Vapor Compression Desalination Proposal

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Abstract

Our goal is to develop a method to provide water for a growing world. The project is designed to optimize the process of distilling salt water using a method called vapor compression. Currently, large potable water plants use reverse osmosis, which cannot be efficiently performed in a small scale basis; however, vapor compression optimizes desalination even at small scale, making it an ideal point of interest for university undergraduates.

Results from Aspen Plus modelling software indicate high temperatures and low pressures are required to achieve the desired separation of saltwater into liquid brine (concentrated saltwater) and vapor distillate (pure water vapor). With the current resources allocated to the project, it was concluded that running tests at these conditions would be unsafe and that the Aspen model could be unreliable because of several simplifications made for the simulation.

To address safety concerns and the validity of the computer models, a new proof of concept test has been proposed. This test will seek to determine the split ratio of water vapor to brine that can be achieved by evaporation of mist-like water droplets in a heated duct at atmospheric pressure—a process believed to be improperly modelled in Aspen Plus.
**Introduction**

As inventor Dean Kamen noted when discussing his Slingshot water purification system, half of all human chronic disease can be attributed to lack of clean drinking water. Economic and physical restraints have created a shortage of water for much of the world. In developed nations, advanced infrastructure allows areas abundant in water to transport their excess water to those that cannot meet demands with local water supplies. In East Porterville, California, for example, most of the wells have dried up as a result of the California drought, leaving its citizens relying heavily on “the county [to install] 53 large potable water tanks, which hold up to 2,500 gallons of water at homes around Tulare.”[1] In this situation, the water demand is still able to be met because water management has taken a priority in the form of imports and government intervention.

However, developing nations are unable to handle water scarcity nearly as well. These countries’ cities often cannot support their inhabitants due to high population growth rates. This overcrowding forces people to live in less desirable places, such as slums, with even more limited water access. "A slum dweller in Nairobi, Kenya pays 5 to 7 times more for a liter of water than an average North American citizen"[2] due to lack of water infrastructure and accessibility. For the millions that receive contaminated drinking water, the consequences are often fatal. The goal of our project is to contribute to the awareness and development of technologies that can potentially alleviate the burden that many people face in acquiring clean, drinkable water. To address this problem, we propose further investigation into small-scale water purification processes which could feasibly be implemented in developing nations.

In addition to vapor compression desalination, other similar methods already exist, such as reverse osmosis (RO) and Dean Kamen’s Slingshot. Reverse osmosis is the most commonly used method for large-scale desalination in the US; however, process efficiency drops significantly for RO as the process is scaled down. Alternatively, the Slingshot, a different vapor compression distillation system, is an existing solution that seeks to address water shortages in the developing world. While it is unlikely a student-constructed unit could perform with the same efficiency as the Slingshot, a realistic goal of this project could potentially be to assemble a working unit that performs the same task, but put together with less expensive parts. Furthermore, the simplicity of our design could lend itself to easier maintenance for the intended users. With the design constraints of small-scale, low-maintenance, and power efficiency in mind, we decided to further investigate vapor compression desalination (VCD).
Theory

Mechanical Vapor Compression Desalination (Distillation)

Mechanical VCD is an energy efficient, scalable water purification system. Its simple design and low operation temperature allows for scaling with minimal heat loss to the environment. The process contains three major components: the preheater, the evaporator, and the compressor. The most critical component of the system is the compressor - compressing the steam results in a superheated vapor, which is then forced through tubes in the evaporator where the heat is recycled and creates more steam within the system. This results in more water per unit energy versus other water purification systems.

![Theoretical Design of an MVC Desalination System](image)

Figure 1: Theoretical Design of an MVC Desalination System

Small scale, low-cost construction and maintenance

Mechanical VCD has already been proven to work in small scales, and has been field tested by humanitarian engineers as the Slingshot water purification system[3]. This system, which this project hopes to emulate, is the size of a dormitory refrigerator, and can produce distilled water from nearly any source, including seawater. This process produces water 5 to 10 times more cost effectively than multiple effect distillation, and 25-40 times more cost effective than single stage-distillation. Using the assumption that each kilowatt-hour of energy costs 10 cents[4]:

<table>
<thead>
<tr>
<th>System</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Vapor Compression (MVC)</td>
<td>0.5 cents / gallon</td>
</tr>
<tr>
<td>Multiple-effect Distillation</td>
<td>7.5 cents / gallon</td>
</tr>
<tr>
<td>Single Stage Distillation</td>
<td>33 cents / gallon</td>
</tr>
</tbody>
</table>

Table A: Relative Costs of Distillation Systems
Description of Process

Before any calculations were performed, several key assumptions were made:

- System is at Steady State
- Negligible energy loss
- Brine Temperature ($T_b$) = Distillate Temperature ($T_d$)
- Feed salinity ($X_f$) = constant
- All heat capacities ($C_{p,i}$) are known for each stream
- Latent heats of vaporization ($\lambda_i$) are known for brine and distillate stream
- $T_{cw}$ (feed seawater temperature before heating) is known

The feed seawater (with a salinity of $X_f$) enters the evaporator at a flow rate of $M_f$ and a temperature of $T_f$, after which it is sprayed over horizontal tubes (which enhances heat transfer). The system has two exit streams - the distillate stream ($M_d$) and the brine stream ($M_b$). The overall mass balance can be described as:

$$M_f = M_d + M_b$$

It is assumed that all of the salt in the system exits in the brine feed. Therefore, a salt balance on the overall system can be written as:

$$M_f X_f = M_b X_b$$

where $X_i$ is the salinity of stream $i$.

Figure 1. Model of Desalination Unit
The temperature of the seawater increases from $T_{cw}$ to $T_f$, using the exit streams to heat up the seawater through preheaters. It is then sent to the evaporator, where the water evaporates into the vapor stream with a latent heat of vaporization $\lambda_b$. The brine, or remainder salt and water, is discarded as waste. The vapor stream (specific heat of $C_{pv}$), with a flow rate of $M_d$ and temperature of $T_b$, is then transferred to the compressor. Upon compression, the temperature of the vapor then increases by $\Delta T_{comp}$. The vapor is fed to the tubing, where it loses energy as heat and its temperature drops to $T_d$ as a liquid. At this point, condensation takes place, and the resulting latent heat ($\lambda_d$) is transferred to the brine. The temperature difference $\Delta T_{comp}$ affects compressor power consumption and is determined by feed seawater temperature. All of these variables can be equated by the following formulas, derived in *Mechanical Vapor Compression Fundamentals*, Chapter 3:

$$T_0 = (T_{cw} - T_f) + (X_f / X_b) T_b + ((X_b - X_f)/X_b) T_d$$

$$T_f = ((X_b - X_p)/X_b) ((\lambda_b - \lambda_d)/C_p - (C_{pv} / C_p)(T_s - T_d)) + T_b$$

From these equations, the feed temperature, as well as the overall outlet temperature of the system, can be calculated.

Next, the heat transfer area for the evaporator and two preheaters must be calculated. For the evaporator, the heat transfer formula can be calculated using correlations from the *Mechanical Vapor Compression Fundamentals* textbook, appendix C. The evaporator heat transfer area can be expressed as:

$$A_e = \frac{M_d \lambda_b + M_f C_p (T_b - T_f)}{U_e (T_d - T_b)}$$

where $U_e$ is the overall heat transfer coefficient.

The heat transfer areas for the two preheaters are obtained in a similar manner; however the overall heat transfer coefficient is replaced by the driving force, LMTD.

$$A_d = \frac{M_d C_p (T_d - T_o)}{U_d (LMTD)_{d}}$$

$$A_b = \frac{M_b C_p (T_b - T_o)}{U_b (LMTD)_{b}}$$

Work, or the amount of energy required, can be calculated using the following equation:

$$W = \frac{\gamma}{\eta (\gamma - 1)} P_v v \left( \left( \frac{P_s}{P_v} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right)$$

where $W$ is the specific power consumption in kW/hr/m$^3$, $P$ is the pressure, $v$ is the specific volume, $\eta$ is the compressor efficiency, and $\gamma$ is the isentropic efficiency. It should be noted that $P_v$ is equal to the vapor pressure of the formed vapor at $T_o$ and the outlet pressure ($P_s$) is equal to the compressed vapor pressure at $T_v$. 
Methodology

The research paper *Design of Single-effect Mechanical Vapor Compression* by Hisham Ettouney of Kuwait University gives insight to the idea of desalination through vapor compression\(^5\). A general model of the system can be seen in Figure 1, which was obtained from the research paper and provides a great visual example of the desalination process. This process is very energy efficient because the excess energy that would normally be lost as heat through the product and rejected brine is used to preheat the intake seawater, thus the main energy consumption would be through the compressor. Further understanding of this topic can also be drawn from the textbook "Fundamentals of Salt Water Desalination," which gives initial mathematical models to work with in MATLAB as well as Aspen\(^4\). The research paper and the textbook essentially provided a more detailed outline of the idea at hand, which needed to be slightly modified in order to accommodate for simplicity as seen in the simpler Aspen design below.

The first Aspen design as seen in Figure 2 includes the rejected brine feed preheater and product feed preheater, but those two elements along with a recycle stream create a very complicated system, and can be removed for simplification of this prototype. Figure 3 more accurately represents the prototype that this project is attempting to replicate because it does not include the more complicated aspects of a recycle stream or the two preheaters. Aspen is a very powerful simulation software that can predict the feasibility of a system and helped inform our decision to not include the preheaters or recycle stream in the prototype.

![Figure 2. Aspen model with preheaters](image-url)
The project was awarded money from Triton Engineering Student Council (TESC) to begin prototyping. This money thus far has been used to buy a compressor, which is one of the most pivotal parts of the design. Other parts of the prototype are currently being discussed with Dr. Rick Martin, the President and Principal Engineer of Martin Thermal Engineering, who has been giving advice on the project. Some of his most valuable input has been about temperature and pressure safety. The prototype would be running at around 100 °C along with varying pressures due to the liquid water being converted to water vapor. In order to ensure a safe prototype, temperature and pressure ratings were researched for PVC piping. After consulting with Dr. Martin, it was decided to forgo the original prototype because it exceeded the desired pressures and temperatures to assure safety. According to Dr. Martin, the best possible idea to overcome the safety issues of high heat and pressure in the PVC piping would be to create an experiment centered on the evaporation aspect, which focuses on how high of a distillate yield can be achieved with evaporation at atmospheric pressure and temperatures below the boiling point of the vapor compression desalination process. Proving that evaporation can occur at safe temperatures and pressures will ensure that this process is feasible. After this phase of the project, preheaters and a compressor can be added onto the evaporation process in iterations that result in a safe and functional vapor compression desalination prototype.
Discussion of Results

MATLAB Modeling of Theory

A MATLAB model was utilized to compare different variables and find ideal operating parameters. Figure 4 displays the relationship between compressor work and the brine temperature with a change in compressor temperature of 2°C. Based on the slope and inflection of the graph, the amount of work does not significantly decrease until about 70°C, but for safety reasons, the operating temperature will most likely not surpass 65°C.

![Figure 4: Vapor compressor’s work versus brine temperature](image)

Figure 5 models the compressor work needed for the change in compressor temperature while the evaporated vapor temperature is at 60°C. The relationship between work and the temperature change appears linear for this range.

![Figure 5: Compressor work versus vapor temperature change at constant brine temperature.](image)
Figure 6 models the relationship between the necessary evaporator area and the compressor temperature output at an initial temperature of 60°C. With a larger change in compressor temperature, a smaller evaporator area is needed.

![Evaporator Area vs. Delta T<sub>comp</sub> (T<sub>p</sub> = 60°C)](image)

**Figure 6:** Evaporator area compared to the change in $\Delta T_{\text{comp}}$

Figure 7 shows the relationship between the evaporator area and the amount of distillate flow. As expected, there is a positive relationship between larger area for heat transfer and the amount of distillate formed via evaporation.

![Evaporator Area vs. Distillate Flow](image)

**Figure 7:** Evaporator area compared to the distillate flow
Figure 8 shows the relationship between compressor work per unit volume and the distillate flow rate. Since the compressor work is per unit volume the energy per unit volume will not increase. As total volume increases, the amount of work will increase.

Aspen modelling software was used as a secondary method to help validate the results achieved in the primary model executed in MATLAB. Using the simplified Aspen model from Figure 3, values for the compressor work and the split fraction between desired product (PRODH) and rejected brine (LIQ) were obtained (note: Stream S6 represents the heat transfer between the compressed vapor and feed; it contains no material). This provided an estimate for the temperature/pressure conditions along with compressor power required to obtain the desired yield of distillate for a given saltwater feed.

Assuming a desired split fraction of 0.5 (half of the feed flows into the product), the required operating conditions in table B were obtained:

<table>
<thead>
<tr>
<th></th>
<th>BRINE</th>
<th>COMPVAP</th>
<th>FEED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature, C</td>
<td>61.1</td>
<td>80.5</td>
<td>60</td>
</tr>
<tr>
<td>Pressure, bar</td>
<td>0.199</td>
<td>0.25</td>
<td>0.198</td>
</tr>
<tr>
<td>Vapor Frac</td>
<td>0.495</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Table B: Aspen Stream Results Summary for Simplified Process (Fig. 3)
At the evaporation stage, the temperature is 61.1°C and the pressure is 0.199 bar. Unfortunately, a very low pressure is required to get a reasonable split fraction if the temperature is kept around 60°C. Higher temperatures were not desirable because of risks to personal safety and the difficulties in achieving high feed temperatures. Additionally, creating pressures of ~0.2 bar are not desirable because this also presents engineering difficulties and risk to safety by implosion.

If the pressure was increased to a more achievable level like 1 bar, virtually no distillate would form (vapor fraction = 0), unless the temperature was significantly increased to 100°C. It was found that vapor did not form unless a saturation pressure and temperature were reached which closely resembles the Antoine’s equation plot for pure water in Figure 9. Essentially, Aspen predicted very little vapor formation unless the process ran at the boiling point. These operating conditions would be infeasible at this project’s early stages of testing.

![Figure 9: Saturation Temperature and Pressure for Pure Water](image)

In conclusion, there was no safe and feasible operating conditions that resulted in the desirable formation of distillate through the use of our Aspen simulation. We believe that desirable distillate yields could be achieved through evaporation below the boiling point, especially when the inlet water is sprayed as a fine mist into the evaporator. Unfortunately, this added complexity to the process could not be incorporated into the Aspen simulation.
Proposed Test

To investigate the effectiveness of evaporation at safe conditions below the boiling point, the following test is proposed. Figure 10 shows a diagram of the setup to be constructed from galvanized sheet metal ducts. The side branch is connected to a hair dryer while the top and bottom extensions have tubing outlets for the liquid and vapor streams. A mist of hot water will be sprayed in from the top. The bottom outlet will form a P-trap to maintain internal pressure of 0.5-1 inches from the hair dryer. The vapor stream tubing outlet on top will lead into an ice bath condenser and then into a collection vessel.

![Diagram of the setup](image)

Figure 10: Setup for proposed evaporation rate test

The goal will be to spray warm/hot water down through the warm/hot air and get as much evaporation as possible. Once the water from both streams are collected, they can be quantified to determine yield. Temperature and flow rates can be varied to determine their effects on rate of evaporation. This provides proof of concept without much hazardous conditions. Caution will be taken with the electrical hazards from the water and hair dryer. Other hazards include risk to scald or burn injuries from water or air.
**Budget**

The described test will require a revised budget from the original one presented in the TESC proposal.

Below is a list of materials that will be required to run the test:

<table>
<thead>
<tr>
<th>Component</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galvanized Exhaust Duct</td>
<td>$12.86</td>
</tr>
<tr>
<td>Galvanized extension</td>
<td>$43.74</td>
</tr>
<tr>
<td>High Temperature Duct Tape</td>
<td>$9.99</td>
</tr>
<tr>
<td>Galvanized caps</td>
<td>$8.98</td>
</tr>
<tr>
<td>Hair Dryer (donated)</td>
<td>$0.00</td>
</tr>
<tr>
<td>Bulkhead fitting</td>
<td>$20.30</td>
</tr>
<tr>
<td>Nozzles</td>
<td>$13.61</td>
</tr>
<tr>
<td>Vinyl Tubing</td>
<td>$10.00</td>
</tr>
<tr>
<td>Bucket</td>
<td>$2.97</td>
</tr>
<tr>
<td>Hose-to-Mister fitting</td>
<td>$17.97</td>
</tr>
<tr>
<td>Teflon Tape</td>
<td>$1.69</td>
</tr>
<tr>
<td>Mist Eliminator (Subsidized)</td>
<td>$70.00</td>
</tr>
<tr>
<td>Total:</td>
<td>$212.11</td>
</tr>
<tr>
<td>Including Tax:</td>
<td>$229.08</td>
</tr>
</tbody>
</table>

Table C: Cost of Materials

**Conclusion**

Desalination is a very important process in today's growing world, and further developing its relevant technologies is of great significance for ensuring the wellbeing of many lives around the globe. Vapor compression desalination is one method that could solve many potential problems associated with the desalination process. Our project aims to develop a semi-portable system which could provide ingestible water in a safe, efficient, and cost-effective manner, and based on our research, this goal is in fact feasible. Considering the positive impact a project like this can have with minimal upfront costs, vapor compression desalination seems a strong candidate to be chosen for the next phase of AIChE Projects. If the proposed prototype achieves acceptable evaporation rates at safe operating parameters, the process can be scaled up to use a compressor and heat exchanger to minimize energy usage, a very important step towards providing much-needed clean water to those without it around the world.
**Project Stakeholders**

VC Desalination Team

Project manager - Corey Shono

Performing organization - AIChE Projects

Project management team - VC Desal Team

Project technical advisor - Dr. Rick Martin

Sponsors - TESC, AS, Global TIES, Studypool

**References**


