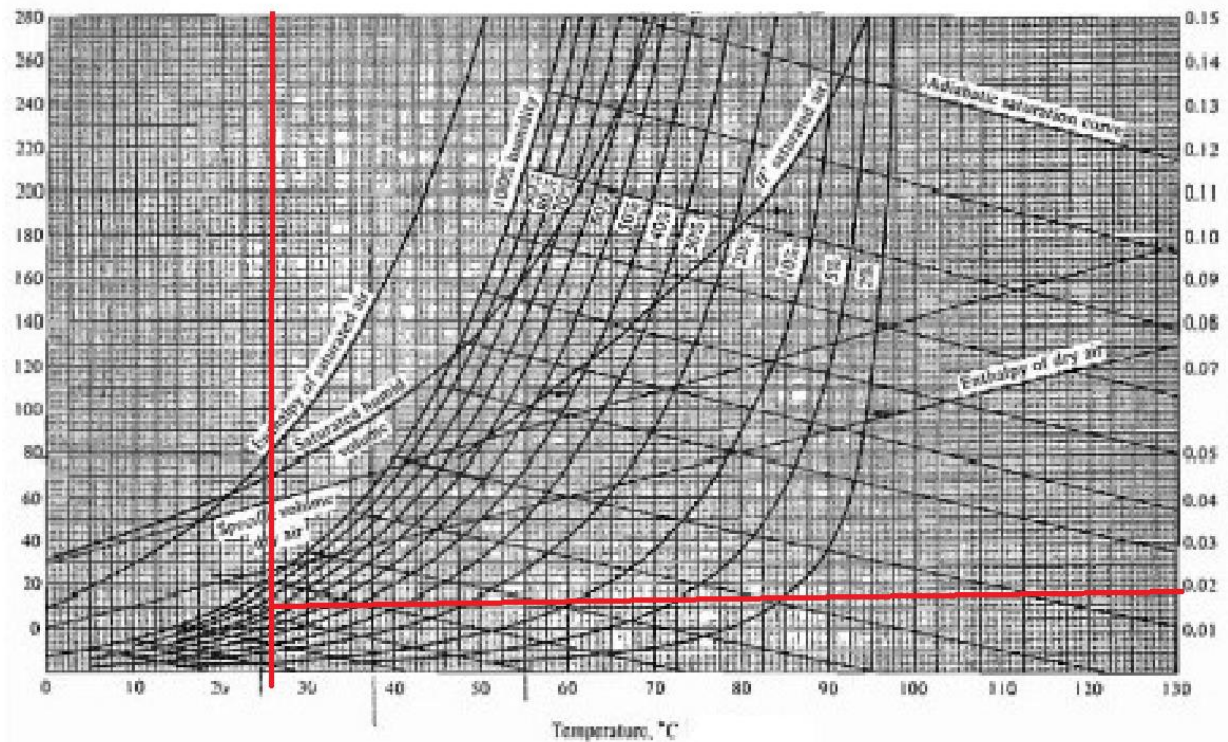


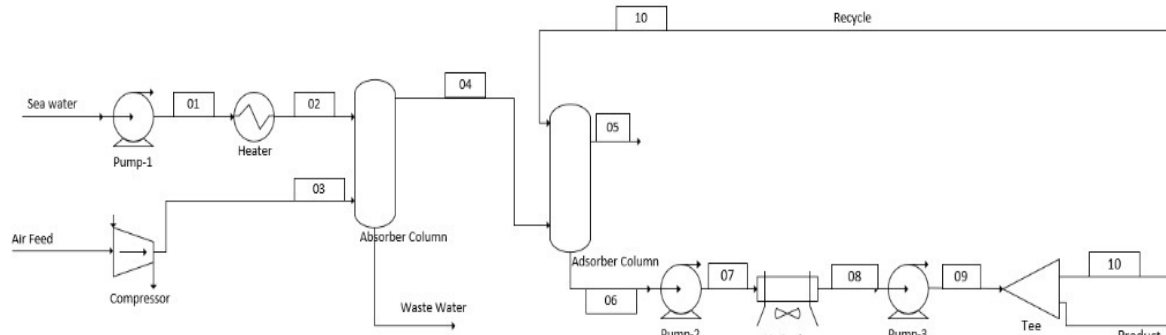
Figure 39: Psychrometric Diagram [54]

So, the absolute humidity is 2%.

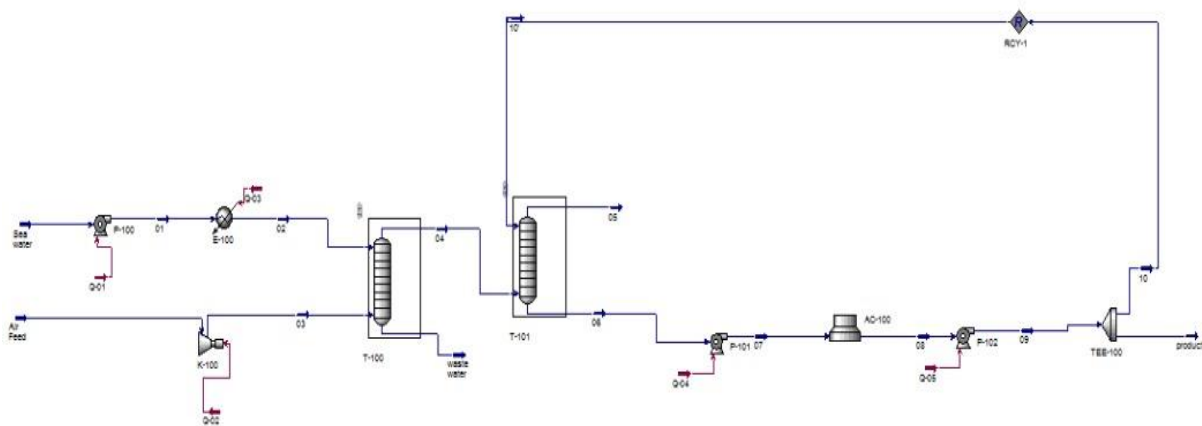
4-2-4: The temperature of the Persian Gulf

The temperature of Persian Gulf water ranges from 24 °C to 32°C. We consider an average of 28°C for the temperature of Persian Gulf water.[55]

4-3: Block Flow Diagram of HDH Process



4-4: HYSYS Simulation of HDH Process



4-5: Assumptions of Simulation

1. The Fluid Package of HYSYS is UNIQUAS
2. In HYSYS, we use a heater. But in reality, we use solar water heating collectors.
3. We use a backup heater to help with solar water heating collectors. We consider that the plants work 24 hours a day. So, we need that backup heater for nights and cloudy days. We

use a TC for the collectors. If the temperature decreases, the backup heater will work and compensate for the lack of heat. Also, we did not calculate this in the economic analysis.

4. In HYSYS, we use an air cooler because of software limitations. But in reality, we use PVC pipelines under the ocean to decrease the temperature of the water.
5. In HYSYS, the pressure of stream 09 is 1.6bar. But in reality, the pressure is 2.6 bar. Although, we calculate the power of pump P102 based on reality with a pressure increase of 1.6 bar.

4-6: Methodology

Sea water with a temperature of 28°C and pressure of 1atm enters to plant. The mass flow rate of seawater is $5000 \frac{\text{kg}}{\text{h}}$ with a TDS of 40,000 ppm. Therefore, the mass fraction of NaOH in water is 0.04. Sea water enters sand filters and after that enters the pump P100. The power of pump P100 is equal to 0.125kW. In pump P100, the pressure increases to 1.7 bar. Then the water enters solar water heating collectors. We use solar water heating collectors to increase the water's temperature. Increasing the temperature of the water increases the evaporation of the water and also increases the efficiency of the humidification tower. Water heating can be done with the help of fossil fuels and in boilers, electrical elements, or solar collectors. Solar collectors are more suitable due to their lower cost and free heating energy. Some of the solar collectors are:

1. Flat plate solar Collectors.
2. Evacuated Tube Collectors.
3. Parabolic Trough Collectors
4. Compound Parabolic Collectors

In the plant, a flat plate collector is used. The choice of the solar water heater depends on the amount of hot water required, temperature, and other factors. Still, in summary, Flat plate solar collectors are usually 32 square feet (4 by 8 feet) or 3 square meters and weigh more than 200 pounds or 100 kilograms. One square foot can increase the temperature of about 2 gallons or 10 liters of water a day above 75°C. Therefore, a panel of 20-30 square meters can heat 60 gallons or 300 liters of water. Since our mass flow rate is 5000 liters per hour, we need about 17 solar panels.[56]

$$\text{Number of panels} = \frac{1 \text{ panel}}{300\text{L}} \times 5000\text{L} = 16.66$$

In solar water heating collectors, the water temperature increases to 75°C. The pressure drop of solar water heating collectors is 0.1 bar. After that, the water enters the top of the absorption tower T100.

Air feed with a temperature of 26.72°C and pressure of 1atm enters to compressor K100. The mass flow rate of air is $5000 \frac{\text{kg}}{\text{h}}$ with absolute humidity of 2%. So, the mass fraction of the water in the air feed is 2%, and the mass flow rate of water is equal to $100 \frac{\text{kg}}{\text{h}}$. The power of compressor K100 is equal to 131kW. In compressor K100, pressure increases to 2.1 bar, and temperature increases to 119.39°C. After that, it enters the bottom of the absorption tower T100.

Tower T100 has five trays and a diameter of 1.5m. Therefore, the tower's surface is equal to 1.766 m². The distance between two trays is 0.5m. The height of the tower is 2.5m.

Therefore, the volume of the tower is equal to 4.415 m³. As per tray, we consider a pressure drop of 0.1 bar. The bottom product of the T100 tower is wastewater. The pressure of wastewater is 1.1 bar, and the temperature of wastewater is 52.17°C. In wastewater, the mass fraction of NaOH is 0.0466, and the mass flow rate of NaOH is $199.996 \frac{\text{kg}}{\text{h}}$. It means that almost all NaOH comes here. The up product is stream 04. Stream 04 has a mass flow rate of $5709.6 \frac{\text{kg}}{\text{h}}$. The mass flow rate of steam water in Stream 04 is $811.2 \frac{\text{kg}}{\text{h}}$. As we discussed before, the mass flow rate of water in Air feed is $100 \frac{\text{kg}}{\text{h}}$. Therefore, we understand that $711.2 \frac{\text{kg}}{\text{h}}$ was absorbed in the air in the absorption tower.

Stream 04 enters at the bottom of the stripper tower T101. The sizing of Tower T101 is like T100. The freshwater with a temperature of 28°C and pressure of 1.6 bar enters at the top of the stripper tower. The mass flow rate of freshwater equals $15,000 \frac{\text{kg}}{\text{h}}$. Stream 05 is the top product of tower T101. It has $116.23 \frac{\text{kg}}{\text{h}}$ of water and a water mass fraction of 0.0231. Stream 06 is the bottom product of T101. It has a temperature of 57.69 and a pressure of 1.1 bar. The mass fraction of water

is equal to 0.9996. the water enters pump P101. The power of pump P101 is 7.04 kW. The water pressure increases to 13bar, and the temperature rises to 57.84 °C.

To recycle fresh water in the stripper tower T101, we must reduce the temperature of the water and keep the temperature at 28°C. To do that, we use a PVC pipeline under the ocean to decrease the temperature of the water. The mass flow rate of the water equals $15695.25 \frac{\text{kg}}{\text{h}}$. With a velocity of $0.5 \frac{\text{m}}{\text{s}}$ in the pipeline, the pipe's diameter is calculated 4.14 inches. So, we have a pipe with a diameter of 5 inches. Therefore, the velocity of the water is equal to $0.34 \frac{\text{m}}{\text{s}}$. The thickness of the pipe is equal to 0.12inches.

We use COMSOL software for calculations. Based on COMSOL results, we have a 0.18°C decrease in temperature per 10m of pipe. We assume natural convection for the simulation. Therefore, the velocity of ocean water is taken 0. Also, the pressure at the end of the pipe assumed 1atm. Based on this information and the assumption of a linear decrease in temperature, we need 1658 meters of PVC pipe. Of course, we know that decreasing the water temperature is not linear.

However, it is evident that at first, due to the tremendous temperature difference, the speed of heat transfer and thus the reduction of water temperature in the pipe is higher. Then, the heat transfer rate gradually decreases as the temperature difference decreases. So, the reduction in temperature cannot be considered linear. Of course, on the other hand, we considered natural convection and set the ocean velocity at 0. Because the ocean is wavy, actual h is higher, resulting in a higher heat transfer flux. However, 3000 meters of pipe is used to ensure the needed temperature. Approximately a range of 0.1 to 0.4 bars is the pressure drop for every 100 meters of pipe length. We consider the pressure drop to be 0.4 bar per 100 meters because we do not consider the pressure drop of the fittings like elbows. As a result, for 3 km of pipe, we have a pressure drop of 12 times. Also, in COMSOL, the water pressure at the end of the PVC pipe equals 1 atmosphere.

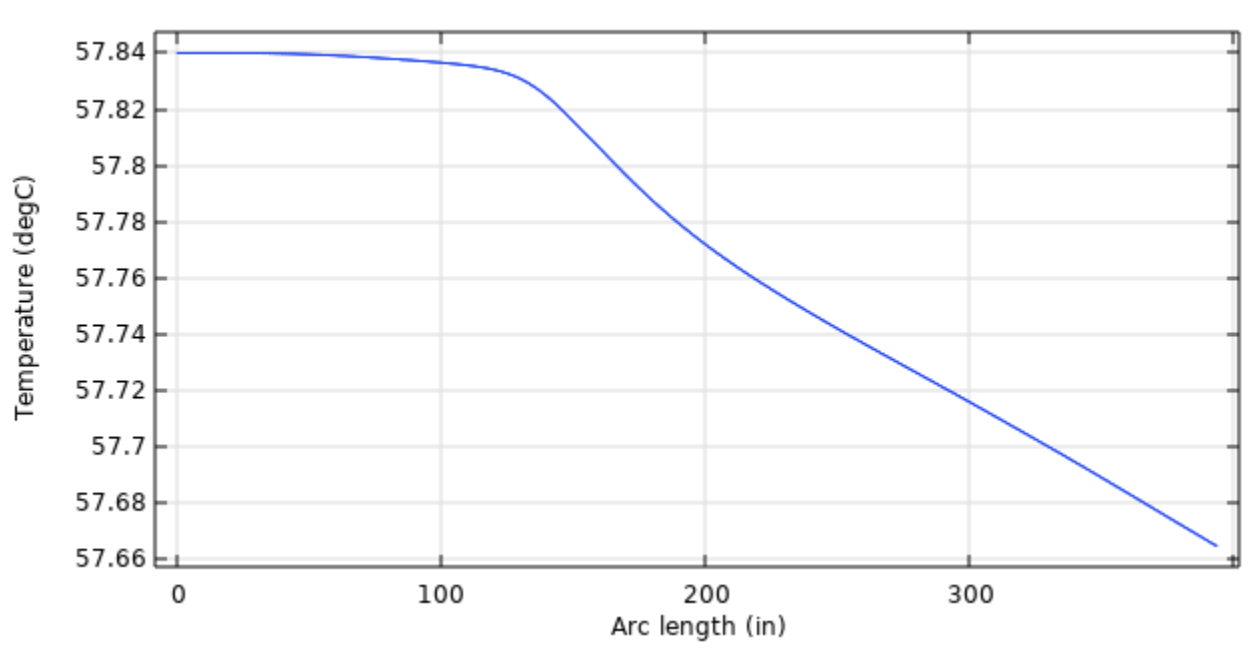


Figure 40: water temperature decrement at 10m PVC pipeline.



Figure 41: Temperature contour in PVC pipeline

After that, the water enters pump P102, and the power of pump P102 is equal to 0.74 kW. The pressure of the water increases to 2.6 bar. This increase in pressure is needed to move the water to the top of the tower. Also, the fresh water above the tower should be 1.6 bars. 15000 $\frac{\text{kg}}{\text{h}}$ of freshwater recycles at the top of the T101 tower again, and the product water with a mass flow rate of 695.25 $\frac{\text{kg}}{\text{h}}$ and TDS of almost 0 ppm is collected.

4-7: The efficiency of the plant

In this method, we consider efficiency as the ratio of the mass flow rate of the freshwater with TDS to almost zero, relative to the mass flow rate of the inlet ocean water. HDH plan efficiency varies in a range of 6 to 10 percent. This method is not inherently high efficiency but instead is economically viable due to its cheapness. In this plant, our return is equal to 13.9%.

$$\text{Efficiency} = \frac{\text{mass flow rate of product}}{\text{mass flow rate of sea water}} \times 100 = \frac{695.25}{5000} \times 100 = 13.9\%$$

4-8: Case studies and results

4-8-1: Mass flow rate of cold recycled water

As we know, increasing the mass flow rate of cold recycled water that enters the top of the stripper tower increases the mass flow rate of the product. To study this topic, we use the HYSYS case study. We change the mass flow rate of cold recycled water from $200 \frac{\text{kg}}{\text{h}}$ to $15000 \frac{\text{kg}}{\text{h}}$, and study the influences of this change on the mass flow rate of the product. It can be seen that the mass flow rate of the product increases from $98.97 \frac{\text{kg}}{\text{h}}$ to $702.5 \frac{\text{kg}}{\text{h}}$. We see the increment of the mass flow rate of the product. But, with a mass flow rate of more than $15000 \frac{\text{kg}}{\text{h}}$, the changes in the mass flow rate of the product decrease. The slope of the graph gradually becomes 0.

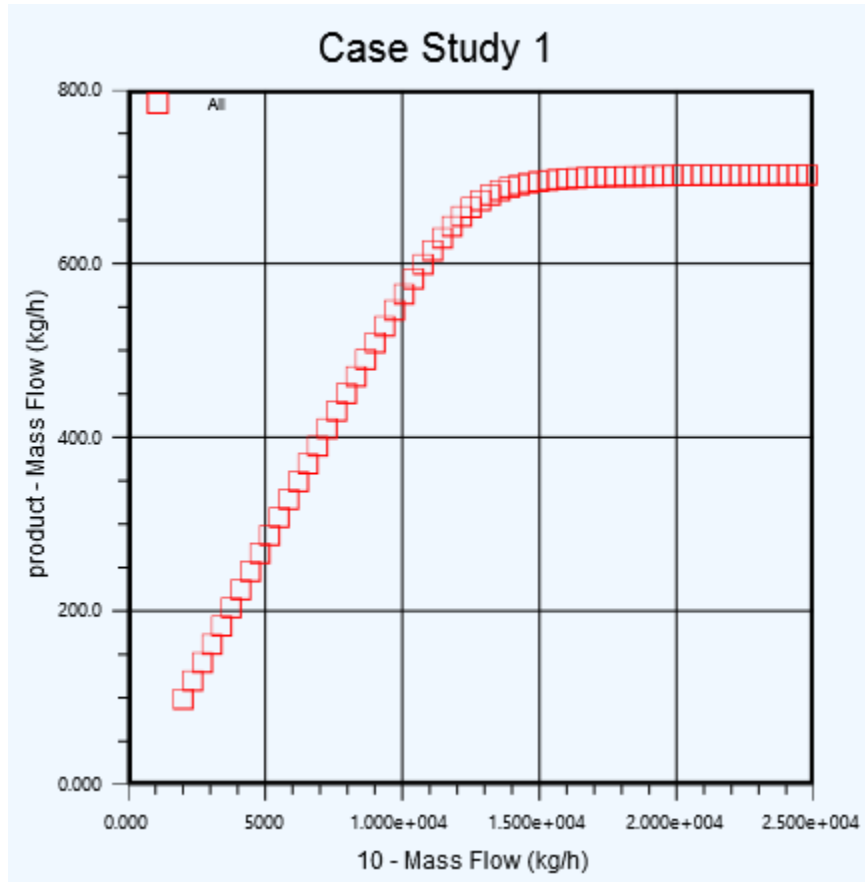


Figure 42: Case Study 1

4-8-2: Temperature of cold recycled water

As we know, decreasing the temperature of the cold recycled water that enters the top of the stripper tower increases the mass flow rate of the product. To study this topic, we use the HYSYS case study. We change the temperature of cold recycled water from 5°C to 60°C and explore the influences of this change on the mass flow rate of the product. It can be seen that the mass flow rate of the product decreases from $766.2 \frac{\text{kg}}{\text{h}}$ to $69.16 \frac{\text{kg}}{\text{h}}$. We see a decrement in the mass flow rate of the product But, it is not linear. The reason for this topic is the decrement of vapor pressure by decreasing the temperature.

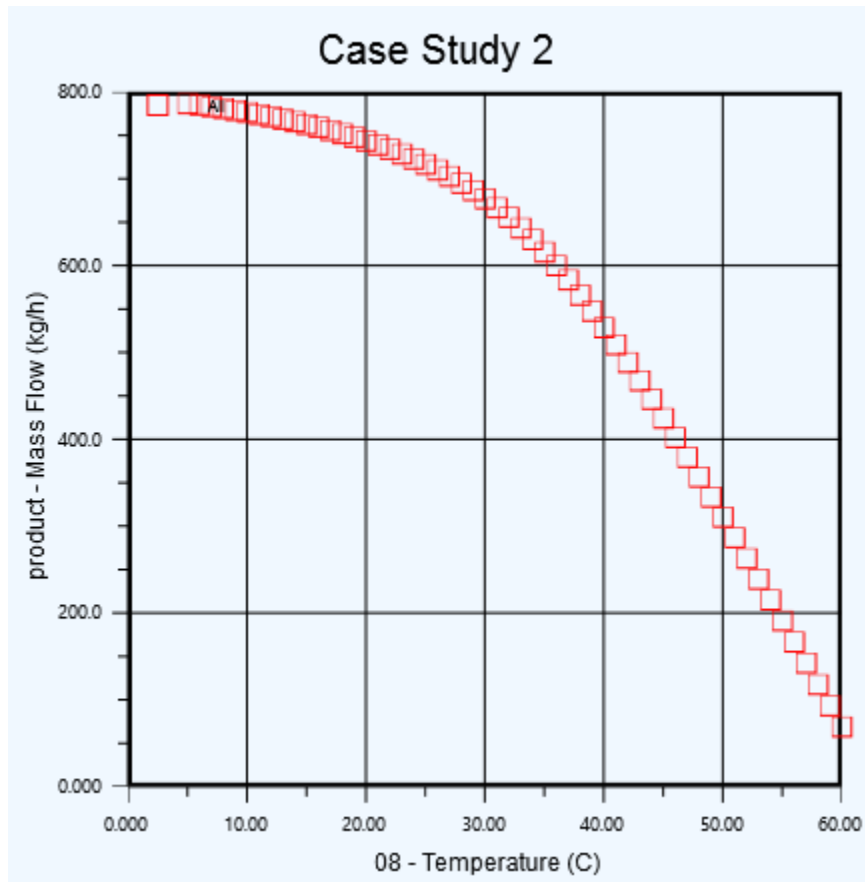


Figure 43: Case Study 2

4-8-3: Temperature of water that enters the absorption tower

As we know, seawater is heated by solar water heating collectors. We want to study the influence of the temperature of the water that enters the absorption water on the H_2O mass fraction at the top product of the absorption tower. To study this topic, we use the HYSYS case study. We change the temperature of seawater from 30°C to 95°C and explore the influences of this change on the H_2O mass fraction at the top product of the absorption tower. It can be seen that the H_2O mass fraction at the top product of the absorption tower increases linearly from 0.026 to 0.1102. The reason for this topic is the increment of vapor pressure by increasing the temperature.

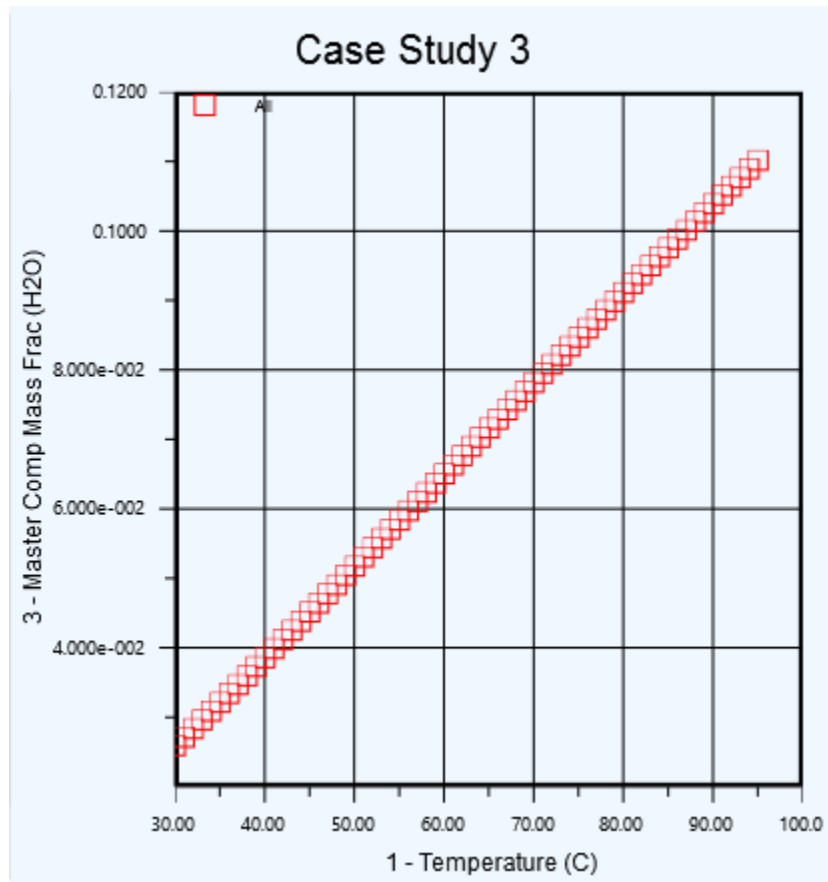


Figure 44: Case Study 3

4-8-4: Humidity of air feed

As we know, increasing the humidity of the air feed increases the H_2O mass fraction at the top product of the absorption tower. To study this topic, we use the HYSYS case study. We change the absolute humidity of the air feed from 0.01 to 0.049 and explore the influences of this change on the H_2O mass fraction at the top product of the absorption tower. It can be seen that the H_2O mass fraction at the top product of the absorption tower increases linearly from 0.0836 to 0.1055.

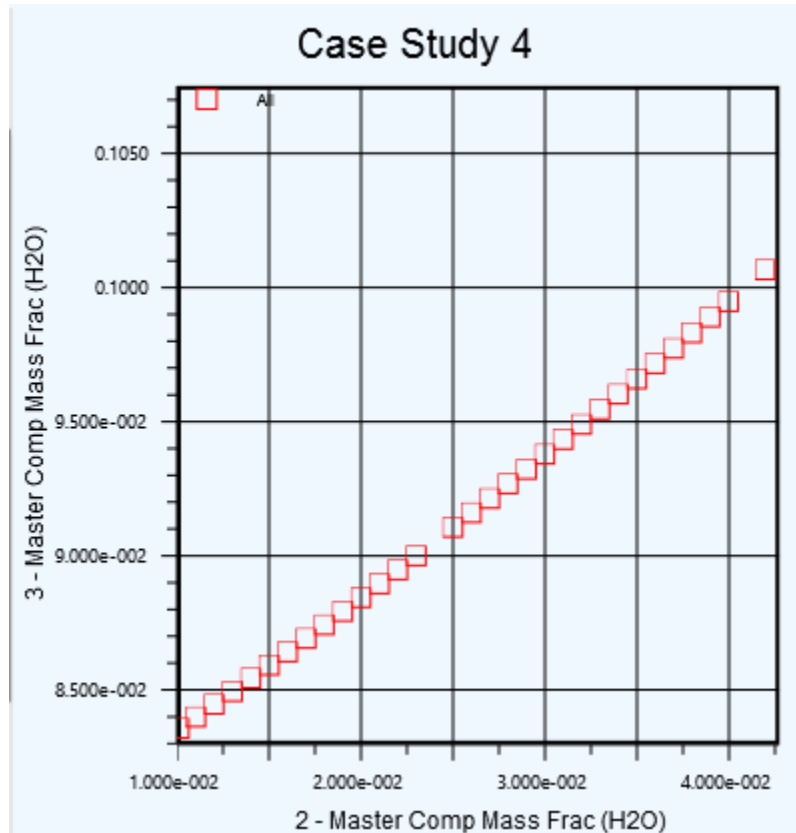


Figure 45: Case Study 4

4-8-5: Pressure of air that enters the absorption tower

We want to study the influence of the pressure of the air that enters the absorption tower on the H_2O mass fraction at the top product of the absorption tower. To study this topic, we use the HYSYS case study. We change the pressure from 2.1 bar to 4.9 bar and explore the influences of this change on the H_2O mass fraction at the top product of the absorption tower. It can be seen that the H_2O mass fraction at the top product of the absorption tower increases linearly from 0.0885 to 0.118. This pressure increment will increase the power of the compressor. The reason for the increment of the H_2O mass fraction at the top product of the absorption tower is the increment of the temperature. It will increase the rate of evaporation, and also it will increase the vapor pressure.

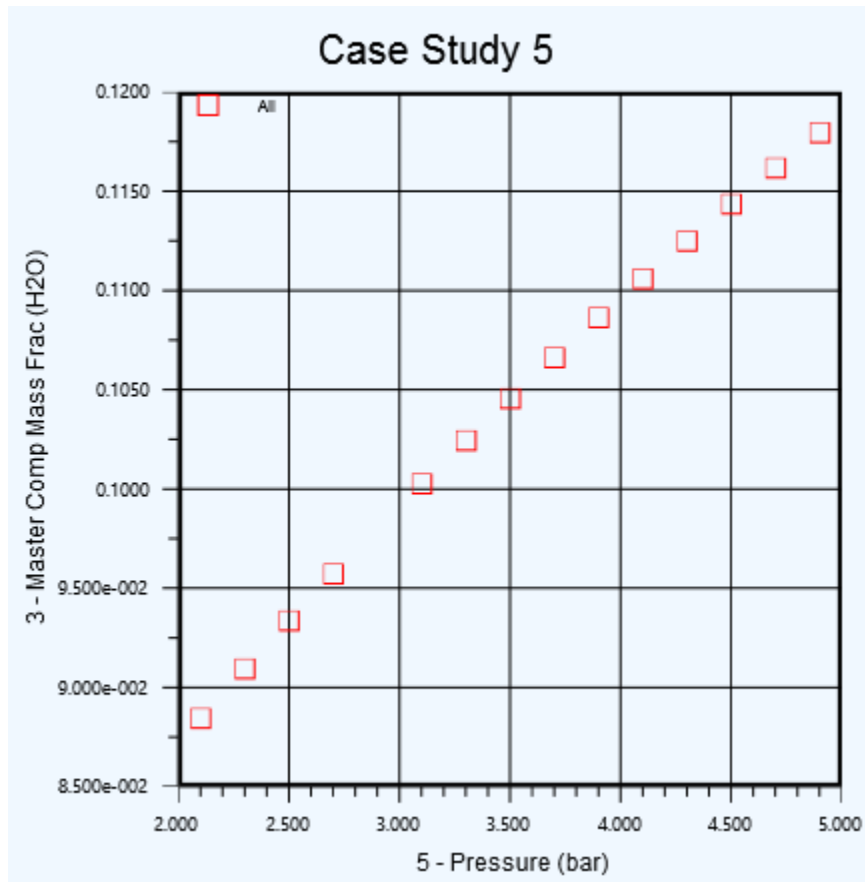


Figure 46: Case Study 5

4-8-6: Pressure of air that enters the absorption tower (no temperature change)

We want to study the influence of the pressure of the air that enters the absorption tower on the H_2O mass fraction at the top product of the absorption tower. We will hold the temperature constant in this case. To study this topic, we use the HYSYS case study. We change the pressure from 2.1 bar to 4.9 bar and explore the influences of this change on the H_2O mass fraction at the top product of the absorption tower. It can be seen that the H_2O mass fraction at the top product of the absorption tower, does not change. It shows that pressure increment does not influence the H_2O mass fraction at the top product of the absorption tower if the temperature stays constant.

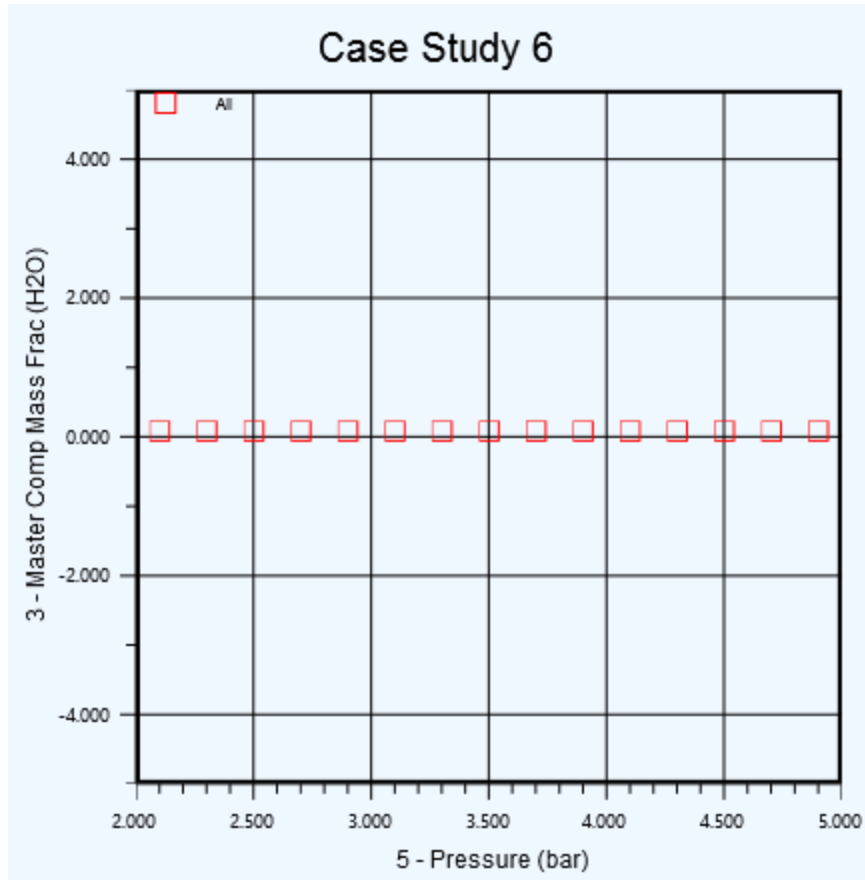


Figure 47: Case Study 6

4-8-7: Air feed to seawater mass flow rate ratio

We want to study the influence of the air feed to seawater mass flow rate ratio on the H_2O mass flow rate at the top product of the absorption tower. To study this topic, we use the HYSYS case study. To do that, we change the mass flow rate ratio from 0.1 to 2 and explore the influences of this change on the H_2O mass flow rate at the top product of the absorption tower. It can be seen that the H_2O mass flow rate at the top product of the absorption tower increases from 113.0444 to $820.44 \frac{\text{kg}}{\text{h}}$.

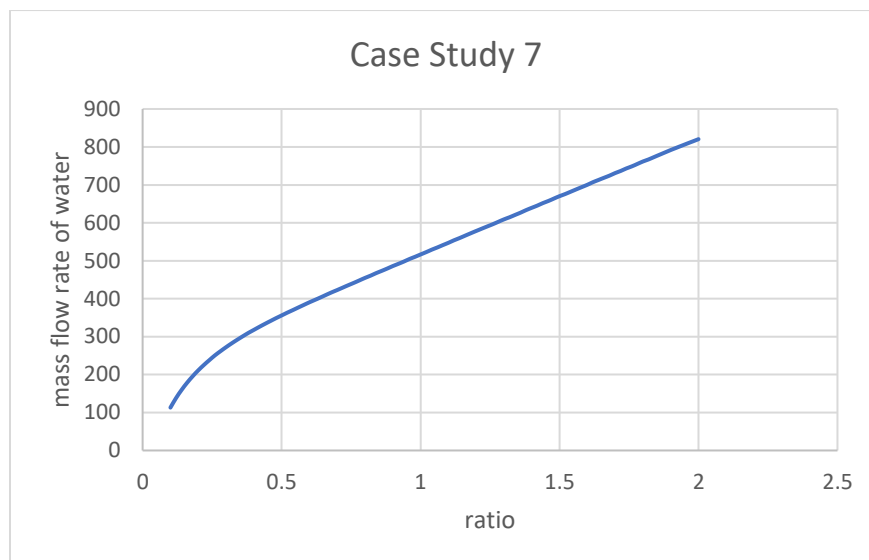


Figure 48: Case Study 7

Section 5

Economy Analysis

5-1: purchased cost of equipment:

5-1-1: The purchased cost of compressor K100

The power of compressor K100 is about 131kW. The type of compressor is air centrifugal. Based on matche site[57], the cost of compressors was 78,500\$ in 2014. It should be calculated in 2022. To do that, the CECPI factor must be used.

CECPI (Jan 2022) = 797.6

CECPI (2014) = 576.1

The cost of compressor in 2022 calculation:

$$\text{The cost} = \frac{797.6}{576.1} \times 78,500\$ = 108,682\$$$

5-1-2: The Purchased Cost of Pumps

The cost of pumps calculated based on figure 49.

Centrifugal Pump
1st Quarter 1998 dollars

Capacity (Gallons/ minute)	Purchased Equipment Cost (\$)	Installed Cost (\$)
100	\$3,400	\$22,800
200	\$4,100	\$23,800
300	\$4,700	\$27,700
400	\$5,300	\$28,500
500	\$5,800	\$29,000
1,000	\$8,700	\$37,500
2,000	\$10,200	\$44,800
3,000	\$15,200	\$58,100
4,000	\$19,500	\$72,300
5,000	\$23,800	\$77,100
6,000	\$28,400	\$93,400
7,000	\$37,800	\$103,000
8,000	\$41,300	\$119,700
9,000	\$47,300	\$126,200
10,000	\$51,200	\$144,800

Figure 49: Cost of pump

$$\text{The mass flow rate in pump P100} = 5000 \frac{\text{kg}}{\text{h}} \times \frac{1\text{h}}{60 \text{ min}} * \frac{0.26 \frac{\text{gal}}{\text{min}}}{1 \frac{\text{kg}}{\text{min}}} = 21.66 \frac{\text{gal}}{\text{min}}$$

$$\text{The mass flow rate in pump P101} = 15696 \frac{\text{kg}}{\text{h}} \times \frac{1\text{h}}{60 \text{ min}} * \frac{0.26 \frac{\text{gal}}{\text{min}}}{1 \frac{\text{kg}}{\text{min}}} = 68.016 \frac{\text{gal}}{\text{min}}$$

$$\text{The mass flow rate in pump P102} = 15696 \frac{\text{kg}}{\text{h}} \times \frac{1\text{h}}{60 \text{ min}} * \frac{0.26 \frac{\text{gal}}{\text{min}}}{1 \frac{\text{kg}}{\text{min}}} = 68.016 \frac{\text{gal}}{\text{min}}$$

Therefore, the minimum pump capacity is enough.

The cost of one pump in 1998= 3,400\$

The cost of one pump in 2022 calculation:

$$\text{The cost} = \frac{797.6}{389.5} \times 3,400\$ = 6,963\$$$

Every pump needs a backup pump. So, 6 pumps are needed.

$$\text{The cost of pumps} = 6 \times 6,963 = 41,788\$$$

5-1-3: The Purchased Cost of Towers

To calculate the cost of the absorption tower and stripping tower, the weight of the tower must be calculated. As said before, the diameter of the tower is 1.5m and the height of the tower is 2.5m and the thickness of the tower is 1cm. and the material is stainless steel. The density of stainless steel is $7750 \frac{\text{kg}}{\text{m}^3}$.

So, the inner diameter is 1.5m, and the outer diameter is 1.51m.

$$\text{Weight of tower} = \pi \frac{D^2 - D_i^2}{4} \times h \times \rho$$

$$\text{Weight of tower} = 460.75 \text{ kg}$$

We consider 50% of the weight of the tower for trays.

$$\text{Therefore, Weight of tower} = 460.75 \text{ kg} \times 1.5 = 691.125 \text{ kg} = 1523.66 \text{ pounds}$$

Based on matche site[57], the cost of the tower is 24,400 in 2014. It should be calculated in 2022. To do that, the CECPI factor must be used.

$$\text{CECPI (Jan 2022)} = 797.6$$

$$\text{CECPI (2014)} = 576.1$$

The cost of tower in 2022 calculation:

$$\text{The cost} = \frac{797.6}{576.1} \times 24,400\$ = 33,778\$$$

$$\text{The cost of two towers} = 67,556\$$$

5-1-4: The Purchased Cost of Cooling Pipeline

The cost of the cooling pipeline with PVC material and a diameter of 5 inches is 8.55\$ for each 6m. We need 3000m of pipe. So, the purchased cost of pipeline calculation:[58]

$$\text{The purchased cost} = \frac{3000\text{m}}{6\text{m}} \times 8.55\$ = 4,275\$$$

The purchased cost of solar water heating collectors:

As said before, we need 17 solar water heating collectors. The cost of each panel with an area of 25 m² is between 1100\$ to 2400\$. We assume an average of 1,750\$ for each.[59] So:

$$\text{The purchased cost of solar water heating collectors} = 1,750\$ \times 17 = 29,750\$$$

5-2: Cost of Installation

We use figure 50 to calculate the installation cost for each piece of equipment.

Type of equipment	Installation cost, %
Centrifugal separators	20–60
Compressors	30–60
Dryers	25–60
Evaporators	25–90
Filters	65–80
Heat exchangers	30–60
Mechanical crystallizers	30–60
Metal tanks	30–60
Mixers	20–40
Pumps	25–60
Towers	60–90
Vacuum crystallizers	40–70
Wood tanks	30–60

Figure 50: installation cost of equipment [60]

Installation cost of towers= $67,556 \times 0.75 = 50,667\$$

Installation cost of pumps= $41,788\$ \times 0.425 = 17,760\$$

Installation cost of compressor= $108,682\$ \times 0.45 = 48,906\$$

We consider 50% of purchased cost as installation cost for cooling pipeline:

Installation cost of cooling pipeline= $4,275 \times 0.5 = 2,137.5\$$

We consider 20% of the purchased cost as the installation cost for solar water heating collectors:

Installation cost of solar water heating collectors= $0.2 \times 29,750 = 5,950\$$

5-3: The Capital Cost of Equipment

The capital cost of equipment= purchased cost of equipment + installation cost of equipment

The capital cost of equipment= $377,471.5\$$

We consider 20% of capital cost for the plant pipeline and fittings cost (except cooling PVC pipeline)

Cost of pipeline and fittings = $0.2 \times 341,771.5 = 68,354.3\$$

We consider 10% of the capital cost for the plant electronics and instrumentations cost.

$$\text{Cost of electronic and instrumentations} = 0.1 \times 341,771.5 = 34,177.15\$$$

$$\text{Cost of land} = 4000\text{m}^2 \times \frac{500,000 \text{ Tomans}}{1 \text{ m}^2} \times \frac{1\$}{30,000 \text{ Tomans}} = 66,667\$$$

$$\text{Cost of fresh water} = 15,000 \text{ L} \times \frac{1200 \text{ Tomans}}{1\text{L}} \times \frac{1\$}{30,000 \text{ Tomans}} = 600\$$$

The capital cost of plant = The capital cost of equipment + Cost of pipeline and fittings + Cost of electronic and instrumentations + Cost of land + Cost of fresh water = 547,270\$

5-4: The Operating Cost of the Plant

5-4-1: Power Cost

$$\text{Power of P100 pump} = 0.125 \frac{\text{kW}}{\text{h}}$$

We consider the minimum of 1.1 kW for P100

$$\text{Power of P101 pump} = 7.043 \frac{\text{kW}}{\text{h}}$$

$$\text{Power of P102 pump} = 0.752 \frac{\text{kW}}{\text{h}}$$

We consider the minimum of 1.1 kW for P102

$$\text{Power of K100 compressor} = 130.944 \frac{\text{kW}}{\text{h}}$$

$$\text{Power of plant per hour} = 140.187 \text{ kW}$$

$$\text{Power of plant per day} = 140.187\text{kW} \times 24\text{h} = 3364.488 \text{ kW h.}$$

$$\text{The cost of power per day} = 3364.488 \text{ kW h} \times \frac{355 \text{ Tomans}}{1 \text{ kW h}} \times \frac{1\$}{30,000 \text{ Tomans}} = 39.81\$$$

$$\text{The cost of power per year} = 39.81 \frac{\$}{\text{day}} \times 335\text{day} = 13,337.4\$$$

5-4-2: Cost of Employees

$$\text{Salary of manager} = 20,000,000 \frac{\text{tomans}}{\text{month}} \times 12 \text{ months} \times \frac{1\$}{30,000 \text{ Tomans}} = 8,000\$$$

$$\text{Salary of 3 engineers} = 3 \times 15,000,000 \frac{\text{tomans}}{\text{month}} \times 12 \text{ months} \times \frac{1\$}{30,000 \text{ Tomans}} = 18,000\$$$

$$\text{Salary of 3 officers} = 3 \times 10,000,000 \frac{\text{tomans}}{\text{month}} \times 12 \text{ months} \times \frac{1\$}{30,000 \text{ Tomans}} = 12,000\$$$

$$\text{Salary of 3 site men} = 3 \times 12,000,000 \frac{\text{tomans}}{\text{month}} \times 12 \text{ months} \times \frac{1\$}{30,000 \text{ Tomans}} = 14,400\$$$

$$\text{Salary of 3 board men} = 3 \times 12,000,000 \frac{\text{tomans}}{\text{month}} \times 12 \text{ months} \times \frac{1\$}{30,000 \text{ Tomans}} = 14,400\$$$

$$\text{Salary of 3 safety men} = 3 \times 12,000,000 \frac{\text{tomans}}{\text{month}} \times 12 \text{ months} \times \frac{1\$}{30,000 \text{ Tomans}} = 14,400\$$$

$$\text{Salary of 3 guards} = 3 \times 10,000,000 \frac{\text{tomans}}{\text{month}} \times 12 \text{ months} \times \frac{1\$}{30,000 \text{ Tomans}} = 12,000\$$$

$$\text{Total salary} = 93,200\$$$

5-4-3: Cost of Maintenance and Repairs

We consider 2% of capital cost for the plant maintenance and repairs cost.

Maintenance cost as percentage of capital investment (on annual basis)			
Type of Operation	Wages	Materials	Total
Simple chemical processes	1-3	1-3	2-6
Average processes with normal operating conditions	2-4	3-5	5-9
Complicated processes, severe corrosion operating conditions, or extensive instrumentation	3-5	4-6	7-11

Figure 51: maintenance cost as percentage of investment (on annual basis) [62]

$$\text{Cost of maintenances and repairs} = 0.02 \times 547,270\$ = 10,945.4\$$$

$$\text{Total operating cost per year} = \text{Total salary} + \text{Cost of maintenances and repairs} + \text{The cost of power per year} = 117,483\$$$

5-5: Total Income

As we know, the production of plants is equal to $695.25 \frac{\text{kg}}{\text{h}}$, and the plant works 335 days per year, 24 hours a day. The cost of 1litr of fresh water with TDS=0 equals 1200 Tomans [63].

Therefore:

$$\text{Total income per year} = 695.25 \frac{\text{kg}}{\text{h}} \times \frac{24\text{h}}{1\text{day}} \times 335 \text{ days} \times \frac{1200 \text{ Tomans}}{1 \text{ kg}} \times \frac{1\$}{30,000 \text{ Tomans}} = 223,608\$$$

$$\text{Net income per year} = \text{Total income} - \text{total operating cost} = 106,125\$$$

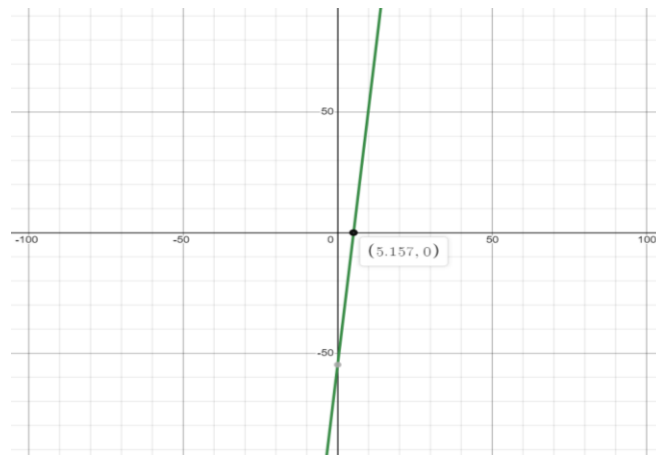


Figure 52: cash return payback period

5-6: Cash Return Payback Period

After 5.157 years, or five years and two months.

After that, we consider 20% of income as tax after that plant goes to benefit.

$$\text{Income of plant after 20 years} = 14.843 \times 0.8 \times 106,125\$ = 1,260,170\$$$

5-7: Cost of Desalination

cost of desalination for generating 1 m³ of potable water

$$\frac{\text{operating cost per year}}{\text{mass flow rate of product per year}} = \frac{117,483\$}{5589.810 \text{ m}^3} = 20.01 \frac{\$}{\text{m}^3}$$

Section 6

HAZOP

Safety is one of the most significant and most important issues for any plant. Even a minor accident can cause much human life damage and financial losses in large and small plants with different processes. These hazards can be due to raw materials, equipment, environmental conditions, etc. Therefore, one of the primary studies related to a plant is its safety. One method of investigating and preventing these hazards is called HAZOP. HAZOP is a systematic method by which potential hazards can be predicted before they occur, and a solution can be considered. This method is usually used when building a plant or making changes. Specialized teams are used to use this method.

This method divides the plant into different nodes and studies each. We write down the potential risks for each and then identify the appropriate solution to solve it if it happens. For each risk, we consider the probability of its occurrence as well as the extent of that risk to understand its importance. This checking can include various parameters such as changes in pressure, temperature, flow, failure of equipment working, malfunction of equipment, fire, etc.

In this plant, due to the lack of reaction, as well as the lack of high temperatures and pressures and the absence of hazardous raw materials (only the presence of water and salt), do not pose many potential dangers. However, we will review the HAZOP Plant.

Study Node	Process Parameter	Guide Word	Possible Causes	Possible Consequences		Risk		Safeguards
					S	L	R	
Pump P100	pressure and volumetric flow rate	low	decrease pressure in the suction	make cavitation and the pump damage	1	1	1	Low-pressure switch

Pump P100	pressure and volumetric flow rate	high	increase pressure in the discharge	pump damage and pipeline damage	1	1	1	High-pressure switch
Pump P101	pressure and volumetric flow rate	low	decrease pressure in the suction	make cavitation and the pump damage	1	1	1	Low-pressure switch
Pump P101	pressure and volumetric flow rate	high	increase pressure in the discharge	pump damage and pipeline damage	1	1	1	High-pressure switch
Pump P102	pressure and volumetric flow rate	low	decrease pressure in the suction	make cavitation and the pump damage	1	1	1	Low-pressure switch
Pump P102	pressure and volumetric flow rate	high	increase pressure in the discharge	pump damage and pipeline damage	1	1	1	High-pressure switch
Compressor	pressure and volumetric flow rate	low	drops of water and dust	compressor damage	1	1	1	air filter
Compressor	pressure and volumetric flow rate	high	increase pressure	compressor damage and pipeline damage	1	1	1	High-pressure switch

Humidification tower	pressure	high	increase pressure and temperature	damage of fittings and pipeline danger of explosion	1	1	1	Pressure Safety Valve
Dehumidification tower	pressure	high	increase pressure and temperature	damage of fittings and pipeline danger of explosion	1	1	1	Pressure Safety Valve
Solar collector	pressure	high	increase pressure and temperature	damage to solar collectors and fittings	1	1	1	high-pressure switch

Section 7

Conclusion and Recommendations

7-1: Conclusion

In this article, we studied different water desalination methods and an in-depth study on the HDH method. The result shows that with a seawater mass flow rate $5000 \frac{\text{kg}}{\text{h}}$, the product equals $695.25 \frac{\text{kg}}{\text{h}}$. The efficiency of the plant equals 13.9%. The result shows that increasing the temperature of the water entering the absorption tower, increasing the mass ratio of air to water, increasing the pressure and temperature of the humid air entering the bottom of the absorption tower, increasing the humidity of the moist air entering the bottom of the absorption, increasing the mass flow of recycled water in stripper tower, And decreasing the temperature of recycled water in stripper tower, will increase the production of fresh water and increase our efficiency.

The economic analyses results show that the capital cost of the plant= 547,270\$, Total operating cost per year= 117,483\$, Net income per year= 106,125\$, Cash return payback period = 5.157 years, cost of desalination for generating 1 m³ of potable water= $20.01 \frac{\$}{\text{m}^3}$

7-2: Recommendations and Suggestions

To improve the process and increase its financial and water production efficiency, changing some parts of the plant and some conditions of the plant can be helpful. The following suggestions can be considered for this purpose. Preheating the sea water before entering the solar water heating collectors with the bottom product stream of the stripper tower:

As we see in the plant, the bottom product stream of the stripper tower has a high temperature. As said before, we decrease the water temperature with a PVC pipeline. On the other hand, the Sea water is heated by solar water heating collectors. Therefore, one of the suggestions to optimize the plant and increase its capacity is to use the heat energy of the bottom product stream of the stripper tower to preheat the seawater. We can use a heat exchanger to do this.

Increasing the capacity of seawater:

As we know, plant costs include initial and operating costs. Since we have paid for the equipment cost and other capital costs once, increasing the capacity of the plant can increase production, and this will increase production. So it improves the economic efficiency of the plant.

Using the solar panel to generate electricity for the equipment:

Since we use the sun's heat to heat the seawater, our plant is definitely in a place where the sun's radiation is high. Also, we pay money for the electricity of compressors, pumps, etc. Therefore, one good way to save plant costs is to use solar panels to generate electricity for the equipment.

Section 8

Appendix or Attachments

	Mass Frac (H2O)	Mass Frac (NACL)	Mass Frac (Air)
Sea water	0.960	0.040	0.000
3.000	0.020	0.000	0.980
wastewater	0.953	0.047	0.000
4.000	0.142	0.000	0.858
Air Feed	0.020	0.000	0.980
1.000	0.960	0.040	0.000
10'	1.000	0.000	0.000
6.000	1.000	0.000	0.000
5.000	0.023	0.000	0.977
7.000	1.000	0.000	0.000
2.000	0.960	0.040	0.000
10.000	1.000	0.000	0.000
product	1.000	0.000	0.000
9.000	1.000	0.000	0.000
8.000	1.000	0.000	0.000

Table 1: Mass Fraction

	Vapor Fraction	Temperature	Pressure	Mass Flow
Unit		C	bar	kg/h
Sea water	0.000	28.000	1.013	5000.000
3.000	1.000	119.397	2.100	5000.000
wastewater	0.000	52.172	1.100	4290.394
4.000	1.000	72.042	1.600	5709.606
Air Feed	1.000	26.720	1.013	5000.000
1.000	0.000	28.007	1.700	5000.000
10'	0.000	28.009	1.600	15000.000
6.000	0.000	57.697	1.100	15695.250
5.000	1.000	29.137	1.100	5014.356
7.000	0.000	57.842	13.000	15695.250
2.000	0.000	75.000	1.600	5000.000
10.000	0.000	28.009	1.600	15000.000
product	0.000	28.009	1.600	695.250
9.000	0.000	28.009	1.600	15695.250
8.000	0.000	28.000	1.000	15695.250

Table 2: Stream Properties

State	Mass Flow of recycled water	Mass flow of product
	kg/h	kg/h
Case 1	2000	98.97
Case 2	2350	119.9
Case 3	2700	141
Case 4	3050	162.1
Case 5	3400	183.1
Case 6	3750	204.1
Case 7	4100	225
Case 8	4450	245.9
Case 9	4800	266.7
Case 10	5150	287.5
Case 11	5500	308.2
Case 12	5850	328.9
Case 13	6200	349.5
Case 14	6550	369.9
Case 15	6900	390.4
Case 16	7250	410.6
Case 17	7600	430.8
Case 18	7950	450.7
Case 19	8300	470.5
Case 20	8650	490.1
Case 21	9000	509.4
Case 22	9350	528.3
Case 23	9700	546.9
Case 24	1.01E+04	565.1
Case 25	1.04E+04	582.7
Case 26	1.08E+04	599.5
Case 27	1.11E+04	615.3
Case 28	1.15E+04	629.9
Case 29	1.18E+04	643.3
Case 30	1.22E+04	655
Case 31	1.25E+04	664.9
Case 32	1.29E+04	673.1
Case 33	1.32E+04	679.5
Case 34	1.36E+04	684.5
Case 35	1.39E+04	688.3
Case 36	1.43E+04	691.2
Case 37	1.46E+04	693.4
Case 38	1.50E+04	695.1
Case 39	1.53E+04	696.4
Case 40	1.57E+04	697.4
Case 41	1.60E+04	698.3

Case 42	1.64E+04	698.9
Case 43	1.67E+04	699.5
Case 44	1.71E+04	699.9
Case 45	1.74E+04	700.3
Case 46	1.78E+04	700.6
Case 47	1.81E+04	700.9
Case 48	1.85E+04	701.1
Case 49	1.88E+04	701.3
Case 50	1.92E+04	701.5
Case 51	1.95E+04	701.6
Case 52	1.99E+04	701.7
Case 53	2.02E+04	701.8
Case 54	2.06E+04	701.9
Case 55	2.09E+04	702
Case 56	2.13E+04	702.1
Case 57	2.16E+04	702.2
Case 58	2.20E+04	702.2
Case 59	2.23E+04	702.3
Case 60	2.27E+04	702.3
Case 61	2.30E+04	702.4
Case 62	2.34E+04	702.4
Case 63	2.37E+04	702.4
Case 64	2.41E+04	702.5
Case 65	2.44E+04	702.5
Case 66	2.48E+04	702.5

Table 3: Case Study 1

State	The temperature of recycled water	Mass flow product
unit	C	kg/h
Case 1	5	786.8
Case 2	6	785.3
Case 3	7	783.4
Case 4	8	781.4
Case 5	9	779.2
Case 6	10	776.9
Case 7	11	774.5
Case 8	12	771.9
Case 9	13	769.1
Case 10	14	766.2
Case 11	15	763

Case 12	16	759.7
Case 13	17	756.1
Case 14	18	752.3
Case 15	19	748.3
Case 16	20	743.9
Case 17	21	739.3
Case 18	22	734.3
Case 19	23	729
Case 20	24	723.3
Case 21	25	717.1
Case 22	26	710.5
Case 23	27	703.2
Case 24	28	695.3
Case 25	29	686.8
Case 26	30	677.4
Case 27	31	667.1
Case 28	32	655.9
Case 29	33	643.7
Case 30	34	630.4
Case 31	35	616
Case 32	36	600.5
Case 33	37	583.9
Case 34	38	566.4
Case 35	39	548.1
Case 36	40	528.9
Case 37	41	509.3
Case 38	42	488.9
Case 39	43	467.9
Case 40	44	446.5
Case 41	45	424.6
Case 42	46	402.4
Case 43	47	379.8
Case 44	48	356.9
Case 45	49	333.8
Case 46	50	310.7
Case 47	51	287.2
Case 48	52	263.2
Case 49	53	239.4
Case 50	54	215.5
Case 51	55	191.4
Case 52	56	167
Case 53	57	142.8
Case 54	58	117.9

Case 55	59	93.58
Case 56	60	69.16

Table 4: Case Study 2

State	Temperature	Mass fraction of Water
unit	C	
Case 1	30	0.026
Case 2	31	0.0272
Case 3	32	0.0284
Case 4	33	0.0297
Case 5	34	0.0309
Case 6	35	0.0322
Case 7	36	0.0335
Case 8	37	0.0348
Case 9	38	0.036
Case 10	39	0.0373
Case 11	40	0.0386
Case 12	41	0.0399
Case 13	42	0.0412
Case 14	43	0.0426
Case 15	44	0.0439
Case 16	45	0.0452
Case 17	46	0.0465
Case 18	47	0.0478
Case 19	48	0.0491
Case 20	49	0.0505
Case 21	50	0.0518
Case 22	51	0.0531
Case 23	52	0.0544
Case 24	53	0.0558
Case 25	54	0.0571
Case 26	55	0.0584
Case 27	56	0.0598
Case 28	57	0.0611
Case 29	58	0.0624
Case 30	59	0.0637
Case 31	60	0.0651
Case 32	61	0.0664
Case 33	62	0.0677
Case 34	63	0.0691
Case 35	64	0.0703
Case 36	65	0.0717
Case 37	66	0.073

Case 38	67	0.0743
Case 39	68	0.0756
Case 40	69	0.0769
Case 41	70	0.0782
Case 42	71	0.0795
Case 43	72	0.0809
Case 44	73	0.0821
Case 45	74	0.0834
Case 46	75	0.0847
Case 47	76	0.0861
Case 48	77	0.0874
Case 49	78	0.0886
Case 50	79	0.0899
Case 51	80	0.0912
Case 52	81	0.0925
Case 53	82	0.0938
Case 54	83	0.0951
Case 55	84	0.0963
Case 56	85	0.0976
Case 57	86	0.0989
Case 58	87	0.1002
Case 59	88	0.1014
Case 60	89	0.1027
Case 61	90	0.1039
Case 62	91	0.1052
Case 63	92	0.1065
Case 64	93	0.1077
Case 65	94	0.109
Case 66	95	0.1102

Table 5: Case Study 3

State	Mass fraction of water	Mass fraction of water
Case 1	0.0101	0.0836
Case 2	0.011	0.084
Case 3	0.012	0.0845
Case 4	0.013	0.085
Case 5	0.014	0.0854
Case 6	0.015	0.0859
Case 7	0.016	0.0864
Case 8	0.017	0.0869
Case 9	0.018	0.0874
Case 10	0.019	0.0879
Case 11	0.02	0.0885

Case 12	0.021	0.089
Case 13	0.022	0.0895
Case 14	0.023	0.09
Case 15	0.024	0.09055
Case 16	0.025	0.0911
Case 17	0.026	0.0916
Case 18	0.027	0.0922
Case 19	0.028	0.0927
Case 20	0.029	0.0932
Case 21	0.03	0.0938
Case 22	0.031	0.0944
Case 23	0.032	0.0949
Case 24	0.033	0.0955
Case 25	0.034	0.096
Case 26	0.035	0.0966
Case 27	0.036	0.0972
Case 28	0.037	0.0978
Case 29	0.038	0.0983
Case 30	0.039	0.0989
Case 31	0.04	0.0995
Case 32	0.041	0.1001
Case 33	0.042	0.1007
Case 34	0.043	0.1013
Case 35	0.044	0.1019
Case 36	0.045	0.1025
Case 37	0.046	0.1031
Case 38	0.047	0.1037
Case 39	0.0479	0.1043
Case 40	0.0489	0.1049
Case 41	0.0499	0.1055

Table 6: Case Study 4

State	Pressure	Mass fraction
unit	bar	
Case 1	2.1	0.0885
Case 2	2.3	0.091
Case 3	2.5	0.0934
Case 4	2.7	0.0957
Case 5	2.9	0.098
Case 6	3.1	0.1003
Case 7	3.3	0.1025
Case 8	3.5	0.1046
Case 9	3.7	0.1066

Case 10	3.9	0.1086
Case 11	4.1	0.1106
Case 12	4.3	0.1125
Case 13	4.5	0.1144
Case 14	4.7	0.1162
Case 15	4.9	0.118

Table 7: Case study 5

State	Pressure	mass fraction
unit	bar	
Case 1	2.1	0.0876
Case 2	2.3	0.0876
Case 3	2.5	0.0876
Case 4	2.7	0.0876
Case 5	2.9	0.0876
Case 6	3.1	0.0876
Case 7	3.3	0.0876
Case 8	3.5	0.0876
Case 9	3.7	0.0876
Case 10	3.9	0.0876
Case 11	4.1	0.0876
Case 12	4.3	0.0876
Case 13	4.5	0.0876
Case 14	4.7	0.0876
Case 15	4.9	0.0876

Table 8: Case Study 6

State	ratio	mass flow rate
unit		kg/h
Case 1	0.1	113.0444
Case 2	0.12	137.8496
Case 3	0.14	159.4215
Case 4	0.16	178.47948
Case 5	0.18	195.6168
Case 6	0.2	211.0475
Case 7	0.22	225.073
Case 8	0.24	238.0632
Case 9	0.26	250.5335
Case 10	0.28	261.6096
Case 11	0.3	272.136
Case 12	0.32	282.1896
Case 13	0.34	291.6396
Case 14	0.36	300.7854

Case 15	0.38	309.659
Case 16	0.4	317.7296
Case 17	0.42	325.8576
Case 18	0.44	333.6408
Case 19	0.46	341.2388
Case 20	0.48	348.7108
Case 21	0.5	355.8276
Case 22	0.52	363.0432
Case 23	0.54	369.8178
Case 24	0.56	376.7752
Case 25	0.58	383.656
Case 26	0.6	390.4917
Case 27	0.62	396.8548
Case 28	0.64	403.332
Case 29	0.66	410.0892
Case 30	0.68	416.6664
Case 31	0.7	422.8398
Case 32	0.72	429.226
Case 33	0.74	435.638
Case 34	0.76	441.8004
Case 35	0.78	448.245
Case 36	0.8	454.792
Case 37	0.82	460.6833
Case 38	0.84	467.364
Case 39	0.86	473.286
Case 40	0.88	479.479
Case 41	0.9	485.9742
Case 42	0.92	491.8032
Case 43	0.94	497.9552
Case 44	0.96	504.5583
Case 45	0.98	510.3871
Case 46	1	516.591
Case 47	1.02	522.6493
Case 48	1.04	529.1243
Case 49	1.06	534.9952
Case 50	1.08	541.2096
Case 51	1.1	547.2992
Case 52	1.12	553.868
Case 53	1.14	559.7184
Case 54	1.16	566.0688
Case 55	1.18	572.3152
Case 56	1.2	578.4576
Case 57	1.22	584.496

Case 58	1.24	590.519
Case 59	1.26	596.3489
Case 60	1.28	602.7621
Case 61	1.3	609.0921
Case 62	1.32	614.6308
Case 63	1.34	620.784
Case 64	1.36	626.854
Case 65	1.38	633.5801
Case 66	1.4	639.5794
Case 67	1.42	645.4098
Case 68	1.44	651.9276
Case 69	1.46	657.602
Case 70	1.48	663.9846
Case 71	1.5	670.3048
Case 72	1.52	675.7504
Case 73	1.54	681.9354
Case 74	1.56	688.1406
Case 75	1.58	694.2005
Case 76	1.6	700.198
Case 77	1.62	706.9974
Case 78	1.64	712.8805
Case 79	1.66	718.7012
Case 80	1.68	724.4595
Case 81	1.7	731.0613
Case 82	1.72	736.7052
Case 83	1.74	743.2134
Case 84	1.76	748.7429
Case 85	1.78	755.1575
Case 86	1.8	761.61
Case 87	1.82	766.9728
Case 88	1.84	773.252
Case 89	1.86	779.4896
Case 90	1.88	785.6856
Case 91	1.9	791.84
Case 92	1.92	797.64
Case 93	1.94	803.4
Case 94	1.96	809.12
Case 95	1.98	814.8
Case 96	2	820.44

Table 9: Case Study 7

Section 9

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