PROTOTYPE DESIGN AND DEMONSTRATION OF
PRODUCED WATER PURIFICATION AT WELLHEAD USING
COPRODUCED ENERGY SOURCES

By

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THESIS

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ABSTRACT

Treatment of produced water for various beneficial uses has always been a vital requirement for the oil and gas industry. In mature fields in particular, an increase in water to oil ratio calls for an increasing need for cost effective produced water treatment. Desalting produced water by using humidification dehumidification process has advantages and is less sensitive to feed water chemistry with a possibility to deploy low-temperature energy such as co-produced geothermal energy and solar energy. In this work, bench scale water desalination by using the humidification dehumidification was investigated. According to the bench scale data, a 10-15 bbls/day produced water treatment prototype was designed, built, and tested for field deployment. This work presents a pilot scale lab study of the process followed by a scale up to a field prototype. The unit was operated under various modes with and without vacuum. The process parameters established for the field prototype was a direct scale up from the laboratory experiments as well as from parametric studies conducted both on the lab scale and field prototype. A “recoverable yield” from the process was found to be 8%, while the “total producible yield” was as high as 40% with a feed water(L/min) to input air(ft³/min) ratio of 1:40. The total producible yield is the sum of condensed and lost vapor, while the total actual yield is the total condensed clean water that was collected during the operation. In sum, the process shows great potential for economic desalination of produced water for smaller producers and the yield could be greatly increased by enhancing the latent heat recovery and deploying new condensation technology.
ACKNOWLEDGMENT

I would like to take this opportunity to thank my committee members for their invaluable assistance during the entire course of this thesis project. My advisor Dr Liangxiong Li and Dr Robert Lee have been instrumental with the basic idea of generating produced water for independent producers and have offered great support throughout the project work from lab scale testing to fabrication of the field prototype. My committee members Dr. Mike Kelly and Dr. Her Yuan Chen have been a great support during the course of this project as well. I would also like to thank Dr Michaelann Tartis, Dr Robert Bretz and Dr Michael Riley for the informative and thought provoking conversations with regard to the chemical engineering concepts behind this work. I would also like to thank the staff at Industrial Electric who fabricated the water purification unit and have offered good support for converting the basic lab scale idea into a field prototype, and also for allowing us to test the field prototype at their facility in Albuquerque before it was taken to New Mexico Tech for further testing.

My acknowledgement would go incomplete without thanking Mr. Jim McLemore for his assistance in setting up the lab prototype and several other retrofits carried out on the field prototype during the course of these two years. Yu Jianjia and Ahmed have been a great help as well in running experiments and recording data while I was away. I’d also like to thank Heidi Guerra for arranging transportation and travel forms at quick notice before my field trips. Ms. Liz Bustamante has been a great help with material for my literature review through my project. Last but not least, I’d like to thank my good friend and office mate Weiwei Li for his constant support over the past two years with lab analysis of produced water and the like.
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Glossary

A  Area of heating surface, m²
Cₚ  Specific heat, J/g°C
Cₚₘ  Specific heat of moisture, J/g°C
Cₚₐ  Specific heat of dry air, J/g°C
Cₚ₃ₕ  Specific heat of water, J/g°C
C_p,ₚsat  Specific heat of saturated steam, J/g°C
D  Diameter, m
f  Function of
G  Mass velocity, kg/s·m²
H  Enthalpy, J/kg
Ha  At entrance
Hₜ  At exit
h  Heat transfer coefficient, W/m²·°C
κ  Thermal conductivity, W/m·°C
m  Mass, kg
P  Total pressure
Pa  Moist air pressure, Pa
P_{ₚₕ}^{ₚₕ}  Saturation pressure of moist air, Pa
Q  Quantity of heat, J
q  Rate of heat transfer, J/hr
R  Gas law constant, 8.31447×10³ J/kg·K mol
r  Distance between two mass points, m
T  Temperature, K
V Volume

H Humidity, mass of vapor per unit mass of vapor-free air; \( H_a \) at the entrance of contactor, \( H_b \) at exit of contactor.

\( \lambda \) Latent heat of vaporization, J/g; \( \lambda_o \) at \( T_o \).

Qs Sensible heat flow rate, W

QL Latent heat flow rate, W

QLoss Loss of heat, W

QR Recovered latent heat transferring from the condensation side to the evaporation side, W

Tw \( \text{in} \) Inlet temperature (K)

Mw \( \text{in} \) Inlet mass flow rate (kg/s)

W Moisture content of air (kg water / kg air)

H Enthalpy of air (kJ/s)

Cw Specific heat (J/kg.K)
CHAPTER 1 INTRODUCTION

Produced water cogenerated with oil and gas production usually contain floating oil, particulates and dissolved components such as salt, metal ions and water soluble organics (i.e., fatty acid and phenol). It is very saline, sometimes nearly six times as salty as seawater, and contains dissolved hydrocarbons and organic matter as well. The components in produced water that contribute to environmental impact include both dissolved salt and hydrocarbons, such as aliphatic hydrocarbons, heavy aromatic compounds and alkylated phenols. In some cases corrosion inhibitors and \( \text{H}_2\text{S} \) also make a significant contribution [1, 2, 3]. For many small oil/gas producers, purification of the produced water at wellhead, and on-site disposal or use of the purified water for beneficial uses such as well drilling and stimulation, will be the primary options for cost-effective produced water management, due to the shortage of storage capacity and limitations of distribution technologies. For every barrel of oil produced, approximately 10-15 barrels of brackish or saline water is generated. Presently the USA generates over 5 billion gallons a day of produced water [4]. In the past, this water was handled as a waste and reinjected, often at significant cost to the producer. As the US demand for fresh water outstrips available supplies, the country is increasingly turning to desalination to create fresh water. Because of the large volumes of brackish produced water being generated, the treatment of this water is increasingly being looked at as a way to supplement the limited fresh water resources in many parts of the country. Several issues still must be addressed to use this water such as, a) Costs of treatment and removal of organic contamination b) Disposal of the associated
concertrate from treatment, c) The treatment level required for beneficial reuse, and d) The regulatory and policy issues associated with produced water used for beneficial reuse [5].

Development of a method that can be deployed for cleaning produced water at the wellhead is highly desirable. The disposal of produced water needs to satisfy the National Pollutant Discharge Elimination System, requiring removal of both floating waste and dissolving contaminants. Current produced water management includes produced water lifting, transportation, separation, and deep-well injection. Unfortunately, the large cost of produced water disposal (Up to $2.5/bbls) and increasing restrictions usually forces the shutdown of high water-cut producing wells, particularly marginal wells. On the other hand, most of landscapes with enriched oil and gas production activities are vulnerable to degradation. Supplying of irritable clean water is critical to maintain native vegetation and restore the natural ecosystems in these areas. The increased economic burden and environmental liability posted by produced water disposal motivate the research of produced water purification.

Unfortunately, the conventional oil/water separations and filtration processes, which are widely deployed in oil/gas industry, can only remove the floating particulates and large oil droplets. Advanced demineralization technologies are in need for removing the salt and dissolved organics and meeting surface water discharge standard. Among the desalination technologies, membrane separation and thermal separation are the most promising and widely deployed technologies for ion removal from seawater. The membrane-based desalination process, such as reverse osmosis (RO) and electro dialysis (ED) are not efficient, especially for small or medium scale water desalination (i.e., <1000 m³/day) [2, 3]. Also, the dissolved organics and high concentration of suspended particulates in produced water will trim the lifetime of membranes due to fouling. Therefore, deployment of sophisticated pretreatment is
usually required to remove the floating particulates, dissolved metal ions and organics and prolong the operation lifetime. Heat-based desalination methods including multistage flash desalination (MSF), multiple-effect evaporation with thermal vapor compression (MEE-TVC) and mechanical vapor compression (MVC) are generally energy intensive due to large heat consumption in phase conversion. Other desalination methods such as freeze-thaw deionization can only be used in cold season. Moreover, sophisticated pretreatment is generally required for prolonged operating lifetime. Dissolved organics, metal oxide (i.e. Fe$_2$O$_3$), and large variation in salt concentration (TDS=1000–100×10$^4$ mg/L) are the main factors limiting the deployment of the conventional desalination technologies for produced water purification.

Humidification–dehumidification (H-DH) is a heating-based desalination process at the mechanism of air humidification at elevated temperature and water condensation at low temperature. The typical characteristics of the humidification-dehumidification include flexibility in capacity, atmospheric pressure operation, and use of low-temperature energy such as solar energy, geothermal, and other industry waste heat. Such a water desalination process is based on the fact that air can carry large amount of water vapor at elevated temperatures. Another interesting feature of the humidification – dehumidification process is that the process could be carried out below the boiling point of the liquid unlike other typical thermal processes where extensive energy is used to heat the water to a certain temperature, induce vacuum in the unit and flash the water to obtain purified vapor. Therefore, the H-DH system clearly is devoid of all those energy requirements, and is a very promising technology for smaller producers and lesser water treatment water capacity. For example, by increasing temperature from 30 to 80 °C, 1 kg air can carry about 0.5 kg water vapor; about 500 g clean water could be collected upon subsequent cooling. By viewing the general humidification and dehumidification process for
producing 1.0 kg clean water, the energy consumption of water heating, evaporation, and air blowing are 209 KJ, 2260 KJ and 8 KJ respectively, where over 90% of energy consumption is for the phase conversion.

One attempt for overcome the high energy consumption of phase conversion is to recover the latent heat released from condensation. Traditionally, the evaporation and condensation occur at two different towers where the latent heat recovered from condensation can be deployed for feed water preheating. A limitation of the referenced desalination process is the low water recovery and high sensitive in heat loss. Recently, Beckman and coworkers reported the modified humidification-dehumidification process named dewvaporation for enhancement in latent heat recovery and improvement in energy efficiency [6]. In the dewvaporation process, humidification and dehumidification occur continuously in two chambers with internal liquid heat exchanger on the evaporation side. This technique uses air as a carrier gas to evaporate liquid from a saline solution, using cross flow configuration, at atmospheric pressure [6]. The experimental set up works on the concept of humidification and de-humidification. The basic concept is to scrub feed solution with air. Feed water is sprinkled from the top and air is pumped from the bottom using an air blower. The chamber is filled with packing material for enhanced water/air contact. The air is humidified as it travels to the top and is de-humidified in another chamber [1, 4].

Two factors are essential to enhance the mass and heat transfer for the humidification and dehumidification process: large air-liquid contact surface area and high latent-heat recovery. Large air-liquid contact area can enhance water evaporation by forming large area of thin water film and contacting with enforced air flow. The recovered latent heat compensate the heat lose
during phase conversion (i.e., water evaporation), improving heat efficiency of the desalination process.

Our recent research indicated that the modified humidification dehumidification process show great advantages in produced water desalination:

(1) Deployment of co-produced energy sources or solar energy for driving the desalination process. A specific advantage of the proposed water purification process is that various low-temperature energies can be used, such as solar energy and co-produced geothermal energy.

(2) Deployment of heat pump technology for enhancing latent heat recovery. Evaporation provokes cooling on the evaporation side while water vapor condensation provokes heat release in the adjacent chamber. Heat released by condensation will transport to the evaporation side for enhancing water evaporation. Heat pump technology can be deployed for recovering the latent heat for feed water preheating [9].

In sum, conventional membrane and thermal processes are not only energy intensive and economically unfavorable for small producers, but also requires a high input volume of water to be treated. Small quantities of produced water to be treated as seen in the case of small producers become uneconomical to have a treatment facility on site. Even if water is to be transported to different locations, transportation costs or laying pipelines makes operating marginally producing wells un-economic.

In this thesis work, a prototype of produced water purification using the fundamental theory of humidification-dehumidification has been designed and constructed. Process
parameters have been established by both parametric studies on the lab unit as well as on the field prototype.

1.1 Water quality and various end uses

Water that is termed saline contains significant concentration of dissolved salts. The concentration is the amount by weight of salt in water, as expressed in parts per million (ppm). For example, if water has a concentration of 10,000 ppm of dissolved salts, then one percent (10,000 divided by 1,000,000) of the weight of the water comes from dissolved salts [6].

Table 1.1 summarizes the water quality requirements for various uses, and also the main concerns for having restriction criteria for suspensions and dissolved components for various end uses.
Table 1.1 Water quality requirements and various end uses

<table>
<thead>
<tr>
<th>Beneficial uses</th>
<th>Water quality requirement</th>
<th>Main Concerns</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suspensions</td>
<td>Dissolved components</td>
</tr>
<tr>
<td><strong>Offshore disposal</strong></td>
<td>Solid &lt;10 mg/l</td>
<td>No limitation</td>
</tr>
<tr>
<td></td>
<td>Oil&lt;5 mg/l</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Environmental impact</td>
</tr>
<tr>
<td><strong>Reinjection</strong></td>
<td>Solid&lt;1 mg/L</td>
<td>No limitation</td>
</tr>
<tr>
<td></td>
<td>Oil&lt;5 mg/l</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MPS&lt;1 μm</td>
<td>Formation damage</td>
</tr>
<tr>
<td><strong>Irrigation [22]</strong></td>
<td>Oil &amp; grease &lt; 35 mg/l</td>
<td>TDS: &lt; 2000 mg/l</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Salinity, trace elements, chlorine residues, and nutrient</td>
</tr>
<tr>
<td><strong>Cooling water [19]</strong></td>
<td>N/A</td>
<td>TDS&lt;2700</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Corrosion, biological growth, and scaling.</td>
</tr>
<tr>
<td><strong>Chemical process [19]</strong></td>
<td>N/A</td>
<td>TDS&lt;1000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low turbidity, suspended solids and silica</td>
</tr>
</tbody>
</table>
Table 1.2 tabulates typical ion composition of produced water samples from two different basins, namely San Juan basin and the Permian basin compared to sea water.

**Table 1.2 Typical characteristics of produced water compared with seawater**

<table>
<thead>
<tr>
<th>Component</th>
<th>San Juan Basin (CBM) mg/L</th>
<th>Permian Basin (Oilfield), mg/L</th>
<th>Typical seawater, mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bicarbonate</td>
<td>5870.3</td>
<td>1538.1</td>
<td>107</td>
</tr>
<tr>
<td>Hydrogen Sulfide</td>
<td>65</td>
<td>22.5</td>
<td>N/A</td>
</tr>
<tr>
<td>Chloride</td>
<td>2389.5</td>
<td>130636</td>
<td>19352.9</td>
</tr>
<tr>
<td>Sulfate</td>
<td>24.1</td>
<td>4594.1</td>
<td>2412.4</td>
</tr>
<tr>
<td>Sodium</td>
<td>4169.3</td>
<td>80421.2</td>
<td>10783.8</td>
</tr>
<tr>
<td>Potassium</td>
<td>35</td>
<td>398.6</td>
<td>399.1</td>
</tr>
<tr>
<td>Magnesium</td>
<td>19</td>
<td>894.1</td>
<td>1283.7</td>
</tr>
<tr>
<td>Calcium</td>
<td>11</td>
<td>4395.5</td>
<td>412.1</td>
</tr>
<tr>
<td>Strontium</td>
<td>6.3</td>
<td>88.9</td>
<td>7.9</td>
</tr>
<tr>
<td>Iron</td>
<td>0.65</td>
<td>65.3</td>
<td>15.5</td>
</tr>
<tr>
<td>Total Dissolved Solids (TDS)</td>
<td><strong>12590.2</strong></td>
<td><strong>223054.3</strong></td>
<td><strong>34774.4</strong></td>
</tr>
</tbody>
</table>
1.2 Thermal technologies for water Desalination

As discussed earlier, desalination is a process that removes dissolved minerals (including but not limited to salt) from feed water sources such as seawater, brackish water or treated wastewater. The techniques for desalination may be classified into two categories according to the process principle used:

- Process based on a physical change in state of the water – i.e. distillation or freezing.
- Process using membranes – i.e. reverse osmosis or electro dialysis

These two processes, based on physical change of the water and filtering via membranes, are regularly used to treat seawater and brackish water and have been developed over many years in large scale commercial applications. In circumstances of more intense TDS produced water with high concentration of suspended solid and floating oil, mechanical and thermal technologies are economically competitive to membrane process. Conventionally, mechanical and thermal desalination technologies include Multi-stage flash distillation, multiple effect distillation, and vapor compression distillation [7,8].

1.2.1 Multistage Flash Distillation

Multistage Flash distillation (MSF) accounts for the major portion of desalinated fresh water currently produced and are used primarily for desalting seawater. This process has been in large scale commercial use for over thirty years and is illustrated in Figure 1.1.
Figure 1.1 Basic illustration of MSF process [7].

The principles of MSF involve seawater feed being pressurized and heated to the plant’s maximum allowable temperature. When the heated liquid is discharged into a chamber maintained slightly below the saturation vapor pressure of the water, a fraction of its water content ‘flashes’ into steam. The flashed steam is stripped of suspended brine droplets as it passes through a mist eliminator and condenses on the exterior surface of the heat transfer tubing. The condensed liquid drips into trays as hot product (fresh) water. The recirculating stream, flowing through the interior of the tubes that condense the vapor in each stage, serves to remove the latent heat of condensation. In doing so, the circulating brine is preheated to almost the maximum operating temperature of the process, simultaneously recovering the energy of the condensing vapor. This portion of the MSF plant is called the ‘heat recovery’ section [7,8].
1.2.2 Multi Effect Distillation

Multi Effect Distillation (MED) is stated as being the most important large-scale evaporative process, and offers significant potential for water cost reduction over other large-scale desalination processes. It is predicted that the use of this distillation technology will expand in the future, over and above the usage of the Multistage-Flash distillation process.

Multiple effect distillation units operate on the principle of reducing the ambient pressure at each successive stage, allowing the feed water to undergo multiple boiling without having to supply additional heat after the first stage. Figure 1.2 illustrates the basic MED process.

![Figure 1.2 Basic illustration of MED process](image)

**Figure 1.2 Basic illustration of MED process [7].**

In MED units, steam and/or vapor from a boiler or some other available heat source is fed in to a series of tubes where it condenses and heats the surface of the tube and acts as a heat
transfer surface to evaporate saline water on the other side. The energy used for evaporation of the saline water is the heat of condensation of the steam in the tube.

The evaporated saline water, now free of a percentage its salinity and slightly cooler, is fed in to the next, lower-pressure stage where it condenses to fresh water product, while giving up its heat to evaporate a portion of the remaining seawater feed [7].

1.2.3 Vapor Compression Distillation

The low temperature Vapor Compression Distillation (VCD) method is a simple, reliable and highly efficient process. Its efficiency comes largely from a low energy requirement and its design that is based on the ‘heat pump’ principle of continuously recycling the latent heat exchanged in the evaporation-condensation process.

VCD is similar in process operation to multi-effect distillation. The main difference is that the vapor produced by the evaporation of the brine is not condensed in a separate condenser. Instead, a compressor returns it to the steam side of the same evaporator, in which it originated, where it condenses on the heat transfer surfaces, giving up its latent heat to evaporate an additional portion of the brine as shown in Figure 1.3 [9].

The energy for the evaporation is not derived from a prime steam source as in the preceding two distillation processes, but from the vapor compressor. In addition, the latter raises the temperature of the vapor by its compressive action, thereby furthering the driving force for the transfer of heat from vapor to brine[7, 10].
1.3 Economics of desalination technologies

A comparison of thermal and membrane desalination processes can be found in the Tables 1.3 and 1.4 [11]. Table 1.3 shows a cost comparison of the major thermal and membrane processes. However, the process of humidification-dehumidification focuses on a much more economical process than the RO process. Initial investment is also modest with an investment of about 80000 USD for a 20 bbls/day, and the cost of production is way lesser than an RO process. The following table shows the cost of a RO plant with and without transportation. Moreover, presence of colloidal suspensions and suspended particles makes operation on reverse osmosis units challenging with high downtime and operating costs such as constant membrane replacement. It clearly shows that a minimum input of inlet water is required for economic production of waste water using this method, which cannot be met by most independent operators. The humidification-dehumidification process holds an advantage in this area where small capacities can be catered to at a low cost of operation with only moderate initial investment costs involved.
Table 1.3 Comparison of thermal and membrane processes[11]

<table>
<thead>
<tr>
<th></th>
<th>MSF</th>
<th>RO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption</td>
<td>~13 kWh/m$^3$</td>
<td>4-5 kWh/m$^3$</td>
</tr>
<tr>
<td></td>
<td>(70 kWh + 3 to 4 kWh)</td>
<td></td>
</tr>
<tr>
<td>Recovery</td>
<td>10% - 20%</td>
<td>30 – 50%</td>
</tr>
<tr>
<td>Investment [$/m$^3$/day)]</td>
<td>~ 1000 – 1500</td>
<td>~700 – 1500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(10% for membranes)</td>
</tr>
<tr>
<td>Chemicals [$/m$^3)$]</td>
<td>~ 0.03 to 0.05</td>
<td>~ 0.06 to 0.1</td>
</tr>
<tr>
<td>Brine Quantity</td>
<td>Distillate x 4 to 9</td>
<td>Permeate x 1 to 4</td>
</tr>
<tr>
<td>Brine Quality</td>
<td>Chemicals, Heat</td>
<td>Chemicals</td>
</tr>
<tr>
<td>Robustness</td>
<td>High</td>
<td>Fouling Sensitivity,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Feed water monitoring</td>
</tr>
<tr>
<td>Improvement Potential</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

Table 1.4 Economics of desalination[11]

<table>
<thead>
<tr>
<th></th>
<th>MSF</th>
<th>MED</th>
<th>VC</th>
<th>RO</th>
<th>H-DH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Investment Cost [$/m$^3$/day]</td>
<td>1200 - 1500</td>
<td>900 – 1000</td>
<td>950 – 1000</td>
<td>700 – 900</td>
<td>NA</td>
</tr>
<tr>
<td>Total Cost Product [$/m$^3]$</td>
<td>1.10 – 1.25</td>
<td>0.75 - 0.85</td>
<td>0.87 – 0.95</td>
<td>0.68 – 0.82</td>
<td>0.45 – 0.8 $/bbl</td>
</tr>
<tr>
<td>Hypothesis</td>
<td>Plant capacity: 30,000 m$^3$/day</td>
<td>7%</td>
<td>20 years</td>
<td>0.065 $/kWh</td>
<td>Plant capacity: 10–20 bbls/day.</td>
</tr>
</tbody>
</table>
However, the standard techniques like multi-stage flash (MSF), multi-effect (ME), vapor compression (VC) and reverse osmosis (RO) are only reliable for large capacity ranges of 100–50,000 m³/day of fresh water production [12]. These technologies are expensive for small amounts of fresh water, and they cannot be used in locations where there are limited maintenance facilities and energy supply. In addition, the use of conventional energy sources to drive these technologies has a negative impact on the environment. Desalination Economic Evaluation Program is a spreadsheet tool used to carry out the economic analysis of various combinations of desalination technologies and the same was used to come up with the cost estimation for the RO process as shown in Figure 1.4.

![Figure 1.4 Water treatment costs for RO process with and without transportation.](image)

**Figure 1.4** Water treatment costs for RO process with and without transportation.
The above plot shows as discussed the cost of producing each barrel of water with and without transportation. The humidification dehumidification process comes into picture here, where transportation costs are totally eradicated and cost of producing a unit barrel is also very low as the process is deployed in the well site and obviously membrane costs, maintenance, high pressure pumping costs etc. all ruled out. The economic estimation for the treatment of produced water using the thermal and membrane processes as shown in Table 1.4 are for very high plant capacities. However, the price in dollars per barrel of treated produced water is also tabulated in Table 1.4 for a very small capacity of up to 20 bbls/day. The only treatment cost incurred for the system in this study is the operating cost, that includes the pumps utilized for introducing the process streams into the unit. Heating of inlet feed is carried out using solar panels which also involves a circulating pump. A good estimate of the operating cost in kWh consumed per barrel of produced water can be calculated easily using the cumulative Kilowatt consumption of all the pumps used in the system multiplied with the number of operating hours. The price of electricity is considered as 0.06 $/kWh, which is the pricing for industrial applications in the state of New Mexico.
CHAPTER 2 LOW-TEMPERATURE DISTILLATION
PHILOSOPHY AND THEORETICAL ANALYSIS

The objective of this work is to test a thermal process for produced water desalination at wellhead by using coproduced energy sources. “Low temperature distillation” defined in this research is distillation at temperature below 80 ºC or a thermal evaporation process that operate below the boiling point of water.

Humidification/dehumidification is a thermal process that operates below the boiling temperature of water. Conventionally, the humidification and dehumidification was carried out in two separate towers in which the part of the latent heat was reused. Recently, Beckman and coworkers have integrated the humidification dehumification process in one single tower named dewvaporation in which the internal heat transfer is more efficient [2]. Multiple evaporation chamber and condensation chamber are separated by thin stainless steel thin plate for enhanced latent heat recovery as shown in Figure 2.1. In the evaporation side, the feed air first contact with concentrate wate for air preheating and then moves upward to contact with water film for water extraction. The resultant humidified air in the water distribution chamber will be directed to the dehumidification chamber for water condensation.

The evaporation of produced water provokes cooling effect on feed side, resulting temperature decline along the upright shell of the steel plate. Water condensation at the condensation chamber releases large amount of latent heat, which will transport from the dehumidification side to the evaporation side. Figure 2.2 is a schematic showing the heat and
mass transport in a H-DH process. The basic thermodynamic analysis is carried out based on the following assumptions:

1. The heat and mass transfer coefficient are constant throughout the heat exchange column.
2. The temperature at each cross section is uniform.
3. Energy losses only occur in liquid phase.
4. Latent heat recovery occurs between liquid phases of evaporation side and condensation side.

**Figure 2.1** Schematic representation of humidification-dehumidification design.
Figure 2.2 Schematic representation of air enhanced H-HD process.

Energy balance

The application of energy balance between falling water film and flowing air stream in the evaporation chamber provides:

Energy balance for gas phase:

$$m_a h_a + dQ_s + dQ_L = (h_a + dh_a) \cdot m_a \quad (1)$$

Energy balance for liquid phase:

$$m_w h_w + dQ_R = (m_w - dm_w)(h_w - dh_w) + dQ_L + dQ_S + dQ_{Loss} \quad (2)$$

The term $h_a$ stands for the specific enthalpy of moist air with an expression as follows [21]

$$h_a = c_p a T_a + H_a (C_{p,s} T_a + \lambda) \quad (3)$$
where \( h_a \) represent the specific enthalpy of moist air, \( C_{pa} \) represent the specific heat capacity of dry air. The term \( dQ_s \) represents the sensible heat transfer from liquid phase to air stream due to the temperature difference with an expression of

\[
dQ_s = a \alpha_{LA} (T_w - T_a) \, dZ
\]  

(4)

where \( a \) is the effective heat transfer area for liquid/air contact, \( m^2/m^3 \). In the term, \( \alpha_{LA} \) represents the mass transfer coefficient between water film and air stream and can be express by the following relation [13]

\[
\alpha_{LA} = Le \cdot K \cdot c_{pm}
\]  

(5)

\[
K = 2\left( \frac{m_w}{A} \right)^{0.4} \left( \frac{m_a}{A} \right)^{0.6}
\]  

(6)

where \( K \) is the mass transfer coefficient and \( Le \) is the Lewis number.

The term \( dQ_L \) is the latent heat transferred to the air stream accompanying water evaporation.

\[
dQ_L = dm_w (C_{p,a}^\text{sat} T_w + \lambda)
\]  

(7)

Substituting eqs (3), (4), and (7) to eq (1), the variation of humidified air temperature along the longitude of evaporation chamber is obtained:

\[
\frac{dT_a}{dZ} = \frac{(T_w - T_a)}{(C_{pa} + H C_{p,a}^\text{sat})} \left( \frac{L \alpha_{LA}}{m_a} + \frac{C_{p,a}^\text{sat}}{dZ} \right)
\]  

(8)

The variation of humidity along the longitudinal axis can be expressed by the following relation [14]
\[
\frac{dH}{dZ} = \frac{L K}{m_a} \left[ H^{\text{sat}}(T_w) - H_{(a)} \right] 
\]  

(9)

where \( H_{\text{sat}} \) is the saturation humidity ratio of air with a definition of

\[
H^{\text{sat}}(T_w) = 0.622 \frac{P_{w}^{\text{sat}}(T_w)}{P_a - P_{w}^{\text{sat}}(T_w)} 
\]  

(10)

The change in gas enthalpy is the change in sensitive heat and latent heat of evaporation.

\[
c_{pm} = c_{pa} + H C_{p,s}^{\text{sat}} 
\]  

(11)

The heat loss through wall to the ambient environment is expressed as,

\[
d Q_{\text{Loss}} = b K_{\text{Loss}} \cdot (T_w - T_{\text{Env}}) \cdot dZ 
\]  

(12)

where \( b \) is the exposure surface area to the environment, \( m^2/m^3 \), \( T_{\text{Env}} \) is the environmental temperature, \(^{\circ}\text{C}\. 

The rate of heat transfer from the liquid phase of condensation side to the liquid phase of evaporation side is proportional to the driving force \( (T_w - T'_w) \) and heat transfer area, with an expression of

\[
d Q_R = c \cdot k \cdot (T'_w - T_w) dz 
\]  

(13)

Where \( k \) is heat transfer coefficient from condensation side to the evaporation side, \( W/m^2.\,^{\circ}\text{C}\. \) \( c \) is the effective heat transfer area between evaporation chamber and condensation chamber, \( m^2/m^3 \).

Substituting eqs. (4), (7), (12) and (13) into eq. (2), water temperature gradient along the longitude of evaporation chamber is obtained:
\[
\frac{dT_w}{dz} = \frac{m_a}{M_w c_{\text{pw}}} (c_{p,j} T_w + \lambda - C_{pw} T_w) \frac{dH}{dz} + \frac{b k_{\text{loss}} (T_w - T_{\text{env}}) - c k (T_w - T_w)}{M_w c_{\text{pw}}} \tag{14}
\]

Similarly, the application of energy balance in the condensation chamber provides:

Energy balance for gas phase:

\[
m'_a h'_a = m'_a (h'_a - dh'_a) + dQ'_s + dQ'_L \tag{15}
\]

Energy balance for liquid phase:

\[
m'_w h'_w + dQ'_L + dQ'_s = (m'_w - dm'_w) (h'_w - dh'_w) + dQ'_R + dQ'_{\text{loss}} \tag{16}
\]

Mass balance:

\[
\dot{m}_a = \dot{m}_a
\]

\(\dot{H}_a(T_a)\) is saturated humidity at temperature \(T\).
CHAPTER 3 BENCH SCALE TESTS

In this chapter of work, bench scale test was carried out and the influence of water flow rate, air flow rate, cooling water flow rate in the dehumidifier on water productivity, and latent heat recovery has been investigated. The result shows an ion rejection of over 75% for the sample collected in one hour, which is also the range required for various end uses. However, the samples collected during the second and third hour shows a remarkable increase in ion concentration. This is due to intermixing of the pure water and the NaCl solution at the base of the unit which is separated by plastic foils. Leakage between each chamber inside the chamber is the reason why a sharp increase in ion concentration is observed. A similar test carried out using tap water alone resulted in an ion concentration decrease from 85 ppm to 42 ppm for Na\(^+\), and 140 ppm to 68 ppm for Cl\(^-\).

3.1 Lab scale experimental set up

The experimental set up consisted of an acrylic body, with humidification-dehumidification chambers inside it. Produced water was introduced into the humidification chamber by using a pump at a rate of about 1.5 L/min. A steam generator of capacity 25 lb/hr is connected to the inlet, which heats the input stream. Air is pumped from the bottom which scrubs through the inlet water. The air is humidified and condensed in the adjacent chamber as water trickles down counter current to the inlet air stream. The air flow rate was adjusted to a value where the water to air ratio was 40 as conducted in the lab scale experiments.

Figure 3.1 is a schematic representation of the pilot scale water purification set up.
Figure 3.1 Schematic representation of bench scale experimental setup.
Label 1 is the steam generator used to heat inlet feed to desired process temperature. The steam generator requires a water inlet pressure at least 20 psi greater than the operating pressure of the steam generator which is about 15 psi. Label 2 is the inlet water pump which feeds the water at the desired flow rate. Label 3 represents the air pump that pumps air counter current to inlet water flow. Label 4 is the water purification unit itself. Label 5 shows the condensed purified water. Label 6 and 7 are the water and air flow meters respectively. Similar to the conventional humidification-dehumidification process [2], the produced water purification by the humidification-dehumidification was carried out through three steps: (1) heating produced water to elevated temperatures; (2) water evaporation in a water-air contactor; and (3) condensing purified water vapor by condensation.

Figures 3.2 displays the bench scale setup of humidification dehumidification unit for produced water desalination test.
Lab tests have been carried out for parametric studies. The process parameters, yield and ion rejection potential of the process were obtained through the lab scale tests. The results of the lab tests are in accordance with data published in literature as well. An increase in water productivity is seen with an increase in inlet water temperature. However, a scale up of this extent needs to take into consideration for scaling up from the bench test to field scale prototype.
The basic parameters established in the lab scale set up are shown in Figure 3.3.

The inlet water flow rate was varied from 20 to 30 ml/min with an inlet air flow rate of 1250 L/hr, giving an air to water ratio varying from 40 to 65. A direct scale up of this system was also used in the field scale prototype with an inlet water flow rate ranging between 1 – 5 L/min and an inlet air flow rate of $19.2 \times 10^4$ L/hr. A parametric study of varying water and air flow rates in the field scale prototype has also been studied and presented in the results section.
The pump sizing for the field prototype was selected to cover the ranges tested in the lab scale tests. Therefore a parametric study could be carried out both within and outside the parameters tested before. The field prototype has the provision to change the air to water ratio from 41 to 114. Results of parametric studies in detail are further discussed in Chapter 5. Table 3.1 shows the inlet water flow rate, air flow rate and the air to water ratio’s tested in the lab scale and the capacity or the possible operating ranges for the field scale prototype.

<table>
<thead>
<tr>
<th></th>
<th>Lab scale</th>
<th>Field scale prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet water flow rate range</td>
<td>20-35</td>
<td>800 - 2000</td>
</tr>
<tr>
<td>(mL/min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet air flow rate range</td>
<td>1250 – 2500</td>
<td>3.2 x 10^4 – 22.8 x 10^4</td>
</tr>
<tr>
<td>(L/ hr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air to Water ratio range</td>
<td>62.5 - 70</td>
<td>41 - 114</td>
</tr>
</tbody>
</table>
3.3 Troubleshooting lab scale prototype process

A fishbone analysis or mind mapping was carried out to circle down upon possible reasons for poor yield after the bench scale laboratory tests. The figure 3.4 shows the fishbone diagram after the analysis.

Figure 3.4 Fishbone diagram for troubleshooting the process.
3.4. Bench scale test results

The process was operated in 2 different scenarios: CONTINUOUS MODE and BATCH MODE, as shown in Figures 3.5 and 3.6 respectively.

Figure 3.5 Experimental set up for continuous process.
The heat transfer rate is calculated for the desired temperature gradient, which is used to determine the mass flow rate of steam. This is used to size the steam generator as well as determine the time required for batch heating with steam for tests.
A steam generator had to be sized for heating the process batch and the basic requirement was:

- To heat a batch of liquid from ambient conditions to 80°C.
- Continuous heating on inlet water by direct steam injection.

The amount of steam required for heating up the inlet stream is calculated as follows. Details are tabulated in Table 3.2 and 3.3 [2].

- Steam generator rating: 25 lb/hr
- Temperature gradient: (158 – 68) deg F
  (Assuming 20°C inlet water and 70°C water entering the purification chamber)
- Heating capacity of steam: 1 lb of steam condensed releases about 1000 Btu.
Continuous heating using steam injection used direct steam injection and the required flow rates for the desired temperature rise are tabulated in Table 3.2.

Table 3.2 Range of input streams for the tests

<table>
<thead>
<tr>
<th>Initial °C</th>
<th>Final °C</th>
<th>Delta T °F</th>
<th>Required water input rate (lb)</th>
<th>Required water input rate (litre)</th>
<th>Required Input rate (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.0</td>
<td>60.0</td>
<td>104.0</td>
<td>240.3</td>
<td>109.1</td>
<td>1.8</td>
</tr>
<tr>
<td>20.0</td>
<td>65.0</td>
<td>113.0</td>
<td>221.2</td>
<td>100.4</td>
<td>1.6</td>
</tr>
<tr>
<td>20.0</td>
<td>70.0</td>
<td>122.0</td>
<td>204.9</td>
<td>93.0</td>
<td>1.5</td>
</tr>
<tr>
<td>20.0</td>
<td>75.0</td>
<td>131.0</td>
<td>190.8</td>
<td>86.6</td>
<td>1.4</td>
</tr>
<tr>
<td>20.0</td>
<td>80.0</td>
<td>140.0</td>
<td>178.6</td>
<td>81.0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Tests on the lab scale prototype yielded results to ensure the capability of the process in terms of ion removal and purifying water to the desired extent. Table 3.3 represents a typical data set from one of the experiments. Ion concentration of both feed and purified water samples were analyzed using ion chromatograph (IC, DX-120, Dionex).
Table 3.3 A typical lab scale result of yield

<table>
<thead>
<tr>
<th>Input water rate (L/min)</th>
<th>Input Temp. (°C)</th>
<th>Time (min)</th>
<th>Recycled water temp (°C)</th>
<th>Output water temp (°C)</th>
<th>Output water quantity (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3 L/min</td>
<td>72</td>
<td>15.0</td>
<td>28.0</td>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30.0</td>
<td>29.0</td>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>45.0</td>
<td>29.0</td>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>60.0</td>
<td>28.0</td>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>75.0</td>
<td>29.0</td>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>90.0</td>
<td>29.0</td>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>105.0</td>
<td>27.0</td>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>120.0</td>
<td>27.0</td>
<td>19.0</td>
<td>1200</td>
</tr>
</tbody>
</table>

An analysis of the water quality was done in experiments carried out in the lab prior to building the pilot scale lab unit. An ion rejection of 99% ion rejection was observed [16]. However, in the above case the Na⁺ and Cl⁻ concentrations before and after the experiment are measured and the result shows an ion rejection of over 75% for the sample collected in one hour, which is also the range required for various end uses. With extended experimental time, the ion concentration increases dramatically. This is due to intermixing of the pure water and the NaCl solution at the base of the unit, which is separated by plastic foils. Leakage between each chamber inside the it is the reason why a marked increase in ion concentration is seen.

This data set is a typical one obtained from the pilot scale lab prototype, and shows the capacity of the process, which also buttresses the results and process capability of the previously carried out lab prototype.
A similar test carried out using tap water alone resulted in an ion concentration decrease from 85 ppm to 42 ppm for Na\(^+\), and 140 ppm to 68 ppm for Cl\(^-\).
CHAPTER 4 DESIGN AND CONSTRUCTION OF WATER TREATMENT PROTOTYPE

4.1 Field prototype fabrication/set up

The water purification unit to be installed at the wellhead was an extension of the laboratory unit. The unit consists of alternate hot and cold chambers, the hot chamber containing the packing material into which the produced water would be introduced. Air would be blown from the bottom of the same chamber, which would be tapped in through the adjacent chamber for water condensation. Alternative low duty Freon condenser was also designed with possibility to induce vacuum in the unit for operations with different system configurations.

The bench scale tests indicated that ions can be effectively removed using the H-DH process. However, the yield was low, and several other challenges were faced such as, insufficient heat transfer within the process chamber, leakage, material of construction etc., which could be attributed to the material of construction.

The factors taken under consideration while designing the field scale prototype were

1) Process
2) Material of construction
3) Manual/ Automatic controls.
4) Environmental factors.
5) External equipment to be hooked to the water purification unit.
Figure 4.1 is a schematic representation of the humidification – dehumidification process flow for the field prototype.

Figure 4.1 Schematic representation of the field prototype.
Main components of the produced water desalination unit include: (1) water heating system by using solar energy sources, (2) water evaporation unit, and (3) water recovery system with high latent recovery. Produced water from wellhead has a temperature around 45-60°C. The produced water will be further heated to the designed temperature (i.e., 60-80°C) by using solar energy. Produced water at elevated temperature is next introduced into the desalination unit as shown in the Figure 4.1 for water vaporization. As water falls to the bottom of the vessel by contacting with air flowing in a counter direction, water vapor will be extracted by flow air and form humidified air stream. The humidified air enters into the adjacent condensation chamber and water condenses on the surface with latent heat recovery: creating clean water for beneficial uses. Temperature and pressure sensors have been installed along the longitudinal of the separation unit to monitor the temperature and pressure changes at different temperature and operating condition. A water meter is installed to record total amount of clean water generated from the process. Both feed water and purified water will be studied for chemistry.
Figure 4.2 is a pre-design mind mapping carried out before the start of fabrication showing all the factors considered to be incorporated in the design. This helped narrow down in the finer aspects of the prototype needed to test the unit both on and off site.
Figure 4.3 Process and Instrumentation Diagram of the water purification unit on site.
Figure 4.4 Plan view of the equipment prototype.
A detailed description of the labeled parts in Figure 4.3 and 4.4 follow.

1) Oil skimmer: The primary function of the oil skimmer would be to separate out the initial oil from the produced water. A simple skimming mechanism will be used for the purpose.

2) Heat Exchanger: A heat exchanger (shell and tube) which performs the function of heat exchange was also considered to be used as a storage tank for the heated water. However, the heat exchanger has been progressed further in the process flow diagram and is being used to condense vapors from the system. A typical shell and tube heat exchanger sized at 2.5 m$^2$ costs over 40000 USD for fabrication. Moreover, there is no utility supply such as chilled water or cooling water in the field, which gave rise to the Freon chilling system. Tests have been carried out using both the Freon chiller as well as a conventional condenser that was previously used for lab scale test purposes. The heat transfer area for the Freon chiller was 1.5 m$^2$, and that of the condenser used was about 2.4 m$^2$.

3) Solar collectors: Flat plate solar collectors and evacuated tubes were considered to perform the required heating on inlet water. However, flat plate solar collectors have been sized to perform the required function. The amount of energy required to heat 20 bbls of water per day from ambient conditions to 70°C was the basis. A detailed description of the sizing the solar system and a flow diagram will be presented at a later stage. For experiments carried out on the field prototype before installing the solar system, a steam generator was used to heat up the inlet water up to 80°C. A n electric water heater was also used, but could only heat the inlet water up to 70°C.
4) A condenser/cold trap will be used to condense out and collect the purified water. The condenser works on a Freon refrigerant for the lack of chilled or cold water utility supply on site. However, test were also carried out using a conventional shell and tube condenser that was fabricated for lab scale tests.

5) Water purification unit: The process of humidification and dehumidification is carried out in this unit. Eleven chambers alternately carry water and air counter currently. The remaining chambers carry the vapor which is carried out into the condenser. The water purification unit is made up of SS304 and the inside chambers are fabricated with SS316 which is more corrosion resistant in produced water. A solar heating system for heating the input produced water to the process has also been procured. A detailed explanation of the water purification unit, the individual chambers and the mechanism of operation has been discussed separately.

6) Transfer pump: The transfer pump serves the purpose of re-circulating the hold up water at the bottom of the unit. The water is pumped back to the top which trickles down the packed column. Alternatively, the transfer pump can also be used to drain any hold up liquid over left at the bottom of the unit before the start of a new trial. Figures 4.5 to 4.8 display the fabricated prototype.
Figure 4.5 Field prototype in the fabrication shop.
Figure 4.6 Fabricated prototype using H-DH cycle.

The process of purifying produced water is achieved through the process of humidification-dehumidification using the field scale prototype in the Figure 4.5. The Figure 4.6 is labeled which also explains the working principle of the system. Label 1 on the figure shows the vacuum pump inducing vacuum within the system. The condenser/cold trap is connected to the water purification unit, which is also induced under vacuum. A maximum vacuum of 20 inHg can be reached within the system. Label 2 shows the inlet of air carrying water vapor from
the process, which is also the purified water exit stream from the process after the condensation process. Label 3 is the cold trap or in other words the condenser which works on a refrigeration system. Label 4 is the water purification unit made of stainless steel, SS304 on the outside. The inside plates separating the humidification and de-humidification chambers are made of SS316 sheets. The water purification unit consists of 11 chambers inside with 5 chambers being the humidification chambers and the other 6 being the de-humidification chambers.

4.1.1 Construction of prototype

The top view of the water purification unit is as shown in the Figure 4.7 and the V-notch weirs shown in Figures 4.7 and 4.8 are designed for introducing water into the system.

![Manifold containing V notched weirs for the water inlet.](image)
A packing material as shown in the Figure 4.9 is placed in each of the 5 humidification chambers. Water trickles down from the top introduced at a flow rate based on which the heat exchangers, the solar panels and the entire system as such was designed. The air pump pumps air from the bottom in each of these 5 chambers. The air water ratio is decided based on parametric studies conducted in the laboratory prior to designing and fabricating the field prototype.

The packing material inside the humidification chambers is shown in the Figure 4.9. The primary purpose of the packing material is to increase the residence time of the fluid inside the chambers and also to maximize contact time between the air and water.
Tests were conducted to ensure stability of the packing material by repeated heating cycles with the packing material in produced water and no significant degeneration of the material was observed.

### 4.1.2 Electrical controls

Figure 4.10 shows the process monitoring, including pressure, temperature, and humidity. The measurement points vertically from the bottom to the top and at adjacent chambers were continuously monitored during the operating process.
The electrical controls for the unit are shown in Figure 4.11. The unit can be operated both using a 240 volts or a 480 volts input supply. The unit can be operated using the automatic mode in which the corresponding water/air pump will be triggered to start at preset conditions. For example, the concentrate drainage pump will be triggered to pump out the concentrate as the concentrated water in the humidification chamber reaches the preset level as shown in Figure 4.12. The manual mode was however used during field tests for ease of operation where input air flow rates, input water flow rates and concentrate discharge / recirculation were manually controlled.
Figure 4.11 Electrical controls for the unit.
4.2 Design Modifications

During the testing phase, several modifications were conducted, including provision for vacuum operation, installing a new condenser, replacement of the existing air blower and installation of recirculation pump. These modifications were primarily carried out for testing under various combinations and also for parametric studies where parameters would be varied as required.
4.2.1 Ball valves for operation under vacuum

The unit was initially tested without vacuum conditions. However, modification by installing ball valves at the inlet air manifold allowed for vacuum operation as well. A maximum vacuum of 22 in Hg was reached in the process. Figure 4.13 shows the modifications carried out.

BEFORE

AFTER

Figure 4.13 Showing modifications with ball valves for vacuum operation.
4.2.2 Air-induced water cooling system

The new water condenser installed is shown in the Figure 4.14.

![Figure 4.14 Before and after installing the condenser.](image)

4.2.3 Automatic drainage system for concentrate recirculation

The concentrate brine discharge pump as shown in Figure 4.15 serves a two-fold purpose of both draining the concentrate from the unit or also re-circulating the inlet feed collected at the bottom.
Figure 4.15 Recirculation pump installed for concentrate drainage.
4.2.4 Field prototype testing site

The water purification prototype in the moving container was set up in the campus of New Mexico Tech, as shown in Figure 4.16. All the testing experiments were carried out by using simulated produced water.

Figure 4.16 Site picture of prototype unit contained in the moving trailer.
4.3 Heat exchanger sizing

A shell and tube heat exchanger rated at about 2.9 m\(^2\) was initially planned to condense vapors. The process calculations that helped arrive at the indicated rating follows:

**Basis:**

<table>
<thead>
<tr>
<th>Inlet feed</th>
<th>Latent heat of condensation</th>
<th>Yield assumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>285 lb/hr.</td>
<td>2260 KJ/kg.</td>
<td>40 %</td>
</tr>
</tbody>
</table>

Total latent heat to be absorbed: 116969 KJ/hr.

\[ Q = U.A\Delta T \quad (17) \]

Where \( Q \) is the total heat to be absorbed in kJ, \( U \) is the overall heat transfer co-efficient in W/m\(^2\).K, \( A \) is the area in m\(^2\), and \( \Delta T \) is the temperature gradient in °K, which is considered as 10 as a standard practice for sizing shell and tube heat exchangers.

An overall heat transfer coefficient value of 4000 W/m\(^2\).K was chosen as a typical value for tube side condensation of vapors in shell and tube exchangers [17].

**Therefore, the calculated area is 2.9 m\(^2\),** and a shell and tube heat exchanger of 2.9 m\(^2\) should be fabricated for our purpose.
However, two problems arose:

a) High cost of shell & tube heat exchanger fabrication.

b) Lack of chilled or cooling (utility) supply on site.

Therefore, a cold trap that works with a Freon compressor as shown in Figure 4.17 was fabricated, which does not require any utility supply. A shell and tube heat exchanger as shown in Figure 4.16 however works on either cold water or chilled water, which is not easily available on site. However, produced water itself could be used to cool the water. The overall heat transfer area for the shell and tube heat exchanger was about 3.5 m$^2$. However, due to monetary constraints a refrigeration system with a 1.5 m$^2$ area was used. A typical shell and tube heat exchanger and the cold trap is shown in the Figures 4.17 and 4.18.

Figure 4.17 Schematic of shell and tube heat exchanger(3.5 m$^2$).
4.5 Deployment of coproduced energy or renewable energy sources

A specific advantage of the humidification-dehumidification water purification process is that various low-temperature energies can be deployed, such as industry waste heat, solar energy, and coproduced geothermal energy. These low-temperature energies are generally available with oil/gas production activities in the western United States. In addition, high solar radiation intensity and the deep reservoir formation (located in southeastern New Mexico) make it possible for deploying or integrating solar and coproduced geothermal energies for produced water heating and desalination. It is estimated that a solar heating system with solar collector area of 70 m² can support a desalination unit with the capacity of 25–30 bbls/d, which is the typical water production rate of an individual well. Other energy resources such as electricity and natural gas can also be deployed for continuous operation at night or in winter.
A variety of solar systems are available for the purpose of heating produced water from ambient conditions to the desired temperature. However, the brackish nature of the water calls for corrosion resistant material. Flat plate collectors were chosen, as there was ample space available, and was more economical than evacuated tube systems. Evacuated tubes and flat plate solar collectors were considered, however glycol based flat plate collectors were chosen due to budget constraints. A tilt angle of 50° was found appropriate for ROSWELL, NM as shown in Figure 4.21.

The basis on sizing the solar collectors was 20 barrels of produced water per day. The heat input required for solar heating was calculated in equation 17 [15].

\[
Q = f \cdot m \cdot C_{wp} \cdot t \cdot \Delta T
\]  

(17)

Where Q is the heat transfer rate (KW or KJ/s), m is the quantity of fluid to be heated, Kg, Cp is the specific heat of water, KJ/Kg.C, t is the time, sec, and ΔT is the temperature gradient, °C, and f is the solar efficiency, 78%.

Total energy required for heating 20 barrels produced water from ambient temperature (15°C) to optimized temperature (80°C) is listed in Table 4.1.

<table>
<thead>
<tr>
<th>Table 4.1 Solar panel design and sizing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial Temperature</strong></td>
</tr>
<tr>
<td><strong>Target Temperature</strong></td>
</tr>
<tr>
<td><strong>Size of solar collector</strong></td>
</tr>
<tr>
<td><strong>No. of solar collectors required</strong></td>
</tr>
</tbody>
</table>
From the Equation 17, 656KBtu of heat is required to heat the daily capacity of produced water per day, which is the theoretical value required. Solar collectors that can cater to this need have to be sized and purchased and 16 solar collectors will be procured to perform the job. The rule of thumb used by solar panel suppliers considers a capacity of 15 barrels per day of water to be treated, which is about 630 gallons of water per day. Water density of 8.34 pounds per gallon(ppg) is used with a 75 degree increase in desired temperature. The solar panel efficiency is considered as 75% and the calculation yields 500 KBtu. A 32 ft² solar collector supplies about 32000 Btu/day. Therefore, 500 KBtu of heat can be catered with 16 solar collectors with each supplying 32000 Btu as mentioned. This method is used by solar collector manufacturers for sizing. The tilt angle of the solar collectors would be 50° which is shown in Figure 4.21.
A basic schematic of the glycol based solar collector design is shown in Figure 4.19. Figure 4.20 describes the hot and cold process loops for the solar system and Figure 4.21 is the placement layout for the solar panels on site with a tilt angle that applies to the location (Roswell, NM).

Figure 4.19 Schematic diagram of the glycol based solar loop for the process.
Figure 4.20 Hot and cold water loops showing the solar process flow diagram.

Figure 4.21 Basic schematic and tilt angle of the solar collectors.
CHAPTER 5 RESULTS AND DISCUSSION

This chapter discusses the results from both the pilot scale lab tests as well as tests carried out on the fabricated field prototype. The field prototype was tested by varying the inlet water flow rate and feed water temperature for monitoring the impact of feed water parameters on the performance.

The primary variables involved in the humidification – dehumidification system are following:

- Inlet water flow rate.
- Inlet water temperature
- Inlet air temperature
- Inlet air flow rate
- Total solar energy incident and solar water heater collector area.
5.1 Test configurations

The process of humidification – dehumidification was carried out in various test configurations, the primary ones being:

1. Operation with blower and water condenser.
2. Operation with blower and cold trap.
3. Operation under vacuum conditions with cold trap.

The following flow chart in Figure 5.1 displays one of the various system configurations. A detailed schematic is explained for each test in the results section. For comparison, water desalination by vacuum distillation was also tested and energy efficiency is discussed.

![Flow chart](image)

**Figure 5.1** Configuration with blower and water condenser.
The productivity of the system can be measured by the moisture content of the humidified air. This can be calculated using humidity charts with the dry bulb and wet bulb temperature of the process streams. An illustration of calculating the moisture content of the exit stream in the present case is presented in APPENDIX 2. The required data for the calculation is the dry bulb temperature of the entering and leaving air and the wet bulb temperature of the entering air.

A schematic representation of the unit itself and the condenser is shown in Figure 5.2.

![Figure 5.2 Schematic representation showing the process streams.](image)
The balance around the humidification unit can be written as

\[ M_{\text{air}} \cdot H_{a2} + M_{\text{wout}} \cdot C_w \cdot T_{\text{wout}} = M_{\text{win}} \cdot C_w \cdot T_{\text{win}} + M_{\text{air}} \cdot H_{a1} \]  \hspace{1cm} (17)

Expressing in terms of enthalpies:

\[ (H_{a2} - H_{a1}) = (M_{\text{win}}/M_{\text{air}}) \cdot C_w \cdot T_{\text{win}} - [(M_{\text{win}}/M_{\text{air}}) \cdot (W_2 - W_1)] \cdot C_w \cdot T_{\text{wout}} = M_{\text{win}} \cdot C_w \cdot T_{\text{win}} + M_{\text{air}} \cdot H_{a1} \]  \hspace{1cm} (18)

The balance around the de-humidification unit can be written as

\[ M_{\text{air}} \cdot H_{a3} - M_{\text{air}} \cdot H_{a3} = M_{w3} \cdot C_w \cdot T_{w4} - M_{w3} \cdot C_w \cdot T_{w3} + M_{w5} \cdot C_w \cdot T_{w5} \]  \hspace{1cm} (19)

Energy balances around the condenser, the solar unit and the storage tank can also be written. However, the solar system will only be hooked up on site and is beyond the scope of the present configuration.

The measured entities throughout the experiments include liquid flow rate, air flow rate, total dissolved solid in both the feed water and concentrate water, and operating parameters at different locations (A, B, C, D, and E) of the unit as shown in Figure 5.3. Figure 5.3 also shows various combinations that could be used in testing system performance such as operation under
vacuum conditions, only blower, and also using the Freon cold trap.

Figure 5.3 Schematic diagram of the field prototype with all possible configurations.

The feed water was heated to preset temperature by an in-line heater or a steam generator. An in-line water flow meter monitors the feed water flow rate. Feed water evaporates under vacuum or flowing air stream and was split to clean water and concentrate with high TDS. Both the concentrate and condensed clean water will be collected for ion concentration analysis by conductivity meter and ion chromatograph. Temperature, pressure, and humidity at locations of A, B, C, D, and E were monitored throughout all the experiments.
5.2. Operation of prototype using the humidification dehumidification configuration

Following the completion and seal testing, operating tests of the prototype under different modes were initiated by using brine and simulated produced water. The first operation was carried out under the humidification dehumidification configuration. Table 5.1 is a typical test data record showing process parameters with the temperature distribution across the unit. The temperature distributions are plotted in Figures 5.4 and 5.5. The temperature distributions not only give an idea of the saturation wet bulb temperatures, but also show uneven distribution of water within the chamber.
Table 5.1 Typical test results for configuration with blower and cold trap

<table>
<thead>
<tr>
<th>Inlet water flow rate, L/min</th>
<th>0.86</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet air flow rate, L/min</td>
<td>3280</td>
</tr>
<tr>
<td>Feed water temperature, C</td>
<td>75</td>
</tr>
<tr>
<td>Entering air dry bulb temp (deg C)</td>
<td>36</td>
</tr>
<tr>
<td>Exit air wet bulb temp (deg C)</td>
<td>29</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TEMPERATURE RECORD (deg F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 min.</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>D</td>
</tr>
<tr>
<td>E</td>
</tr>
</tbody>
</table>
Figure 5.4 Temperature change at same height of adjacent chambers.

Figure 5.5 Temperature change from top to bottom of humidification chambers.
### 5.2.1 Operation of prototype using modified water condenser

A schematic of the field prototype for testing with the water condenser configurations as shown in the Figure 5.6. Table 5.1 is the test data from this trial and Figure 5.7 shows the temperature distribution within the unit.

![Figure 5.6 Schematic diagram of prototype with blower and water condenser.](image)

---

83
Table 5.2 Results for configuration with blower and water condenser

<table>
<thead>
<tr>
<th></th>
<th>Inlet water flow rate (litre/min)</th>
<th>Blower rate (Hz) / ft³/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.8</td>
<td>45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>0min</th>
<th>30mins</th>
<th>60mins</th>
<th>90mins</th>
<th>120mins</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>89</td>
<td>87</td>
<td>85</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>B</td>
<td>78</td>
<td>77</td>
<td>77</td>
<td>77</td>
<td>78</td>
</tr>
<tr>
<td>C</td>
<td>99</td>
<td>97</td>
<td>94</td>
<td>91</td>
<td>89</td>
</tr>
<tr>
<td>D</td>
<td>81</td>
<td>81</td>
<td>81</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>E</td>
<td>78</td>
<td>78</td>
<td>77</td>
<td>77</td>
<td>76</td>
</tr>
</tbody>
</table>

A temperature profile within the unit as labeled in the schematic diagram is shown in Figure 5.7.

![Temperature profile graph](image-url)

Figure 5.7 Temperature profile within the unit.
A second trial using vacuum was conducted to confirm the results of trials that provided a higher yield. The trial resulted in an actual yield of about 8%, and a total productive yield of 12.5%, in comparison to 15% and 5% in the previous trials using the vacuum method.

**5.2.2 Operation of prototype under vacuum distillation configuration**

The purpose of inducing vacuum in the system is to compare the energy efficiency of produced water desalination under different configurations. Under vacuum, water starts to evaporate at much lower temperature compared to that at atmospheric pressure due to the reduced vapor pressure of water inside the system.

A schematic of the field prototype is as shown in the Figure 5.8, and the labeled parts in this schematic representation will be used in the mass balance analysis:

![Schematic representation of prototype with vacuum and cold trap](image)

*Figure 5.8 Schematic representation of prototype with vacuum and cold trap*
### Table 5.3 Results for configuration with vacuum and cold trap

<table>
<thead>
<tr>
<th>Inlet water flow rate (L/min)</th>
<th>1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum applied (in Hg)</td>
<td>22</td>
</tr>
<tr>
<td>Feed water temperature (deg C)</td>
<td>76</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TEMPERATURE RECORD (deg F)</th>
<th>0min</th>
<th>20mins</th>
<th>40mins</th>
<th>60mins</th>
<th>80mins</th>
<th>100mins</th>
<th>120mins</th>
<th>140mins</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>96</td>
<td>98</td>
<td>101</td>
<td>103</td>
<td>102</td>
<td>105</td>
<td>107</td>
<td>109</td>
</tr>
<tr>
<td>B</td>
<td>94</td>
<td>94</td>
<td>97</td>
<td>100</td>
<td>104</td>
<td>103</td>
<td>104</td>
<td>104</td>
</tr>
<tr>
<td>C</td>
<td>106</td>
<td>100</td>
<td>108</td>
<td>112</td>
<td>114</td>
<td>115</td>
<td>116</td>
<td>116</td>
</tr>
<tr>
<td>D</td>
<td>97</td>
<td>102</td>
<td>107</td>
<td>110</td>
<td>111</td>
<td>112</td>
<td>112</td>
<td>112</td>
</tr>
<tr>
<td>E</td>
<td>97</td>
<td>98</td>
<td>102</td>
<td>104</td>
<td>106</td>
<td>108</td>
<td>108</td>
<td>108</td>
</tr>
</tbody>
</table>

A temperature profile within the unit is shown in Figures 5.9 and 5.10.

Figure 5.9 Temperature change along horizontal direction.

Figure 5.10 Temperature change along vertical direction.
A dramatic increase in productivity is seen in the case of vacuum operation. The actual yield increased from less than 2% up to 5%. The total productive yield shows an increase in case of blower operation because vacuum contains the vapor within the system, while bowing forces vapors out of the system leaving very less time for condensation with the facility available on site. A total loss of vapor dramatically reduced to just 9% as compared to 37% as in the case of blowing only without vacuum. This goes to show, in case of blowing only, vapors are lost out of the system, while vacuum aids in the dehumidification or condensation process, thereby not only increasing the yield of the process, but also by reducing the vapor lost into the surroundings. The temperature gradient also shows a more stable range which can be attributed to the presence of vacuum within the system.

5.3 Ion rejection potential of the field prototype

The field prototype was not extensively tested with produced water and NaCl on the present testing location due to disposal problems. However, a few tests were conducted with NaCl and produced water to establish the ion rejection potential of the process, and the results are discussed in this section.

Table 5.4 tabulates the ion rejection results for a NaCl solution with concentration of 8421 ppm. The ion rejection observed during the lab scale tests was over 95% [16]. The ion rejection observed on the field prototype with NaCl solution was 92% with a starting TDS of 8421 ppm and the purified water with a TDS content of 647 ppm. The conductivity as in Figure 5.13 also shows a dramatic drop due to the ion rejection of over 93% after purification.
Table 5.4 Ion rejection results for NaCl feed

<table>
<thead>
<tr>
<th>Quantity Measured</th>
<th>Inlet feed</th>
<th>Purified water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium (Na) (mg/L)</td>
<td>3220</td>
<td>165</td>
</tr>
<tr>
<td>Chloride (mg/L)</td>
<td>4920</td>
<td>105</td>
</tr>
<tr>
<td>Fluoride (F-) (mg/L)</td>
<td>3</td>
<td>1.2</td>
</tr>
<tr>
<td>Phosphate (mg/L)</td>
<td>8.8</td>
<td>0.4</td>
</tr>
<tr>
<td>Potassium (K) (mg/L)</td>
<td>4.9</td>
<td>5.7</td>
</tr>
<tr>
<td>Magnesium (Mg) (mg/L)</td>
<td>6.5</td>
<td>11</td>
</tr>
<tr>
<td>Calcium (Ca) (mg/L)</td>
<td>23.7</td>
<td>37.0</td>
</tr>
<tr>
<td>Bromide (mg/L)</td>
<td>3</td>
<td>0.1</td>
</tr>
<tr>
<td>Total cations (meq/L)</td>
<td>142</td>
<td>10</td>
</tr>
<tr>
<td>Total anions (meq/L)</td>
<td>143.8</td>
<td>9.9</td>
</tr>
<tr>
<td>Percent difference</td>
<td>-0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Conductivity (uS/cm)</td>
<td>15100</td>
<td>1060</td>
</tr>
<tr>
<td>TDS calculation (mg/L)</td>
<td>8420.7</td>
<td>647.3</td>
</tr>
</tbody>
</table>
Figure 5.11 Ion rejection for NaCL feed.

Figure 5.12 Ion rejection for NaCL feed.
Figure 5.13 Ion rejection summary displaying TDS and conductivity for NaCl feed.

Figure 5.11 and Figure 5.12 shows the ion concentration of the inlet feed and purified water. The plot of trace elements is plotted separately in Figure 5.12 as it lies within a smaller range (<100 ppm).
Table 5.5 Ion rejection results for Produced water feed

<table>
<thead>
<tr>
<th>Quantity Measured</th>
<th>Inlet feed</th>
<th>Purified water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium (Na) (mg/L)</td>
<td>2390</td>
<td>165</td>
</tr>
<tr>
<td>Chloride (mg/L)</td>
<td>3780</td>
<td>105</td>
</tr>
<tr>
<td>Fluoride (F-) (mg/L)</td>
<td>4</td>
<td>1.3</td>
</tr>
<tr>
<td>Phosphate (mg/L)</td>
<td>8</td>
<td>0.4</td>
</tr>
<tr>
<td>Potassium (K) (mg/L)</td>
<td>220</td>
<td>5.8</td>
</tr>
<tr>
<td>Magnesium (Mg) (mg/L)</td>
<td>22</td>
<td>12</td>
</tr>
<tr>
<td>Calcium (Ca) (mg/L)</td>
<td>145</td>
<td>39</td>
</tr>
<tr>
<td>Bromide (mg/L)</td>
<td>11</td>
<td>0.12</td>
</tr>
<tr>
<td>Total cations (meq/L)</td>
<td>118</td>
<td>10</td>
</tr>
<tr>
<td>Total anions (meq/L)</td>
<td>126</td>
<td>9.8</td>
</tr>
<tr>
<td>Percent difference</td>
<td>-3.3</td>
<td>1.7</td>
</tr>
<tr>
<td>Conductivity (uS/cm)</td>
<td>12500</td>
<td>1030</td>
</tr>
<tr>
<td>TDS calculation (mg/L)</td>
<td>7207</td>
<td>648</td>
</tr>
</tbody>
</table>

Ion rejection for produced water has not been plotted, as a satisfactory ion rejection is seen. A total ion rejection potential of over 93% is seen with NaCl and 91% is seen with produced water.
Figure 5.14 Ion rejection for produced water feed.

Figure 5.15 Ion rejection for produced water feed.
Figure 5.16 Ion rejection summary displaying TDS and conductivity for produced water.

5.4 Parametric analysis of the system

A detailed parametric analysis of the humidification dehumidification process was carried out in the lab scale tests as well. To investigate the influence of input water temperature and air flow rate on the performance of the field scale prototype desalination tests were carried out at varied operating parameters.

Figure 5.17 shows a comparison of the parametric study between the lab scale and field scale prototypes and comparison with the data from literature. Though the parametric study for changing temperature was established during the lab scale tests, it was repeated to observe the field scale prototype perform. An increasing temperature was found to increase the productivity. A look at the psychometric chart also shows that an increase in the wet bulb saturation temperature implies an increased water carrying capacity of air. This explains the phenomena and the substantial increase in yield with increased temperature. Tests carried out with water at
room temperature shows almost no yield with only a few drops after about three hours of operation. Therefore, the temperature that could be achieved most economically by the solar system was chosen, based on which the solar system was also sized.

A parametric study on the inlet water flow rates and inlet air flow rates were also carried out in the lab study as shown in Figure 5.18 and Figure 5.19. Their effects are also extensively published in literature. However, due to the larger scale of this unit compared to the laboratory scale, changing air flow rates and inlet water flow rates did not show a marked difference in productivity as far as the parametric study is concerned.

![Figure 5.17](image.png)

**Figure 5.17** Effect of feed temperature on the total production yield.
Figure 5.18 Effect of air flow rate on the total production yield [16].

Figure 5.19 Effect of feed water flow rate on the total production yield [16].
5.5 Comparison of results the various configurations

Table 5.6 compares the yield from various combinations. The Total Actual Yield is the volume of condensed vapors, while the Total Productive Yield is the sum of condensed vapors and the vapor volume unaccounted for during the mass balance calculation.

<table>
<thead>
<tr>
<th></th>
<th>Capacity (bbls/day)</th>
<th>Water to air ratio. (LPM/CFS)*</th>
<th>Total actual yield (%)</th>
<th>Total productive yield (%)</th>
<th>Vapor lost (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blower with Freon cold trap</td>
<td>10</td>
<td>1:45</td>
<td>1.3</td>
<td>40</td>
<td>37</td>
</tr>
<tr>
<td>Vacuum with Freon cold trap</td>
<td>10</td>
<td>1:40</td>
<td>8</td>
<td>12.5</td>
<td>4.7</td>
</tr>
<tr>
<td>Blower and water condenser</td>
<td>10</td>
<td>1:40</td>
<td>4</td>
<td>28</td>
<td>24</td>
</tr>
</tbody>
</table>

After a comparison of various combinations, the actual yield, total productive yield and the vapor lost in different test configurations are presented in Figures 5.20 - 5.23.
Figure 5.20 Actual yield comparison of all combinations.

Figure 5.21 Total productive yield comparison of all combinations.
Figure 5.22 Total vapor lost in different combinations.
CHAPTER 6 CONCLUSIONS AND FUTURE WORK

A low temperature distillation in which water evaporates at a temperature below boiling point in the flowing air stream (or in other words humidifies the inlet air stream) was designed and tested for produced water desalination. Bench scale tests indicated that both organics and salt can be removed by the air enhanced distillation process. Based on bench scale test results, a pilot scale prototype water desalination unit was designed and constructed in this work for produced water desalination. The fabricated water purification prototype was investigated for maximum productivity under different configurations. The ultimate goal of this work was to establish a process with maximum possible yield with the least operating cost.

The water treatment prototype with a designed capacity of 20bbls/day was tested using different configurations. According to the experimental results, modification of the prototype including deployment of the air-enhanced condenser and recirculation pump was carried out. The experiment results indicated that about 52.7% water will evaporate with an air flow rate of 3516 L/min with a feed water temperature of 90 °C. Due to the limitation of feed water flow rate during experimental conditions, about 4.7% of water could be recovered as clean water. The experimental results are compared with vacuum distillation and the observations are summarized as:

1. Produced water can be effectively desalinated by the humidification dehumidification process. Specifically, the process can be operated at atmospheric pressure and relatively low temperature (60-80 °C) and thus low-temperature heat sources like coproduced geothermal energy could be deployed for the desalination process.
2. Conventional thermal processes, i.e., vacuum distillation, is energy intensive to attain vacuum, and also requires a large quantity of cooling water for vapor condensation, and the same is not applicable at the wellhead where cooling water supply is limited.

3. The total productive yield defined as the total vapor generated including water condensed and water vapor lost which varies from 12.5% to 40% depending on the system configuration. Specifically, the total productive yield at an air flow rate of 3516 L/min varies from 29.5% to 38.8% when the feed water temperature increases from 70 °C to 90 °C. A total productive yield of 9.4% of feed water is observed in the vacuum distillation configuration.

4. In terms of economics and an overall appraisal of the various configurations, the configuration with the air blower and water condenser was found to be more efficient than vacuum distillation both in terms of yield and energy requirement.

5. A parametric study was already carried out during lab tests, and the optimum temperature for the humidification dehumidification was set at 70 – 80 °C.

6. An ion rejection capacity of 93% was observed with NaCl feed solution and an ion rejection of 91% with produced water feed solution. The total TDS was reduced from 8421 ppm to 647 ppm in both cases, which also falls within the environmental regulations for use in various end uses such as cooling towers, irrigation and in chemical processes as shown in Table 1.2.

7. A parametric study on the field prototype for inlet feed water rate indicated that the current water flow rate is too low and thus experimental testing with extended range of feed water flow rate is needed for onsite testing.
8. A solar system was sized based on the feed requirement or the desired capacity. The basis was to process up to 20 barrels a day. Both evacuated solar heating systems as well as flat plate collectors were considered. Flat plate collectors were chosen as it was cheaper and space was not a constraint on site. About sixteen flat plate collectors of 32 ft\(^2\) each were chosen to cater to a load of 500 KBTU/day. The solar system has been sized to heat the inlet water from ambient conditions (5\(^\circ\)C- the worst case scenario during winter was considered) up to 80\(^\circ\)C, which serves the required purpose for this study.
6.1 FUTURE WORK

The field prototype was tested extensively and the following steps will be the future plan of action:

1. The field prototype will be tested on site with the solar system that has been procured.
2. The unit can still be operated under different modes or configurations such as vacuum, air blower, Freon cold trap or the water condenser with the parameters established with each combination.
3. Produced water has been tested only once on the field prototype due to disposal concerns in the area where the unit is located presently. The present unit also uses a water heater for continuous operation and a steam generator for batch operation to perform the function of heating and repeated use of produced water at the present site with the available infrastructure would lead to severe corrosion issues and disposal concerns. However, the well site would not face any of these concerns and extensive testing will also be carried out at the site.
REFERENCES


[9] Fath HES, “Desalination technology, the role of Egypt in region” IWT C, Alexandria,


[22] Rowe, D. and Abdel Magid, M., Handbook of Wastewater Reclamation and Reuse, Lewis
APPENDIX 1: H-DH PROCESS CALCULATIONS

Calculation for humidified water yield by blowing method

The experimental results show a low vapor purified yield. However, theory supports the fact that the vapor carrying capacity of air blowing by the process of humidification is low. Therefore, considering the amount of vapor lost in the process from a basic mass balance calculation, it is evident that the majority of the latent heat transfer resulting in vapor is due to heat transferred between the walls of the humidification and dehumidification chambers.

The following calculation gives the theoretical yield from a process using the blowing method to humidify air from ambient conditions upto 90%, as in our case.

The inlet conditions of entering air were 30 deg C, with a relative humidity of 25%. The humidified air exiting the system has a relative humidity of 90%. The inlet water is fed at 70 deg C.

![Diagram of water and air flow process]

- **WATER IN**
  - 75°C

- **ENTERING AIR**
  - 30°C
  - Relative humidity: 25%

- **HUMIDIFIED AIR**
  - Relative humidity: 90%

- **CONCENTRATE DRAIN**
The following calculations calculate the ultimate amount of water per hour exiting the system.

a. **Absolute humidity of entering air:**

At 30 deg C and a relative humidity of 25%, the psychometric chart gives an absolute humidity reading of 0.0052 kg water/ kg dry air.

\[ 0.052 \text{ kg water/ kg dry air} \]

b. **Adiabatic saturation temperature of entering air:**

The psychometric chart reads an adiabatic saturation temperature of 15.5°C.

\[ 15.5^\circ C \]

c. **Amount of humidified air leaving the unit:**

The amount of vapor in air at a relative humidity of 90% and 15.5°C can be read out of the psychometric chart as:

\[ 0.0105 \text{ kg water/ kg dry air} \]

Inlet flow rate of dry air:

326 kg/hr. (1 kg dry air/1.0052) = 326 kg dry air/hr in input into the system.

Therefore, the amount of water being carried out in the exit stream by the process of humidification alone is

\[ (326 \text{kg dry air/hr}) \cdot (0.0105 - 0.0052) = 1.72 \text{ kg water/hr}. \]
Figure: Psychometric chart used for the theoretical recovery calculations [10].
APPENDIX 2: MOISTURE CONTENT CALCULATIONS

Illustration of calculating the moisture content of exit stream:

The dry bulb temperature of the entering and exit stream of air is 39 °C and 28 °C respectively. The wet bulb temperature of the entering stream of air is 31 °C.

Table: Temperature of process streams

<table>
<thead>
<tr>
<th></th>
<th>Dry bulb temperature</th>
<th>Wet bulb temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entering air</td>
<td>39 °C</td>
<td>31 °C</td>
</tr>
<tr>
<td>Leaving air</td>
<td>28 °C</td>
<td></td>
</tr>
</tbody>
</table>

Solution:

Assuming the process to be adiabatic, and that the web bulb temperature remains constant at 31 °C due to constant inlet flow rate at constant temperature, the following values can be obtained from the humidity chart:

At BDT 39 °C and WBT 31 °C, the moisture content is 0.03 kg water/kg dry air.

At BDT 28 °C and WBT 31 °C, the moisture content is 0.025 kg water/kg dry air.

Therefore the exit stream carries 0.005 kg H₂O/Kg dry air.
The following is the psychometric chart used for the calculation:

Figure: Psychometric chart used to calculate moisture content of exit stream [10].
APPENDIX 3: ELECTRICAL AND MECHANICAL CHECKLISTS

Before the start of any tests, a series of electrical and mechanical tests were carried out and the results are tabulated in the table

<table>
<thead>
<tr>
<th>Test item</th>
<th>Specification/ Requirement</th>
<th>Measurement System</th>
<th>Observations</th>
<th>Remedy</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage test of the module.</td>
<td>No leakage</td>
<td>Pressure test using air blower.</td>
<td>Slight leakage on ceiling</td>
<td>Hinged ceiling to be modified</td>
<td>DONE. Ceiling modified at NMT.</td>
</tr>
<tr>
<td>Mechanical damages test</td>
<td>No Mechanical damages</td>
<td>Visual Inspection.</td>
<td>Found OK</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Feed weirs and all flow lines check</td>
<td>Work as required.</td>
<td>Visual Inspection and tests.</td>
<td>Top weir for inlet water flow not in level.</td>
<td>Top cover to be dismantled and V-notch weirs to be adjusted.</td>
<td>DONE at Industrial Electric.</td>
</tr>
<tr>
<td>Spray nozzles, pumps and filters test</td>
<td>Work as required.</td>
<td>Visual Inspection.</td>
<td>Recirculation pump missing</td>
<td>Provide a recirculation pump at lower sump.</td>
<td>DONE at Industrial electric.</td>
</tr>
<tr>
<td>Heating and Control in the</td>
<td>Control in the</td>
<td>Temperature gauges.</td>
<td>Freon system to Optimum</td>
<td>Optimum</td>
<td>DONE at</td>
</tr>
</tbody>
</table>

Table: Equipment electrical and mechanical tests checklist
<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Action</th>
<th>Responsible Party</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling system test</td>
<td>Right temp. area should be modified due to excess refrigerant.</td>
<td>Freon level to be maintained.</td>
<td>Industrial electric.</td>
</tr>
<tr>
<td>Temperature and pressure gauges.</td>
<td>Ensure adequate quantity for process readings.</td>
<td>Temperature gauges missing at top and bottom section.</td>
<td>Procure and fit the same.</td>
</tr>
<tr>
<td>Valves.</td>
<td>Work as required and ensure adequate number.</td>
<td>5 valves missing to operate unit under vacuum.</td>
<td>2&quot;Ball valve installed.</td>
</tr>
<tr>
<td>Controls and hardware test</td>
<td>All work as required.</td>
<td>All automatic and manual controls work as required.</td>
<td>Control box.</td>
</tr>
</tbody>
</table>