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INTEGRATED INDUSTRIAL WASTEWATER REUSE BY HEAT RECOVERY

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Integrated Industrial Wastewater Reuse By Heat Recovery is the final report for the Integrated Waste Heat and Wastewater Recovery DOME for Food Processing Applications project (contract number PIR-09-004) conducted by Gas Technology Institute. The information from this project contributes to Energy Research and Development Division's Industrial/Agricultural/Water End-Use Energy Efficiency Program.

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ABSTRACT

This report presents results from evaluating wastewater recovery and reuse technology that could lead to substantial water savings along with increased energy efficiency in California's food processing industry.

Wastewater recovery and reuse technologies have expanded rapidly in recent decades. A variety of technologies, primarily thermal and membrane processes have been developed for different industrial applications. This project evaluated various wastewater distillation techniques for application to the food processing industry. This project demonstrated a cost-effective and efficient technology concept that combines wastewater recovery and waste heat use.

A novel distillation technique for wastewater reuse via heat recovery was developed and experimentally evaluated. The main component of the new wastewater and waste heat recovery system is a plate heat-mass-exchange module that has been successfully used for evaporative air conditioning applications. The heat-mass-exchange module uses a multilayer design composed of parallel perforated plastic plates. These plates create an air counter flow/cross flow thermodynamic design between the air streams in dry, evaporating, and condensing channels. Wastewater is evaporated at a low temperature and condensed with atmospheric air in the heat-mass-exchange module at ambient pressure and without boiling. Waste heat is used to preheat the wastewater to increase the efficiency of the distillation process. Laboratory experiments on the new distillation unit achieved a high wastewater distillation rate of 55 percent.

This new technology significantly increases the energy efficiency of wastewater recycling and reduces electricity consumption associated with conventional wastewater recovery methods. Successful development and commercialization of the technology for food processing applications would provide substantial energy and water savings to the industry by increasing energy efficiency and reducing pumping power for process water supply. Integrating waste heat recovery with wastewater reuse also leads to reducing product costs for California food processors.

Keywords: Wastewater, waste heat, reuse, recovery, recycling, utilization, energy efficiency, distillation, heat-mass-exchange

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Introduction

Industry accounts for about one quarter of all water consumption globally and there are few industries that do not use large volumes of water (Judd and Jefferson, 2003). With approximately 50,000 industrial plants, California's industrial sector consumes almost 50 billion kilowatt hours of electricity and more than six billion therms of natural gas each year. This represents 19 percent of the state's total end-use electricity and 47 percent of the state's end-use natural gas consumption.

California's $50 billion food processing industry is an important, diverse, and dynamic sector of California's economy, and the third largest industrial energy user in the state. Over the past decades, such pressures as urbanization, regulations, higher costs for energy, water, and other resources, global competition, and limits on wastes have motivated the food processing industry to search for ways to reduce energy and water use, while maintaining product quality and increasing productivity. Even a modest increase in water and energy savings can have a significant impact on the industry.

Wastewater recovery and reuse technologies have been expanding rapidly in recent decades. The market is also driven by the falling costs of wastewater recovery, which are due to technological advances in the process. Clean water costs, produced by the wastewater recovery process, dropped considerably over the years as a result of reductions in equipment prices and power consumption, and advances in system design and operating procedures.

A variety of industrial wastewater recovery technologies, primarily thermal and membrane processes have been developed over the years for different areas and applications. The main thermal processes include:

- Atmospheric distillation
- Distillation with mechanical vapor compression
- Vacuum distillation
- Multi-stage flash distillation

The membrane processes include:

- Reverse osmosis
- Electrodialysis
- Nanofiltration

The multi-state flash distillation and reverse osmosis processes are dominate in most applications.

There are three primary and interlocking technical reasons why more water is not currently recycled:

- Available water recovery technologies are too complex and costly.
- Wastewater volumes, wastewater compositions, and recycled water quality requirements vary greatly across the industry.
- Waste heat available to recover water is limited, and buying natural gas or electricity solely to recover water is too costly.

Successful wastewater and waste heat recovery systems for the food processing industry must address these concerns. These systems should take maximum advantage of the energy in low-to-moderate temperature exhaust liquid and gas streams (between 140 degrees Fahrenheit [°F]—500°F [60—260 degrees Centigrade [°C]) to recover clean water from wastewater. Systems should also be inexpensive and flexible to provide a wide market for potential applications.

Project Purpose and Objectives

This project demonstrated a cost-effective and efficient technology concept that combines wastewater recovery and waste heat use applied to the food processing industry. The new technology would allow a significant increase in the energy efficiency of wastewater recycling and would reduce electricity consumption associated with conventional wastewater recovery methods. Successful development and demonstration of the technology for food processing applications would provide substantial energy and water savings to the industry. These savings are tied to energy efficiency increases and reducing the electricity (pumping power) required for process water supply. Integrating waste heat recovery with wastewater reuse also cuts product costs for California food processors.

Project Results

The project evaluated different distillation techniques for achieving wastewater reuse by heat recovery, including reverse osmosis, atmospheric distillation, mechanical vapor compression, vacuum distillation, and multi-stage flash distillation. A novel distillation technique for wastewater recovery by waste heat use was developed and experimentally evaluated.

The main component of the new wastewater and waste heat recovery system is a plate heat-mass-exchange module that has been successfully used for evaporative air conditioning applications. This module has a multilayer design composed of parallel perforated plastic plates that create an air counter flow/cross flow thermodynamic design between the air streams in dry, evaporating, and condensing channels. Wastewater is evaporated at a low temperature (up to 140°F [60°C]) and condensed with atmospheric air in the heat-mass-exchange module at ambient pressure and without boiling. Waste heat is used to preheat the wastewater to increase the efficiency of the distillation process.

Laboratory experiments on the distillation unit showed that it achieved a high wastewater distillation rate of 55 percent. These experiments found that the distillate production rate is essentially increased when wastewater is preheated to 140°F (60°C), and with higher air flow rates.

Project Benefits

The food processing industry in California is about 75 percent efficient in using energy use, annually consuming 600 million therms of natural gas, 3,700 million kilowatt hours of electricity, and 36,000 million gallons of clean water. Many industrial facilities have access to low-level waste-heat streams (e.g., exhaust gases and hot liquids) as well as wastewater streams from which clean water can be reclaimed for reuse. This new technology is able to recover 20 percent of the available waste heat and reclaim wastewater.

Calculations show that water reclamation is limited by the amount of waste heat available. Using conservative numbers for the cost of electricity, natural gas, clean water, and water disposal, the new technology is capable of reducing clean water demand from California's food processing industry by 440 million gallons per year and energy and water cost savings of $40 million annually. This provides a one-year return of more than 100 times the full Energy Commission investment in this challenging effort.

Annual statewide energy savings resulting from using the new technology are estimated at 30 million therms of natural gas and 185 million kilowatts of electricity. These energy savings are double the potential savings from all other wastewater recovery techniques combined because the new technology's operating efficiency of 20 percent (the portion of available waste heat energy used to reclaim water) is twice the efficiency of other heat exchange methods for wastewater recovery. Adopting this new technology also helps to generate more plant efficiencies by allowing plants to continue using natural gas rather than more costly electrically heated processes. In addition, reduced demand for natural gas and electricity cuts carbon dioxide and nitrogen oxide emissions.

CHAPTER 1:
Integrated Wastewater Reuse by Heat Recovery

1.1 Scientific and Technical Baseline for Integrated Wastewater Reuse via Heat Recovery

The United States Department of Energy's (DOE) Industrial Technologies Program data shows that California consumes six percent of the total energy used by the nation's industrial sector.

It has been estimated that up to 50 percent of the energy consumed in the United States is discharged as waste heat to the environment. Typical process industries could save 20 percent of their fuel consumption through proper waste-heat recovery and management [1]

With approximately 50,000 industrial plants, California's industrial sector consumes almost 50 billion kilowatt hours (kWh) of electricity and over 6 billion therms of natural gas each year. This energy represents 19 percent of the state's total end-use electricity and 47 percent of the state's end-use natural gas consumption [2]

California's $50 billion food processing industry, a subset of the state's industrial sector, is an important, diverse, and dynamic part of California's economy, and the third largest industrial energy user in the state, consuming over 590 million therms of natural gas and over 3,700 million kWh of electricity, including the electricity used in refrigerated warehouses. Over the past decades, such pressures as urbanization, regulations, higher costs for energy, water, and other resources, global competition, and limitations on effluents have motivated the food processing industry to search for ways to reduce energy and water use, while maintaining product quality and increasing productivity.

It was reported that California's food industry spent about $6 billion for energy in 2005. Table 1 provides the estimated annual water and energy use of major food processing sectors in California.

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[1] Mull T.E. Practical Guide to Energy Management for Facility Engineers and Plant Managers, 2001, ASME Press.

[2] California Energy Commission Energy Demand Analysis Office 2006 statistics

Table 1: Estimated Annual Water and Energy Use of Major Food Processing Sectors in California (California Energy Commission Roadmap 500-2006-073)

Food Processing Sector	Water (Million Gallon)	Gas (Million Therm)	Electricity (Million KWH)
Fruits & Vegetables[1]	30,000	300-400	600-800
Dairy			
Cheese[2]	600	43	583
Milk Powder/Butter[3]	360	33	130
Meat			
Beef[4]	1200	5	88
Poultry[5]	2000	40	360
Wine[6]	2900	23	406
Rice[7]	Negligible	41	316
Refrigerated Warehouses[8]	Negligible	Negligible	1000

[1]CLFP data, 2003. Post-harvest only and does not include irrigation water.

[2]Personal communication, T. Struckmeyer, Hilmar Cheese, 2004. Does not include water and energy for production of raw milk but does include whey processing, which is an integral part of cheese making.

[3]Personal communication, J. Gomes, California Dairies, Inc., 2004

[4]Personal communication, Jim Oltjen, UC Davis, 2004 (608gal/animals slaughtered) and Cattle Buyers Weekly, Dec 2003 (# animals slaughtered), and personal communication, J. Maxey, Beef Packers, Fresno. Numbers reflect slaughtering plants only.

[5]Personal communication, Bill Mattis, California Poultry Federation, 2004.

[6]Alcohol, Tobacco, Tax and Trade Business, Dec. 2001 (574 M gal wine produced), and Wine Institute report (5 gal water per gal wine), does not include water inputs to production of grapes.

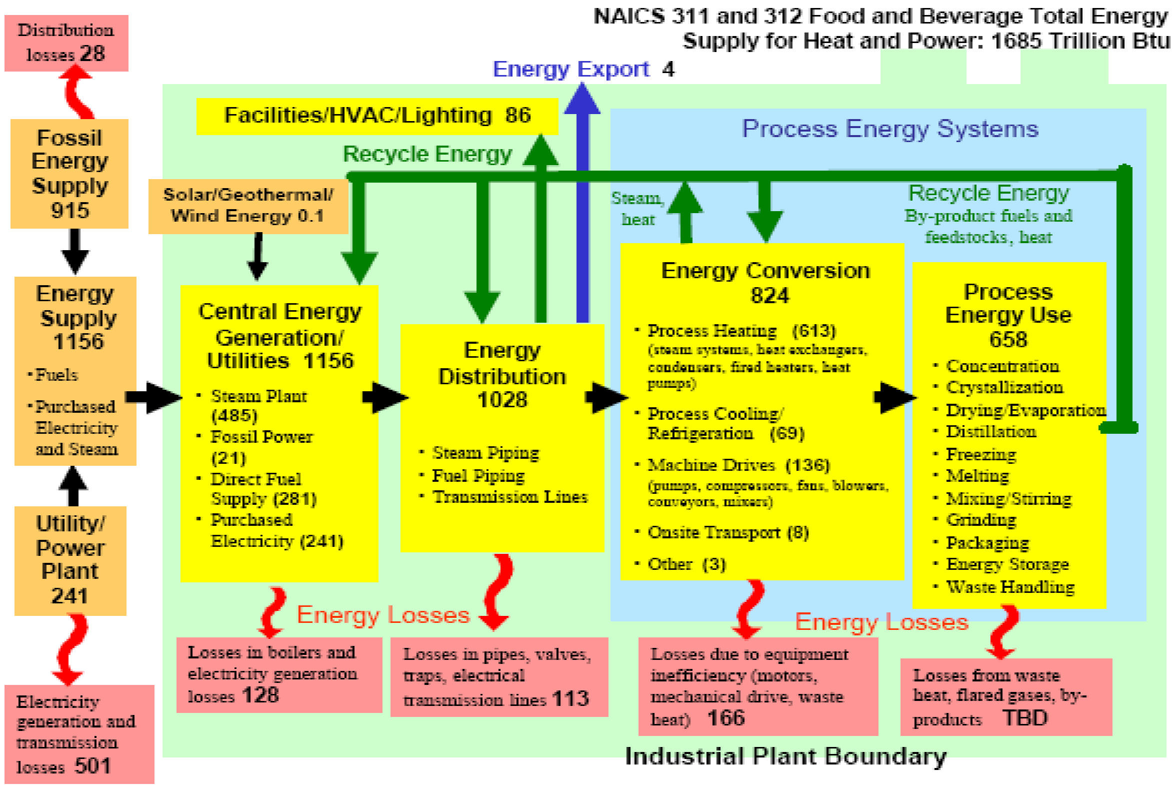
[7]Personal communication, J. Mannapperuma, 2003 (drying only).

[8]Personal communication, International Association of Refrigerated Warehouses, and World Food Logistics Organization, 2004.

As a large consumer of water and energy, the food processing industry naturally generates large amounts of waste heat and wastewater that significantly reduces the energy efficiency of its operations and increases costs. Unfortunately, few options are available in today's commercial market for waste heat and wastewater recovery systems that could improve energy efficiency and reduce product costs within the food processing industry.

Figure 1, illustrates the total energy supply for the UnitedStates (U.S.) food and beverage industry.

Figure 1: Total Energy Supply for the U.S. Food and Beverage Industry



Source: Energy Use, Loss and Opportunity Analysis, Energetics Inc. for U.S. DOE, December 2004.

The applicability of a particular waste heat recovery approach depends strictly on the particular food processing site, and can be optimized per specific product type and production rate. In the dairy industry, for example, pasteurization is already highly efficient (up to 95 percent) in terms of heat recovery. Sterilization, however, is more energy-intensive, with bottle sterilization consuming up to 0.5 MM Btu/ton.

The majority of plant sites in the food processing sector share a number of common components which all have a great potential for waste heat recovery, such as boilers, air compressors, prime movers, and refrigeration facilities. There are many additional types of plant equipment from which waste heat can also be available for cost-effective energy integration and beneficial use.

Off-the-shelf equipment for waste heat recovery in the food processing industry is available but extremely limited, and is not universally applicable to a wide spectrum of waste streams in multiple services. The majority of the available waste heat recovery technologies involve heat exchangers, either directly or indirectly, but there are others devices such as heat pumps and systems that can use waste heat for cooling purposes.

For specific applications in waste heat recovery, heat exchangers may be referred to as:

- Recuperators
- Regenerators
- Waste-heat boilers or steam generators
- Condensers
- Economizers
- Feed water heaters

There are many types of heat exchange equipment that can be used for low temperature waste heat recovery and utilizations. Some of the most popular types are:

- Shell and tube
- Gasketed plate
- Double pipe
- Heat pipe or thermosyphon
- Spiral
- Coiled
- Tubular
- Rotary regenerator

Among the types of equipment listed above, a heat pipe/thermosyphon can transfer up to 100 times more thermal energy than a copper rod of the same size. A heat recovery system built on a heat pipe basis is capable of operating at temperatures up to 500°F—600°F (260°C—315°C). Because only a small temperature difference is required for operation, such a system could reach a heat recovery capability as high as 60—80 percent [3]

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[3] The applicability of a particular waste heat recovery approach depends strictly on the particular food processing site, and can be optimized per specific product type and production rate. In the dairy industry, for example, pasteurization is already highly efficient (up to 95 percent) in terms of heat recovery. Sterilization, however, is more energy-intensive, with bottle sterilization consuming up to 0.5 MM Btu/ton.

The majority of plant sites in the food processing sector share a number of common components which all have a great potential for waste heat recovery, such as boilers, air compressors, prime movers, and refrigeration facilities. There are many additional types of plant equipment from which waste heat can also be available for cost-effective energy integration and beneficial use. Off-the-shelf equipment for waste heat recovery in the food processing industry is available but extremely limited, and is not universally applicable to a wide spectrum of waste streams in multiple services. The majority of the

One of the potential downsides of using heat exchangers in recovery systems is the tendency for some waste heat streams to foul heat transfer surfaces. Proteins, sugars, salts, and other waste stream constituents are readily deposited on the working surfaces of the heat exchangers, thereby reducing the heat transfer efficiency of the entire system. In some food processing applications, pre-treatment of the waste stream would be necessary to minimize the rate of fouling. There are several heat exchanger cleaning techniques on the market; however, these involve additional resources and in some cases require maintenance shut downs during operation.

Because in most cases the liquid and gaseous exhaust gas streams discharged from food processing facilities are not at high temperatures and do not carry high-grade heat, extraction of work directly from such sources is usually impractical. Depending on processing site needs, a heat pump may be used to raise the temperature of a waste source so that the waste heat can be transferred to a process or another stream at a higher temperature.

Finally, thermal energy storage (TES) approaches have been practiced for many decades and currently these processes are gaining popularity in some food processing facilities. TES has a great potential for being integrated with many others techniques, including solar-assist for heating and ice-assist for refrigerating of food products.

Another way to improve the operating efficiency of the food processing industry and save California water resources is through wastewater recycling and reuse, which has gained much attention during recent years. Wastewater must be properly treated in order to bring it to the required water quality specification prior to its reuse.

Water has always been an important element in food processing, so mitigation of water use through wastewater recycling could positively affect the California food processing market and reduce electricity consumption by significantly cutting pumping power and providing water treatment optimization. With pollution problems and the scarcity of clean water supplies, the recycling of water from wastewater streams has become a common practice in most food processing industries around the globe.

Selection of the right water recycling technology very much depends on the nature and composition of the wastewater, as well as the degree of water purity required for its final utilization. Basically, wastewater treatment technologies may be divided into four categories[4]

- Preliminary treatment
- Primary treatment
- Secondary treatment

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available waste heat recovery technologies involve heat exchangers, either directly or indirectly, but there are others devices such as heat pumps and systems that can use waste heat for cooling purposes.

[4] Handbook of water and energy management in food processing. Ed. By J.Klemes, R.Smith, J.Kim, CRC Press, 2008, 1029p.

- Advanced and specific treatment

Selection of an optimum type of water recycling technology is contingent on information regarding the reclaimed water application and the purity required for that application. Generally, the utilization of water in food processing plants may be divided into the following categories:

- Cooling — cooling towers
- Heating — boilers, heat exchangers
- Process — ingredient of the product
- Potable — offices
- Washing — equipment, floor
- Rinsing — raw food, final product
- Sanitation — general cleaning, toilet flushing
- Fire fighting
- Transport medium

Any wastewater treatment process should not involve too many operating units as this would increase operational and maintenance costs. The best treatment method would be a combination of physical, chemical, and biological processes able to reduce the contaminants to levels below the regulatory limits. The best treatment system would be one that is effective in removing constituents, low in cost, environmentally friendly, and which requires minimal supervision.

Prior to deciding on the type of treatment method to be employed, an analysis of the wastewater constituents is necessary. Generally, constituents present in wastewater streams may be categorized as conventional, non-conventional, and emerging[5]. Conventional constituents include biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total organic carbon (TOC), nutrients, and microbes, and they may be removed using conventional treatment methods such as clarification, activated sludge system, filtration, nutrient removal, and disinfection. Non-conventional constituents include volatile organic compounds (VOCs), metals, surfactants, organics, and total dissolved solids, which may be removed by physical or mechanical means, followed by biological treatment, nutrient removal, and disinfection. Emerging constituents include new pollutants comprising organics and inorganics which come from modern drugs, pharmaceuticals, industrial materials, and household products. These emerging constituents may be removed via secondary treatment, followed by advanced treatment methods such as membrane separation processes and reverse osmosis, plus a final disinfection step.

[5] Wastewater Engineering, G. Tchobanaglous, F.Burton, H.Stensel, 2003, McGraw-Hill.

Energy-efficient membrane technologies have been used to replace or combine with energy-intensive unit operations of distillation and evaporation to concentrate dilute solutions in different food processing facilities. Membrane treatment has also been used to recover solid by-products from wastewater, such as sugars from fruit and vegetable processing wastewater. Microfiltration and ultra-filtration have been used to remove bacteria and spores from liquid foods and special wastewater streams. Membrane techniques cannot, however, process large volumes of wastewater and cannot use waste heat.

Some of the wastewater streams contain heat that is lost from primary or ancillary processes, so it also can be utilized along with the gaseous and solid waste heat carriers for the energy benefit of the food processing facility.

Heat recovery is a viable option in the food processing industry. Its major attractiveness is enhanced with accompanying water recovery and/or effluent reduction.

Table 2 breaks down electricity and natural gas use by food processing sectors into energy-using systems. The values and percentages are estimates, as there is a wide range in the types of plants within each category. For example, within the fruit and vegetable sector, tomato processing dominates operations in thermal processing. In contrast, pumping and refrigeration processes are the dominant users of energy in dairy and wine processing.

Table 2: Estimated Energy Distribution within Major California Food Processing Sectors

Food Processing Sector	Pumps Motors Fans Conveyors Lighting	Pasteurization Heating Systems Evaporators Dryers Sterilization	Cooling Freezing Refrigeration	Sanitation Clean in Place
Fruits & Vegetables	10	70	15	5
Dairy				
Cheese	35	40	20	5
Milk Powder	25	55	15	5
Meat				
Beef	30	20	40	10
Poultry	30	20	40	10
Wine	50		40	10
Rice (drying)	20	80		
Refrigerated				
Warehouses	15		80	5

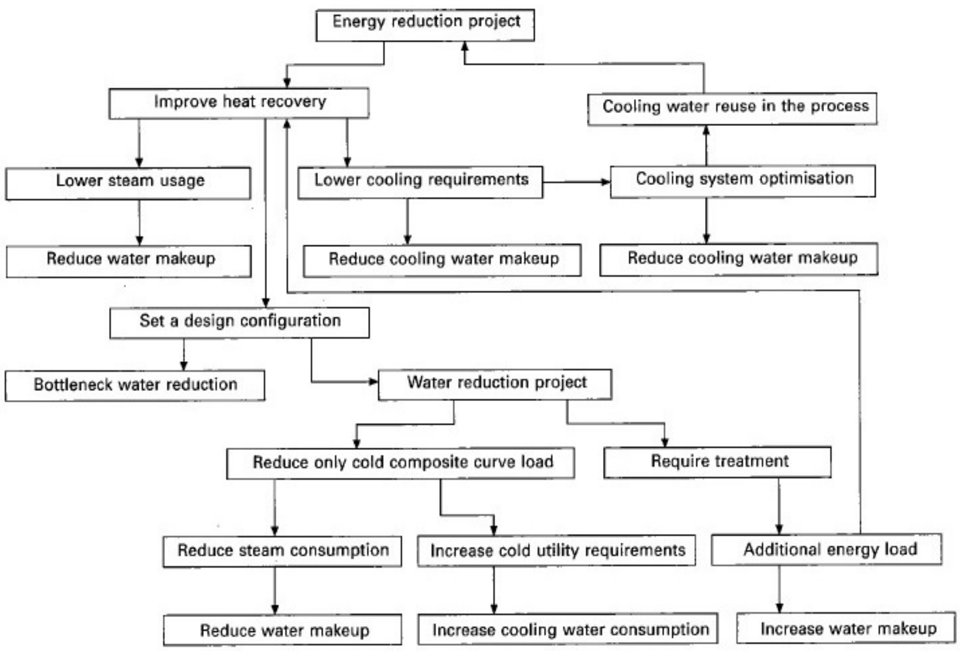
Source: CEC Roadmap 500-2006-073

Various food processors implement in-depth analyses of the implications of water projects for energy systems, and vice versa, within the context of an integrated energy and water usage assessment. A few of the possible water/energy effects are presented in Figure 2.

Waste heat and wastewater streams are diversified across the food processing industry so there is no common data available to allow proper estimating of global impacts from implementing the technological innovation. Instead, the potential energy and water savings from use of the new technology have been calculated based on application across the total energy rather than in comparison with other specific waste heat recovery technologies.

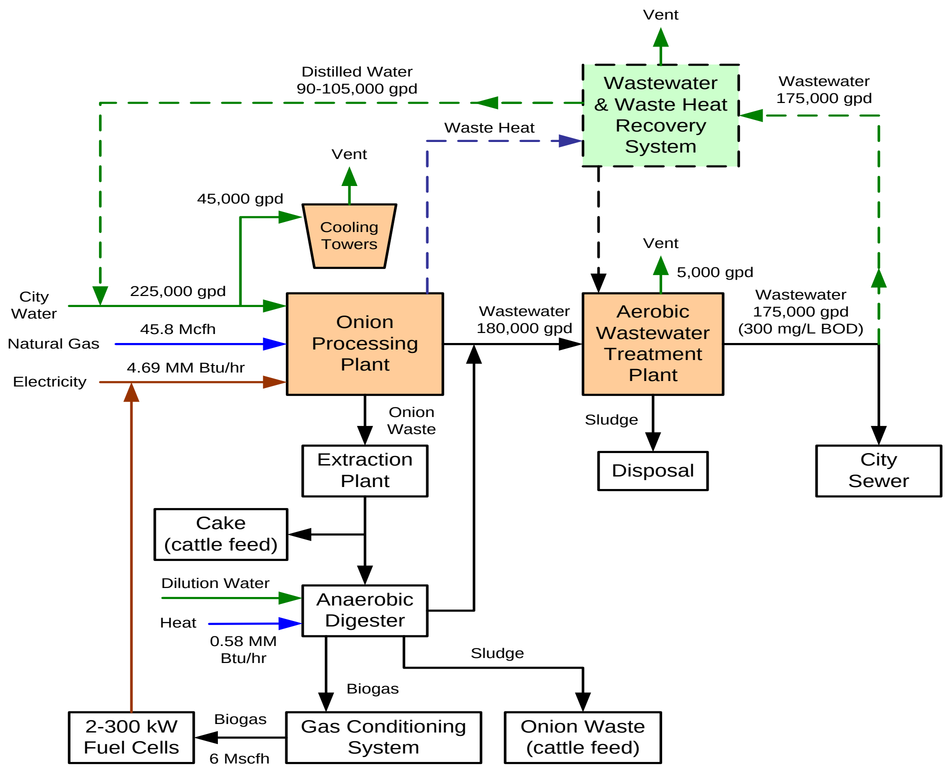
For this project, a selected food processing plant was used to evaluate the application of a wastewater and waste heat recovery system for water reuse purposes (Figure 3). The light green block in the figure represents a prospective wastewater and waste heat recovery system. The plant uses 225,000 gallons per day (GPD) of city water total; 175,000 gallons of wastewater per minute (GPM) are discharged to the city sewer. It is obvious that any wastewater that could be cost-effectively returned back to the process would significantly reduce operational costs and save the water supply.

Figure 2: Effects of Integrated Energy and Water Usage Assessment



Source: Handbook of water and energy management in food processing. Ed. By J.Klemes, R.Smith, J.Kim, CRC Press, 2008, 1029p

Figure 3: Wastewater and Waste Heat Recovery Process for a Fresh Onion Processing Plant: Dashed Lines — Prospective Wastewater and Waste Heat Recovery System



Wastewater quality is one of the main factors that should be taken into account when a wastewater and waste heat recovery system is developed and designed. The project chose the wastewater effluent quality for an onion processing plant as a base for evaluation and development (Appendix B).

Existing thermal (distillation) and membrane systems for wastewater and waste heat recovery were considered to be appropriate systems for contrastive analysis for the study. Distillation is the process of purifying a liquid by successive evaporation and condensation. Commercial membrane filtration is used worldwide in the chemical and biotechnology industries to concentrate streams and maintain product quality in manufacturing.

1.2 State-of-the-Art Wastewater Recovery

A variety of industrial wastewater recovery technologies, primarily thermal and membrane processes have been developed over the years for different areas and applications. The main thermal processes include atmospheric distillation, distillation with mechanical vapor compression, vacuum distillation, multi-stage flash distillation, multi-effect distillation with thermal vapor compression, etc. (Chen and Wang, 2007; Younos and Tulou, 2005). The membrane processes include reverse osmosis, electrodialysis, and nano-filtration. The multi-stage flash distillation and reverse osmosis processes dominate in most applications.

Wastewater recovery and reuse technologies have been expanding rapidly in recent decades. The market is also driven by the falling costs of wastewater recovery, which are due to technological advances in the process. The costs of clean water produced by the wastewater recovery process dropped considerably over the years as a result of reductions in the price of equipment, reductions in power consumption, and advances in system design and operating procedures.

In this project, the features and costs of state-of-the art and innovative wastewater recovery/reuse technologies were estimated and compared. The project discusses a new technology that would significantly increase the energy efficiency of wastewater recycling and would reduce electricity consumption associated with conventional wastewater recovery methods. The successful development and demonstration of the new technology for food processing applications would provide substantial energy and water savings to the industry. These savings are tied to an increase in energy efficiency and a reduction in pumping power needed for process water supply. The ability to integrate waste heat recovery with wastewater reuse also leads to product cost reduction opportunities for California producers.

The major pros and cons of the most popular wastewater recovery and distillation techniques were considered in the framework of this research and development effort.

1.2.1 Reverse Osmosis (RO)

Osmosis is the movement of a solvent through a semi-permeable membrane into a solution of higher solute concentration. This action tends to equalize the concentrations of solute on the two sides of the membrane. The RO process uses pressure as the driving force to overcome the osmotic pressure of the salt solution. It is a relatively new process that was commercialized in the 1970's. It is currently the most widely used method for desalination in the United States. A typical RO plant consists of four major systems: pretreatment system, high-pressure pumps, membrane systems, and post-treatment.

Pretreatment is very important because membrane surfaces need to remain clean. All suspended solids and microbial bacterial must be removed. Processes include coagulation/flocculation/sedimentation. High-pressure pumps supply pressure from about 150 pounds per square inch (psi) for brackish water to 800—1,000 psi for seawater if it is used for desalination. Membrane materials consist of cellulose acetate or of other composite polymers. Pressure applied to feed water causes clean water to permeate across the membrane into a central collecting tube. Salts are rejected from the membrane and separation is complete. Post-treatment consists of stabilizing the water by adjusting the pH and disinfection.

1.2.1.1 Pros

- The process operates continuously, 24 hours a day.
- New membranes have a high rate of water flow per unit area.
- There is a high overall water recovery rate and salt removal (up to 99.8 percent).
- Power consumption is low and minimal maintenance is required.

1.2.1.2 Cons

- Pesticides, herbicides, and chlorine are molecularly smaller than water and can pass through the membrane if not pretreated properly.
- Many healthy, naturally occurring minerals are removed from the water.
- A portion of the water flow that runs through the system is wasted.
- The process is slower compared to other water treatment alternatives.

1.2.2 Atmospheric Distillation by Water Boiling (AD)

Atmospheric distillation is conducted at atmospheric pressure, in contrast to vacuum distillation or pressure distillation. Distillation by boiling is probably the oldest method of water purification. Water is first heated to boiling. The water vapour rises to a condenser where cooling water lowers the temperature so the vapour is condensed and collected. Most contaminants remain behind in the liquid phase vessel.

1.2.2.1 Pros

- A simple apparatus is used.

1.2.2.2 Cons

- Organic substances with boiling points lower than 212°F (100°C) cannot be removed efficiently and can actually become concentrated in the product water.
- Investment costs are high.
- Large amounts of energy and cooling water are required.

1.2.3 Mechanical Vapor Compression (MVC)

Mechanical vapor compression is a distillation method by which a blower or compressor is used to compress, and thus increase, the pressure of the vapor produced. The vapor-compression process uses mechanical energy rather than direct heat as a source of thermal energy. Water vapor is drawn from the evaporation chamber by a compressor and is condensed in the heat exchanger. The heat of condensation is used to evaporate saline water/wastewater applied within the heat exchanger. Since the pressure increase of the vapor also generates an increase in the condensation temperature, the same vapor can serve as the heating medium for wastewater, from which the vapor was generated to begin with. If no compression was provided, the vapor would be at the same temperature as the boiling water, and no heat transfer could take place

1.2.3.1 Pros

- The operating costs are low compared to multi-stage or multi-effect flash distillation systems.
- The equipment is smaller than the multi-stage flash or multi-effect flash distillation systems.

1.2.3.2 Cons

- Maintenance requirements for compressors and heat exchangers are greater than for other systems.
- Energy consumption is high.
- Capital costs are high.

1.2.4 Vacuum Distillation (VD)

Vacuum distillation is a method of distillation whereby the pressure above the liquid mixture to be distilled is reduced to less than its vapor pressure (usually less than atmospheric pressure), causing evaporation of the most volatile liquid(s) (those with the lowest boiling points). This distillation method works on the principle that boiling occurs when the vapor pressure of a liquid exceeds the ambient pressure. Vacuum distillation is used with or without heating the solution. The principle behind the process can be illustrated by considering two barometric columns at ambient temperature, one with distilled water and one with wastewater. The head space of these two columns will be occupied by the vapors of the respective fluids at their respective vapor pressures. Suppose these head spaces are connected to one another. Since the vapor pressure of distilled water is slightly higher than that of wastewater at ambient temperature, water vapor will distill from the distilled water column into the wastewater column.

A schematic arrangement of the distillation system (Gude and Nirmalakhandan, 2009) demonstrating the above principles (Figure 4). Components of the distillation unit include an evaporation chamber, a natural draft condenser, heat exchangers, and three tall columns. These three columns serve as the wastewater column, the brine withdrawal column, and the distilled water column, each with its own constant-level holding tank (shown as WT, BT, and DWT, respectively). These holding tanks are installed at ground level while the evaporation chamber is installed atop the wastewater and brine withdrawal columns at the barometric height of about 10 meters above the free surface in the holding tanks to create a Torricelli's vacuum in the head space of the evaporation chamber. The top of the distilled water column is connected to the outlet of the condenser.

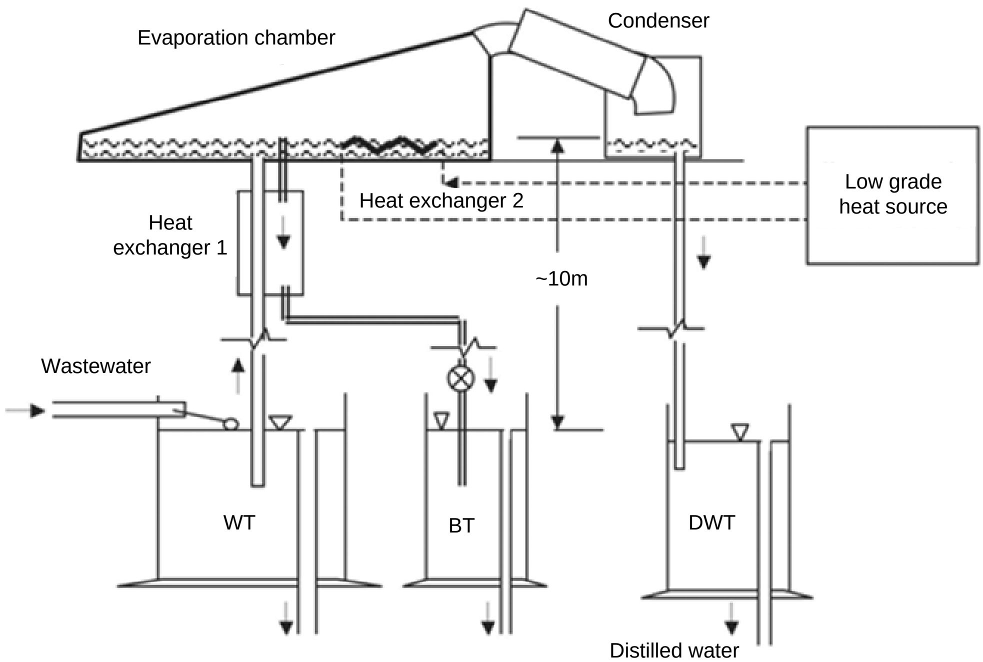
1.2.4.1 Pros

- The process enables the extraction of volatile components at lower temperatures and reduced pressures.
- The process reduces the number of equilibrium stages within separation processes.
- Merely shortens the process and can also reduce the residue build up associated with distillation.
- For many systems, the products degrade or polymerize at elevated temperature.
- The energy requirement for both heating and cooling is reduced.
- Capital costs are reduced at the expense of slightly higher operating costs.

1.2.4.2 Cons

- A vacuum pump is needed to exhaust trace amounts of non-condensed vapors and non-condensable gases to the atmosphere.

Figure 4: Vacuum Distillation with Low Grade Heat (Gude and Nirmalakhandan, 2009): WT — Wastewater Tank; BT — Brine Tank; DWT — Distilled Water Tank



Source: Gude, V.G. and Nirmalakhandan, N. Desalination at Low Temperature and Low Pressures. Desalination. 244 (2009), pp 239-247.

1.2.5 Multistage Flash (MSF) Distillation

In the MSF unit, the incoming wastewater passes through the heating stages and is heated further in the heat recovery sections of each subsequent stage. After passing through the last heat recovery section, and before entering the first stage where flash-boiling (or flashing) occurs, the wastewater is further heated in the brine heater using externally supplied steam. This raises the wastewater to its highest temperature, after which it is passed through the various stages where flashing takes place. The vapor pressure in each of these stages is controlled so that the heated brine enters each chamber at the proper temperature and pressure (each lower than the preceding stage) to cause instantaneous and violent boiling/evaporation. The distilled water is formed by condensation of the water vapor, which is collected at each stage and passed on from stage to stage in parallel with the brine. At each stage, the product water is also flash-boiled so that it can be cooled and the surplus heat recovered for preheating the wastewater.

Because of the large amount of flashing brine required in an MSF plant, a portion (50 □75 percent) of the brine from the last stage is often mixed with the incoming wastewater, recirculated through the heat recovery sections of the brine heater, and flashed again through all of the subsequent stages. A facility of this type is often referred to as a "brine recycle" plant. This mode of operation reduces the amount of water-conditioning chemicals that must be added, and can significantly affect operating costs. On the other hand, it increases the salinity of the brine at the product end of the plant, raises the boiling point, and increases the danger of corrosion and scaling in the plant. In order to maintain a proper brine density in the system, a portion of the concentrated brine from the last stage is discharged. The discharge flow rate is controlled by the brine concentration at the last stage.

1.2.5.1 Pros

- Operating costs are low when waste heat is used for the distillation process.
- The quality of the wastewater is not as important as with the reverse osmosis system technology.
- The multi-stage flash system has a high gain output ratio (i.e., the ratio of pounds of water produced to pounds of steam condensed in the brine heater).

1.2.5.2 Cons

- Operating costs are high when waste heat is not available for the distillation process.
- Rates of corrosion and scale formation are relatively high due to high operating temperatures.

1.2.6 Integrated Multi-Effect Distillation with Thermal Vapor Compression (IMED-TVC)

The IMED-TVC evaporator represents a typical MED evaporator fitted with a thermocompressor. The purpose of the thermocompression of the vapor is to take advantage of the pressure of the available steam, when this pressure is sufficient (i.e., above 2 bar), to enhance the units' performance.

The incoming steam, called motive steam, is fed into the thermocompressor through a sonic nozzle. Its expansion will allow low-pressure steam from a cell of the evaporator to be sucked out. Both steams will be mixed in the thermocompressor body. The mixture is then compressed to the pressure of the first bundle through a shock wave. The latent heat of the sucked vapor is thus recycled in the evaporator and is again available for distillation, leading to energy savings.

The performance of a thermocompressor is expressed by the mass of sucked steam (in kilograms [kg]) per kg of motive steam. This ratio is usually called w. The higher the motive steam pressure, the greater the w value. On the other hand, for a given motive steam pressure, the higher the temperature difference, the lower the value of w. Very high gain output ratios can be obtained with IMED -TVC units.

1.2.6.1 Pros

- Electrical consumption is low (less than 1.0 kWh/m3) compared to other thermal processes.

- Pre-treatment of wastewater is not needed, because the process tolerates variations in wastewater conditions.
- The process is highly reliable and simple to operate.
- Maintenance costs are low.
- The process operates 24 hours a day with minimum supervision.
- The process can be adapted to any heat source, including hot water.
- The process allows very high thermal efficiencies and savings in fuel cost.

1.2.6.2 Cons

- Scale formation can be a problem; the system must be operated at low temperatures (< 158 □F [70˚C]) and at low con

1.3 Advanced Approaches

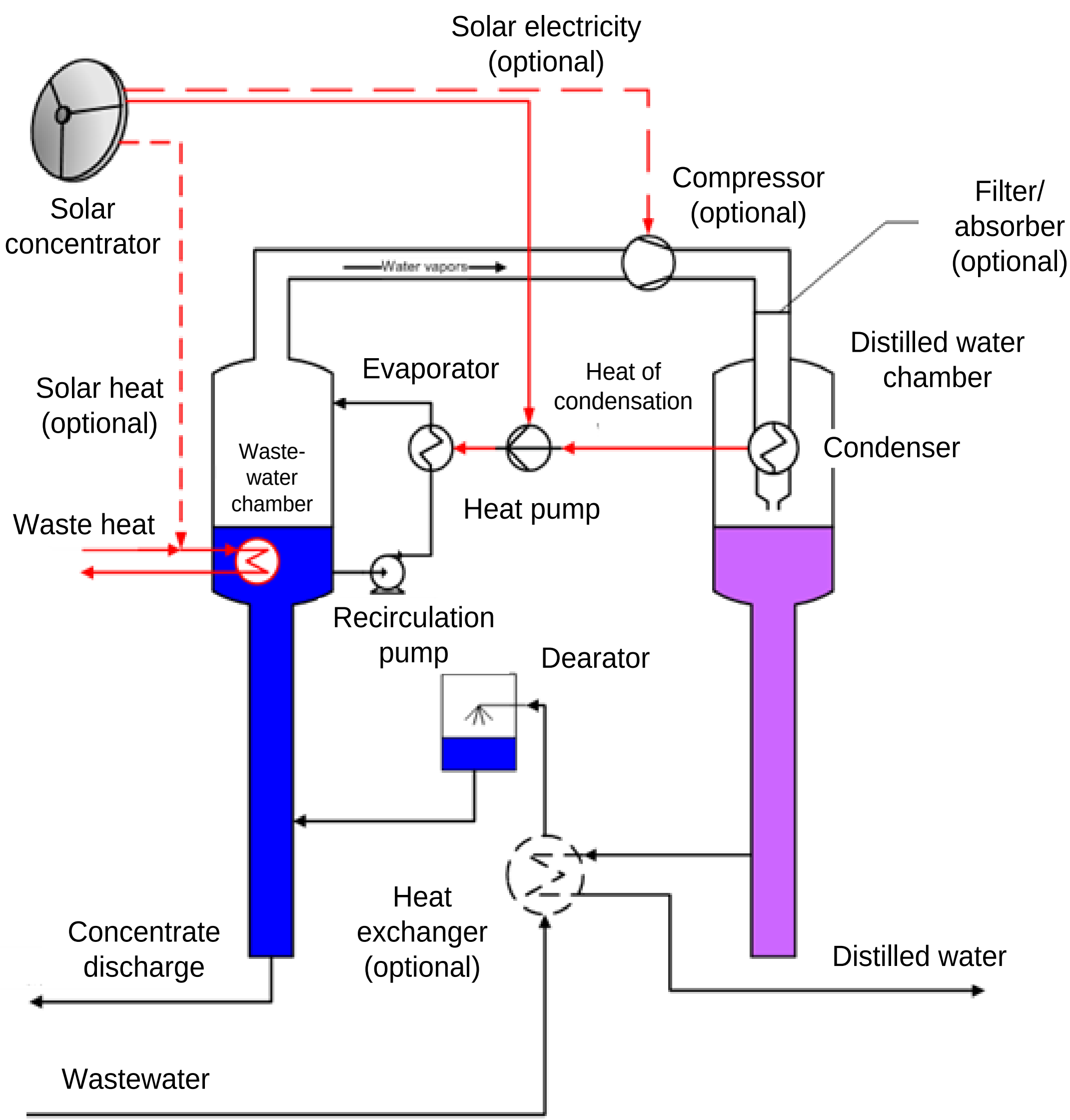
Upon comprehensive technical and economic feasibility analysis, a few advanced approaches were suggested by the project team for further consideration.

1.3.1 Vacuum Distillation with Heat Pump (VDHP)

Modification of the vacuum distillation system can make the distillation process much more efficient. One of the modified systems considered by the authors in this work is focused on distillation processes where there is a lack of heat required for distillation and, hence, there are needs for condensation heat recycle. The system uses wastewater cleanup by low-temperature vacuum distillation with waste heat and/or solar energy as a thermal source. The technology schematic is shown on Figure 5.

Wastewater and distilled water chambers are kept under vacuum formed by gravity forces on top of ~ 30-foot water columns. To maintain vacuum, preliminary de-aeration of wastewater may be necessary. Waste heat and, optionally, solar heat are used for incoming wastewater heating and heat losses compensation. Heat of condensation is recycled by compression or by absorption heat pump driven by either waste heat or solar energy, depending on the waste heat source assessment. Water vapors condense in a clean water chamber, transferring condensation heat to the colder end of the heat pump. Water vapors can optionally be passed through a filter and/or absorber for additional cleaning. Use of such a filter/absorber may create an additional pressure drop that should be compensated by an additional compressor driven by waste heat or solar energy. Hot distilled water formed in the condenser can be used for incoming wastewater preheat, if the wastewater is cold. In this process, the heat of condensation is transferred to wastewater by absorption/compression heat pump.

Figure 5: Vacuum Distillation of Wastewater With a Heat Pump For Condensation Heat Recycle



In such a way, the process demand for heat decreases, providing a higher clean water production rate. Another specific feature of the new technology is that it runs the distillation process under vacuum created by gravitation forces. Lower process pressure allows better separation of organic components found in food industry wastewater and decreases formation of carbonate depositions on heating elements. For further water purification (to drinkable/potable quality, for example), the post-process purification systems could be added to the distilled water discharge.

1.3.1.1 Pros

- Energy demand is reduced due to recycling of condensation heat.
- The production rate per unit is higher due to more intensive heat use inside the process.
- Solids deposition on heating elements is reduced due to reduced process temperature.
- Separation of organic components is higher due to reduced process temperature and pressure.
- The process is capable of using low-grade exhaust heat that currently must be vented.
- Using vacuum allows a greater temperature difference between water and exhaust waste heat, which allows a larger fraction of available heat in exhaust to be utilized.

1.3.1.1 Cons

- The process is dependent on heat loads from low-grade exhaust gases and/or solar energy.

1.3.2 Low Temperature Evaporation with Water Separation Membrane (WSM)

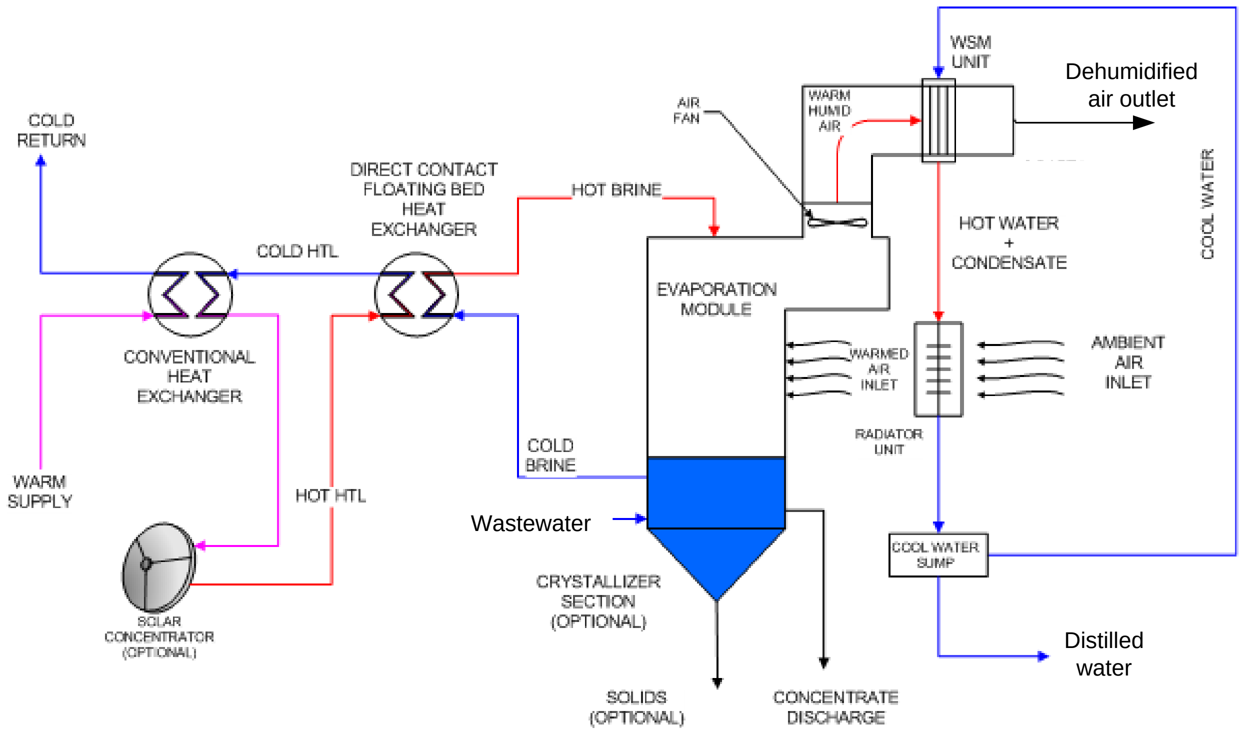
An efficient water distillation process can be realized by modifying an evaporative system such as a cooling tower and using a water separation membrane to return water condensate to a plant. The process flowchart is an air-driven low-temperature evaporative process of volumetric reduction and concentration of wastewater and production of clean water with optional crystallization of solid impurities (Figure 6). Such a system is based on patented EVRAS™ technology and concentrates wastewater, reducing the volume of liquid waste to be discharged. The system produces some amount of distilled water that can be used either directly or after additional cleanup by filters and/or membranes.

Wastewater from the bottom of the evaporation module is heated up in the direct contact floating bed (DCFB) heat exchanger, which eliminates problems associated with the fouling/scaling of heat transfer surfaces. A proprietary non-toxic heat transfer liquid (HTL) that has no solubility for scale-forming minerals is used in the DCFB heat exchanger. Hot brine partially evaporates and simultaneously cools down in a falling film evaporator.

Concentrated brine falls to the bottom of the evaporation module and, after mixing with wastewater, again goes to the DCFB heat exchanger. Water vapors from the evaporator are removed by ambient air flow induced by the fan installed upstream of the evaporator. Hot humid air from the fan exhaust goes through the WSM unit that partially condenses water vapors. Hot distilled water from the WSM unit is cooled in a radiator installed at the air inlet of the evaporation module. In this way, the heat of condensation returns to the process, decreasing external heat demand. Cooled condensed water is extracted from the cooling loop while the main part is reused to condense water vapors in the WSM unit. Solar energy can provide additional heat required for wastewater (brine) evaporation.

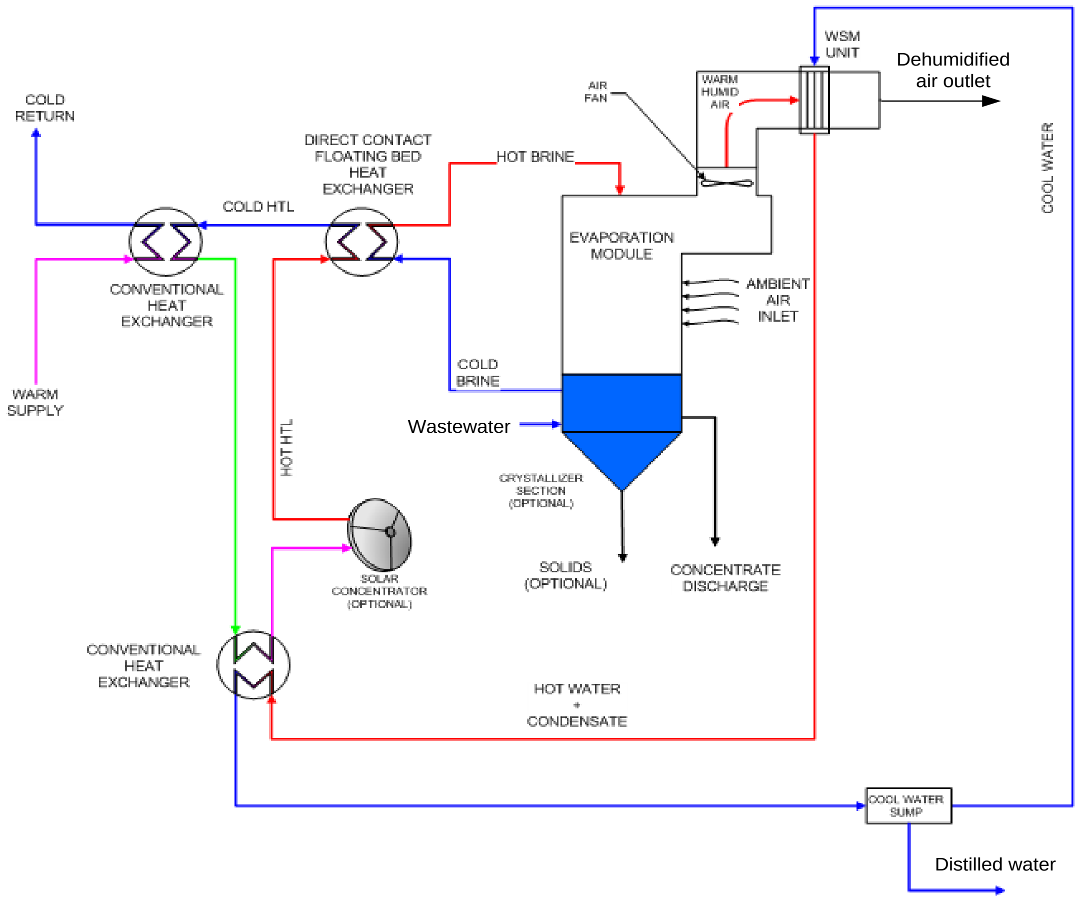
Condensation heat absorbs by cool process water supplied to the production process (e.g., washing, cleaning) that generates the wastewater to be cleaned. If the process requires potable grade water, the common water cleanup unit (e.g., filter, reverse osmosis) can be added. Dehumidified air is vented to the atmosphere. The heat required for evaporation is supplied to the DCFB heat exchanger by heating up the HTL in the conventional heat exchanger by waste heat generated in the same or an integrated production process and/or solar energy.

Figure 6: Low Temperature Evaporation With Water Separation Membrane



Condensation heat can also be recycled in the system modification (Figure 7). In this case, condensation heat absorbed in the WSM unit by distilled water is returned to the process by heating HTL in a conventional heat exchanger installed before the DCFB heat exchanger. Solar energy can also be used for additional heating of the HTL before the DCFB heat exchanger.

Figure 7: Low-Temperature Wastewater Concentrator/Cleanup Process with Water Condensation



1.3.2.1 Pros

- The process produces no scaling and fouling of heat transfer surfaces.
- The process produces no corrosion.
- The process does not require exotic construction materials.
- The process does not require excessive chemical treatment.
- Waste heat is partially returned into the production process.
- Condensation heat is regenerated.
- Distilled water demand is decreased.
- The process runs under atmospheric pressure, with no need for pressurized/vacuum equipment.

1.3.2.2 Cons

- The process requires accurate integration of the EVRAS™ system with the WMS.
- WMS technology must be upgraded for desiccant use.

1.4 Technologies Comparison

Reverse osmosis, atmospheric distillation, mechanical vapor compression, vacuum distillation, multistage flash distillation, and multi-effect distillation with thermal vapor compression technologies were all analyzed and compared against two advanced techniques (vacuum distillation with heat pump [VDHP], and low temperature evaporation with WSM) to determine the feasibility of the new techniques for application to the food industry. The feasibility of each system was analyzed based on the following criteria (Table 3):

- Complexity
- Waste heat recovery consumption
- Distilled water quality
- Water recovery
- Costs for 175,000 GPD of wastewater processing

Waste heat consumption, electricity consumption, and fuel energy consumption were taken into account to estimate the operating costs of each system under evaluation. Current electricity and fuel prices were used in the estimations.

The VDHP, WSM/EVRAS-WSM advanced systems have lower operating costs compared to existing distillation techniques, due to use of the waste heat recovery.

Table 3: Tentative Comparison of Different Water Distillation Techniques

Technology	RO	AD	MVC	VD	MSF	MED-TVC	VDHP	EVRAS-WSM
Waste heat consumed, Btu/lb	0	0		1000	104	73	700	1200
Operating temperature, °F	50-90	212	220	130-150			130-150	90-140
Electricity consumed, kWh/m^3	1-5	0.5-1	20	1-2	3.5-4	1.5-2	1-2	1-2
Fuel energy consumed, Btu/lb	0	1000	35	0	0	0	0	0
Water quality (TDS reduced), %	95	99	99	99	99	99	99	99
Water recovery, %	40-50	70-98	95-99	70-98	70-98	70-98	70-98	60-95
Concentrate discharge, %	50-60	2-30	1-5	2-30	2-30	2-30	2-30	1-15
Cooling water required, lb/lb	0	50-60	0	50-60	0	0	15-20	12
Unit capacity, GPD, 10^3	175	175	175	175	175	175	175	175
Operating cost, \$/m^3	0.77	0.38	0.81	0.38	0.40	0.28	0.24	0.20

Reverse osmosis; AD – atmospheric distillation; MVC – mechanical vapor compression; VD – vacuum distillation; MSF – multi-stage flash distillation; MED-TVC – multi-effect distillation with thermal vapor compression; VDHP – vacuum distillation with heat pump; EVRAS WSM – evaporative reduction and solidification with water separation membrane

CHAPTER 2: Novel Indirect Dew Point Evaporation System for Wastewater Recovery and Reuse

This chapter discusses a new technology that increases the energy efficiency of wastewater recycling and reduces electricity consumption associated with conventional and advanced wastewater recovery methods. Successful development and implementation of the technology for food processing applications would provide substantial energy and water savings to the industry. These savings are tied to an increase in energy efficiency and a reduction in pumping power for process water supply. The ability to integrate waste heat recovery with wastewater reuse also leads to product cost reduction opportunities for food producers.

2.1 Indirect Dew Point Evaporation Concept

Further analysis of the distillation techniques led the research and development team to the integrated concept of wastewater recovery via waste heat utilization by using an indirect dew point evaporative concept for cooling (Gillan, 2011; Chudnovsky and Kozlov, 2013). Detailed information about the indirect dew point evaporative cooling concept can be found in Appendix C.

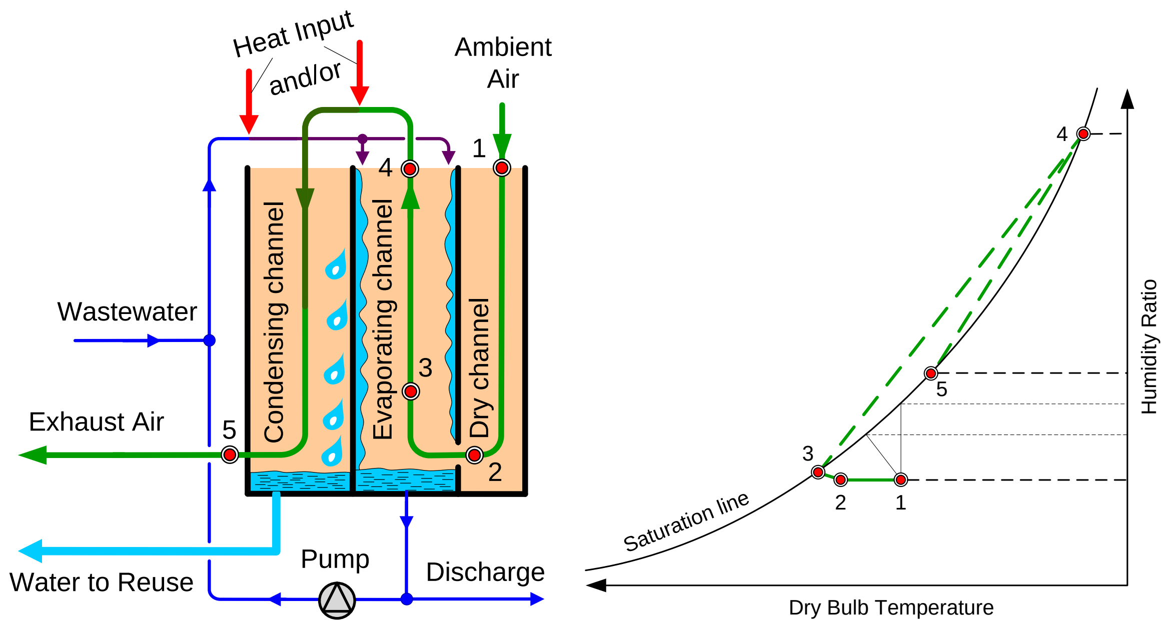
Based on the indirect dew point evaporation concept, a water distillation unit was developed. The water distillation unit consisted of three adjacent channels: dry, evaporating, and condensing channels (Figure 8). Ambient air is cooled down in the dry channel, providing a driving force for water condensation in the condensing channel. Deep cooling (below wet bulb) of ambient air in the dry channel also provides a higher evaporation rate in the evaporating channel so that more wastewater can be evaporated in the channel, resulting to more water condensation in the adjacent condensing channel.

Waste heat can be used to preheat the saturated air or wastewater to increase the efficiency of the distillation process. The higher the temperature of the saturated air or wastewater on the top of the unit, the more condensate (distilled water) can be produced. Ideally, the amount of produced condensate is equal to the mass of water evaporated in the evaporating channel. The driving force for evaporation and condensation processes is characterized by the difference between the temperature of the hot saturated air at the top of the unit and the due point temperature of the ambient air.

2.2 Distillation Unit Development and Design

To test the concept of the indirect dew-point evaporation approach with waste heat utilization support for the purposes of industrial wastewater recovery and reuse, a laboratory-scale test unit was designed and fabricated by Idalex Technologies, Inc., based on the patented HMX module that is successfully used for evaporative air conditioning applications (Gillan, 2008). Figure 9 illustrates the HMX selected for the laboratory-scale unit that was extensively evaluated at the Gas Technology Institute (GTI) test facility.

Figure 8: Indirect Dew-Point Evaporative Concept for Water Distillation



The HMX module has a multilayer design composed of parallel perforated plastic plates that create an air counter flow/cross flow thermodynamic design between the air streams in dry, evaporating, and condensing channels. A wicking fiber material is coated on one side of the sheet to act as a moisture barrier and heat transfer surface. The primary fabric characteristics are described in Attachment D.

Figure 9: Idalex's HMX Views and Overall Dimensions

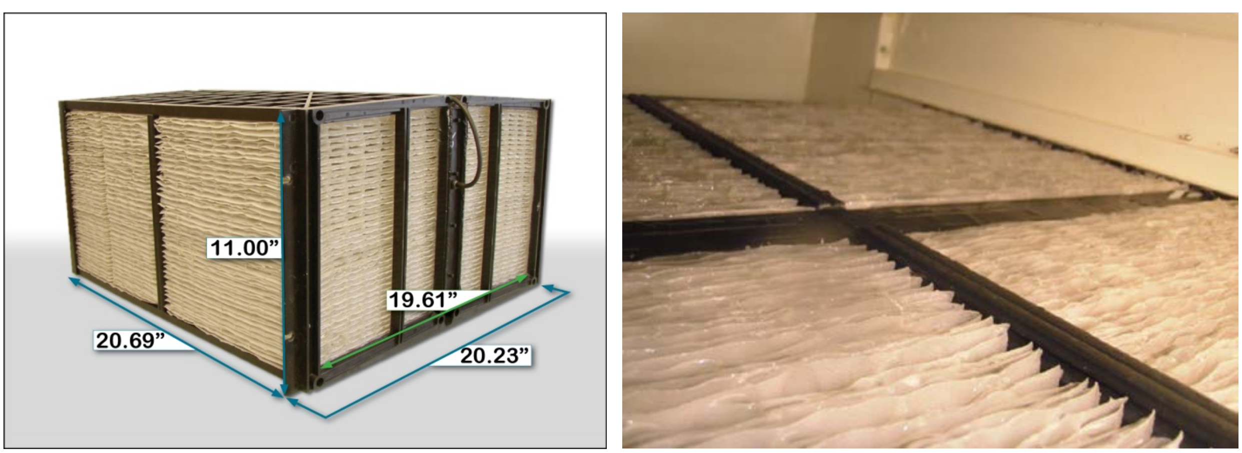
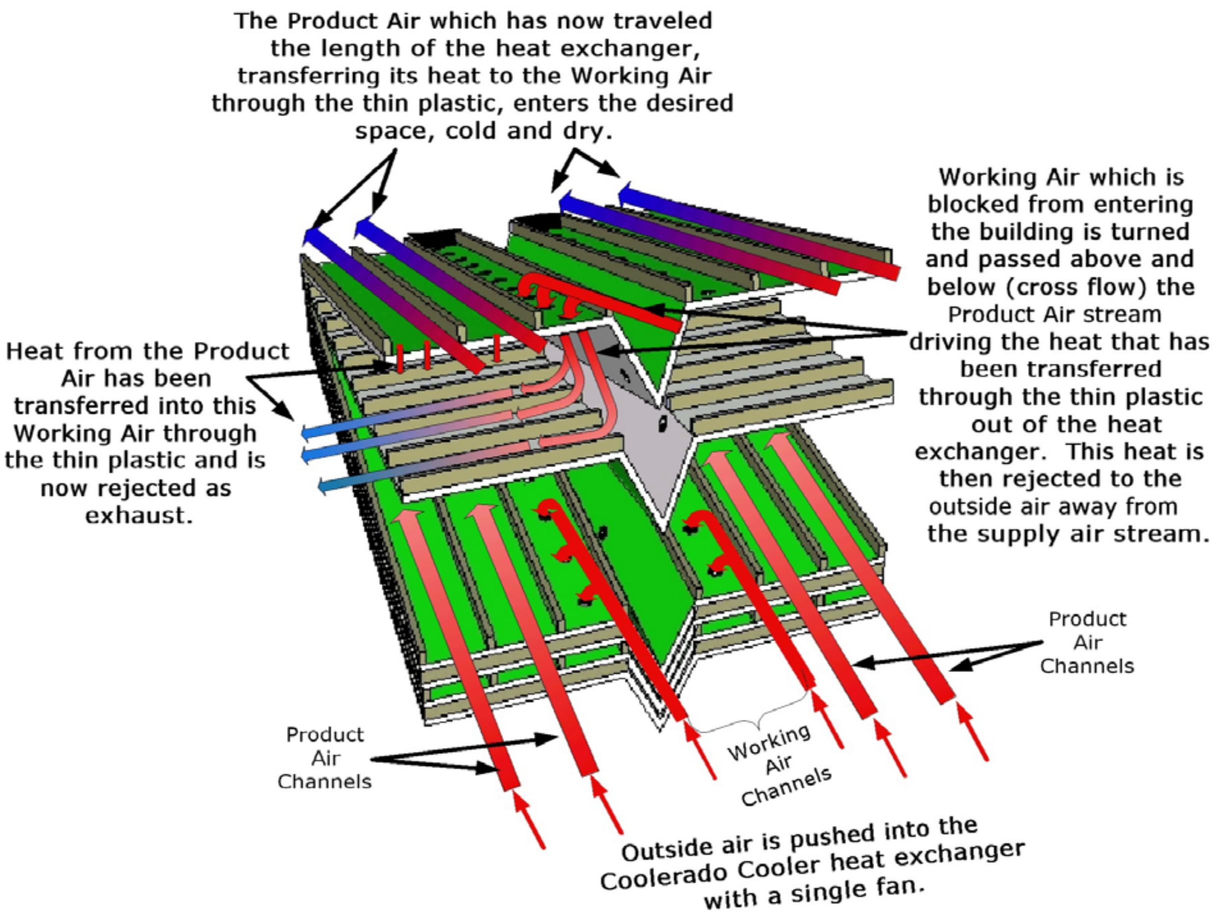


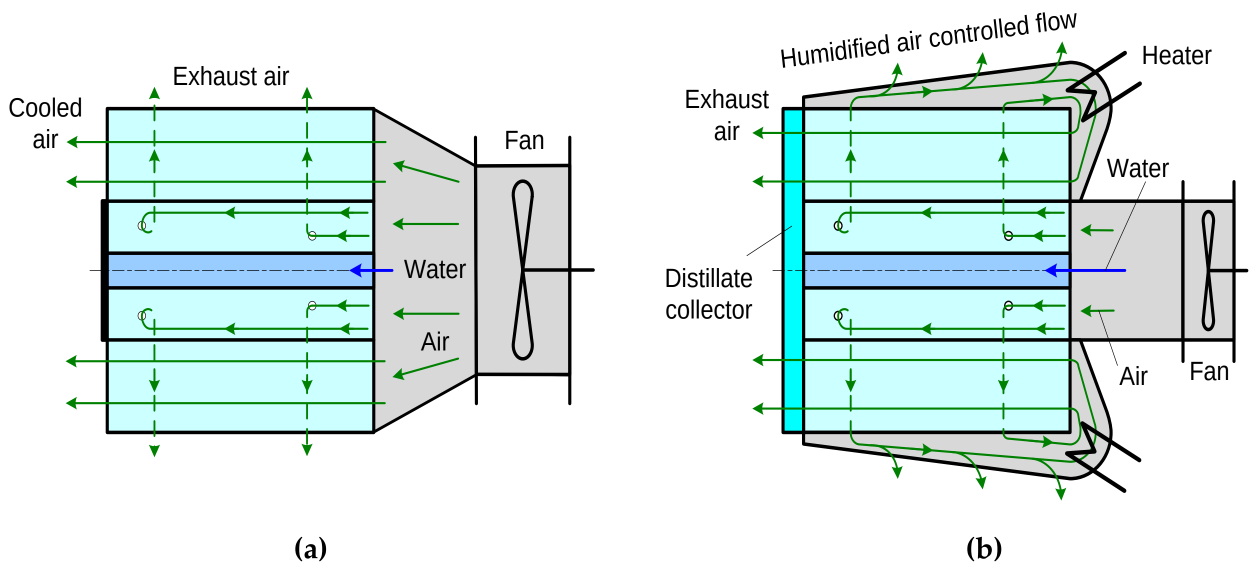
Figure 10 shows a three-dimensional view of the HMX unit inside and explains air flows and heat and mass transfers in the unit. The HMX divides the incoming air stream into "product fluid" and "working fluid." The product fluid is always separate from the working fluid and remains within dry channels the entire length of the core. The product fluid is cooled sensibly (it is actually rejecting its heat to the working fluid).

Figure 10: HMX Unit Multilayer Design and Flow Structure



This unit could not be directly used to distill water, but rearranging the air and water flows around the unit would allow adapting the unit for water distillation (wastewater recovery). To modify the unit, laboratory-scale unit design engineering was initiated jointly by GTI and Idalex Technologies, Inc., GTI's research and manufacturing partner. The team proposed rearranging the air flow in Idalex's HMX unit by adding return channels for exhaust air on the sides of the HMX unit (Figure 11 (a) and (b). Idalex accomplished the design engineering and fabrication of the core components for the GTI laboratory test unit. While there is no condensing channel in the commercial HMX evaporative module (which uses a dry channel with product air instead), in the distillation unit the moist air from the evaporating channel is redirected to the dry channel for condensation.

Figure 11: HMX Unit Flow Diagram (Top View): (a) Initial and (b) Rearranged Air Fl



The distillation unit design specifications noted that the unit was needed for laboratory testing and listed the test objectives, which included evaluating:

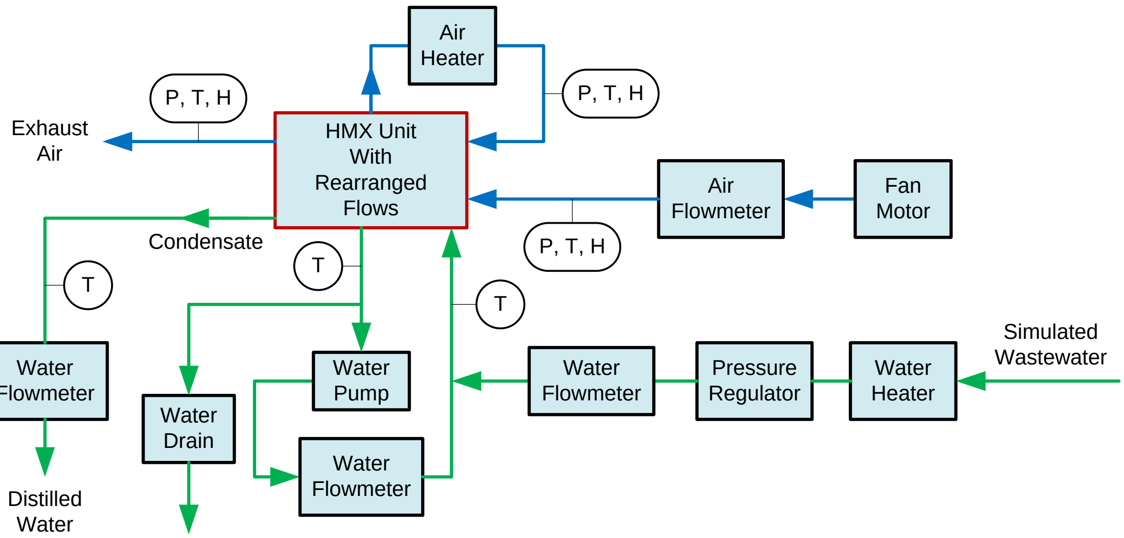
- The effect of wastewater temperature on the wastewater recovery process
- The effect of the humidified air recirculation fraction (Figure 11, b) and the air preheat temperature on the wastewater recovery process
- The effect of the total air flow rate to the wastewater flow rate ratio on the wastewater recovery process
- The effect of ambient air absolute humidity on the wastewater recovery process

The following main measurement parameters were identified, and proper measuring ports were required to be incorporated into the distillation unit design:

- Temperature, humidity, and flow rate of ambient air
- Temperature, humidity, and flow rate of dehumidified air at the distillation unit outlet
- Flow rate of rejected humidified air
- Temperature of humidified air after the air heater
- Temperature and flow rate of wastewater
- Temperature and flow rate of distilled water
- Temperature and flow rate of recirculating water

Idalex provided GTI with ranges of the measuring parameters. The required measuring port locations are shown in Figure 12.

Figure 12: Real-Time Monitoring Scheme of the Distillation System for Wastewater Recovery:P – Pressure; T – Temperature; H – Humidity



The following requirements were specified for the test procedure:

- The experimental set-up should allow for controlling air, wastewater, and water condensate flow rates and temperatures.
- The amount of water condensate compared to inlet wastewater flow rate characterizes the system production rate.
- The quality of the water condensate/distilled water characterizes the distillation system efficiency.

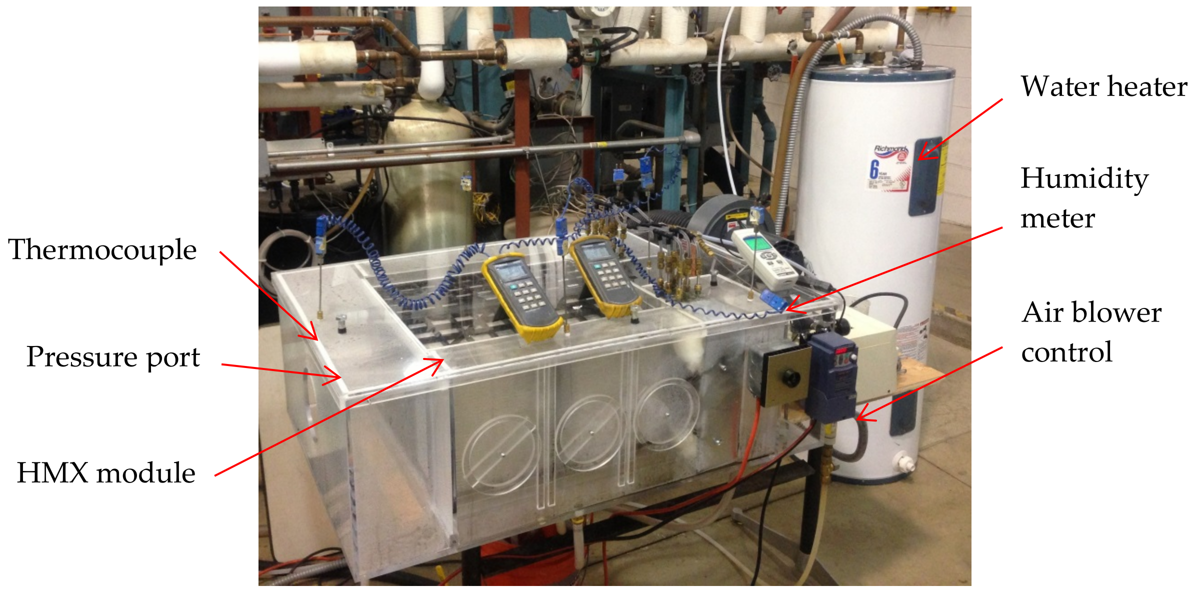
Based on the distillation unit design specifications, Idalex team designed and fabricated the unit and shipped it to GTI for laboratory testing. Representative photographs showing the fabrication progress are presented in Attachment E.

2.3 Laboratory Scale Unit Test Setup

Figure 13 illustrates the overall view of the test unit installed at the GTI laboratory and equipped with the temperature, flow, and humidity measurement means. The distillation test unit allowed controlling air and water flow rates as well as heat input to evaluate the influence of different parameters on the distillation process efficiency and distilled water production. The air flow rate through the unit was maintained in the range of 100—300 SCFM. Total water flow rate supplied to the unit was in the range of 0.1—0.5 GPM. Ambient air temperature was 67 °F —80 °F (19—27 °C) and the relative humidity was 20—70 percent. City water was used to simulate the wastewater to be distilled in the distillation unit. The water was preheated to the

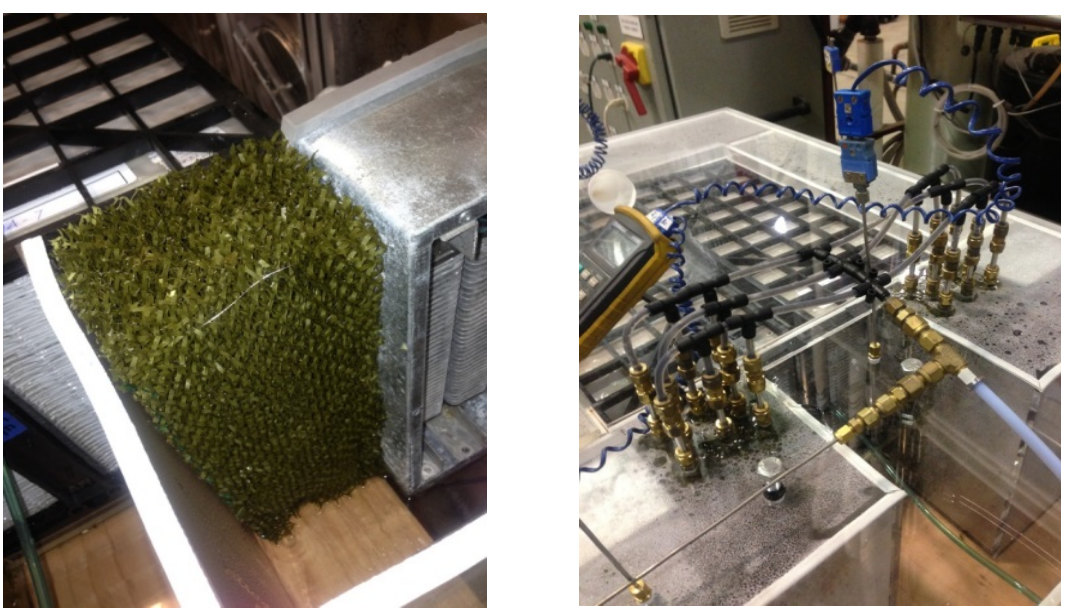
temperature of 90 □F40 □F60 (32□C □C). An electr
(Figure 13). More photographs showing details of the experimental setup are presented in Attachment E.

Figure 13: Overview of the Distillation Unit Test Setup at GTI Laboratory



As shown in Figure 14, additional packing fills were installed at the condensing channels inlet (a), and hot water was supplied to the fills in order to evaporate more water to humidified air (b).

Figure 14: Packing Fill (a) and Hot Water Supply to the Fill (b)



(a) **(b)**

2.4 Methodology of Evaluation

The key indicators of the effectiveness of a wastewater recovery system are percentage of water recovery and clean water quality (total dissolved solids reduction). To evaluate distillation system efficiency, the project measured wastewater and water condensate flow rates and temperatures, moist air temperature, humidity, and flow rates at the evaporating channel outlet.

Laboratory test objectives included evaluation of the following parameters and effects:

- Evaporated water flow rate
- Distilled (condensed) water flow rate
- The effect of wastewater temperature on wastewater recovery process
- The effect of air flow on wastewater recovery process
- The effect of ambient air humidity on wastewater recovery process
- Quality of distilled water (based on visual observation)

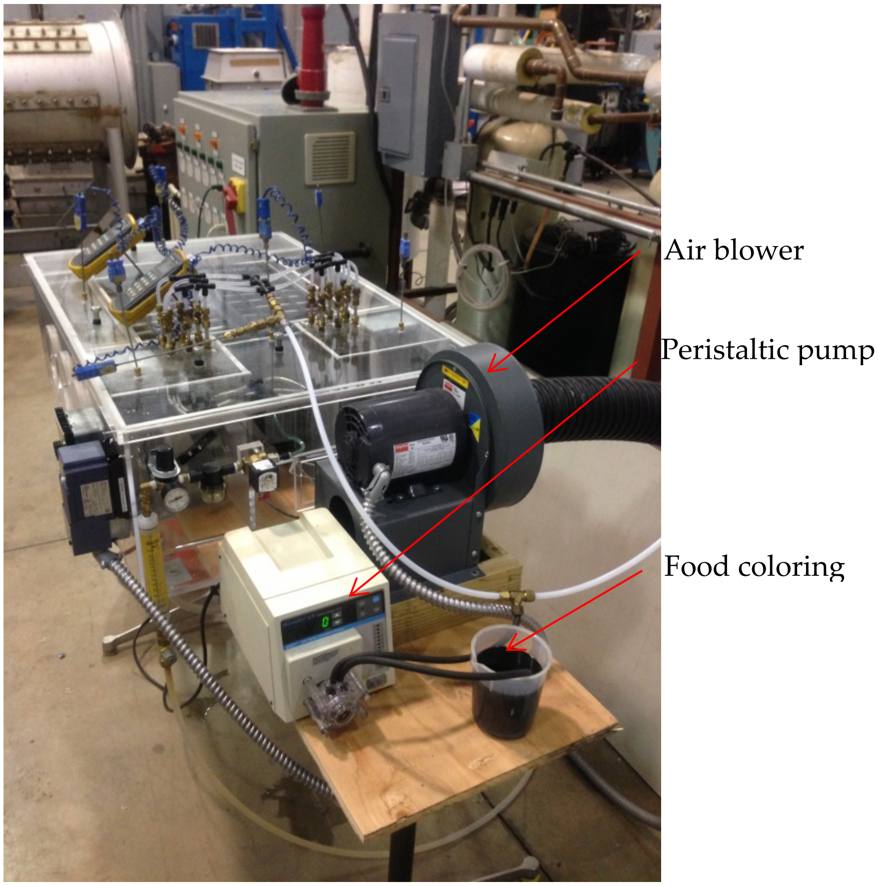
Evaporated water flow rate mw evap was estimated as the difference between inlet water flow rate and drained water flow rate. Inlet water total flow rate is the sum of the water flow rate supplied to the HMX unit and the water flow rate supplied to the packing fill. Both flow rates were measured by flow rotameters. Drained water flow rate was estimated gravimetrically by weighing the quantity of water collected in a vessel.

Distilled (condensed) water flow rate mw cond was estimated using two different approaches. The first approach estimated the difference between the amount of water vapor in the exhaust air flow and the amount of water vapor in the inlet air flow. The amount of water vapor in the air was estimated from psychrometric equations using measured air dry bulb and wet bulb temperatures and air flow rate. The air flow rate was estimated by measuring the air velocity profile and temperature across the inlet section of the HMX unit. A pitot-static (Prandtl) tube was used to measure air velocity. The second approach to estimating distilled water flow measured the weight of water collected in a vessel.

The wastewater recovery process efficiency was characterized by the distillation rate. The distillation rate was estimated as the ratio between measured distilled water flow rate mw cond and measured evaporated water flow rate mw evap, namely, mw cond/mw evap×100%.

To enable visual observation of the distilled water quality, liquid food coloring was used as an additive to water distillated during the test. A peristaltic pump was used to add the food coloring to the inlet stream of city water during the experiment (Figure 15).

Figure 15: Food Coloring Water Supply

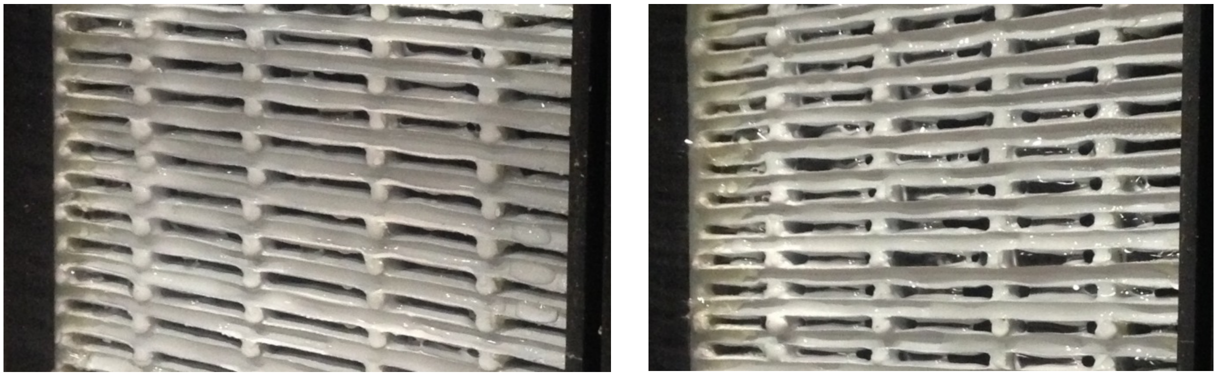


2.5 Results and Discussions

Preliminary experiments on the distillation unit allowed evaluating the new indirect dew-point evaporative concept for wastewater recovery. The experiments showed very little or no condensate flow if there was no heat provided to the saturated air or wastewater. Preheating (up to 200°F [93°C]) the saturated air coming from the evaporating channel outlet creating moist air would slightly increase the water condensate flow (up to 2—10 percent of evaporated water). Preheating the wastewater up to 140°F (60°C) increased the water condensate flow up to 56 percent of evaporated water.

Figure 16 shows a view of the HMX unit from the exhaust air side for two different regimes of the distillation process. The photograph on the left (a) was taken when no heat was supplied to the water. The photograph on the right (b) corresponds to test conditions when water was preheated to 90°F (32°C). As clearly shown in the figure, preheating the wastewater substantially affects the condensate yield, which increases distillation unit efficiency.

Figure 16: HMX View From Exhaust Air Side and Condensate Discharge:(a) Without Water Preheat (b) With Water Preheat



(a) ***(b)***

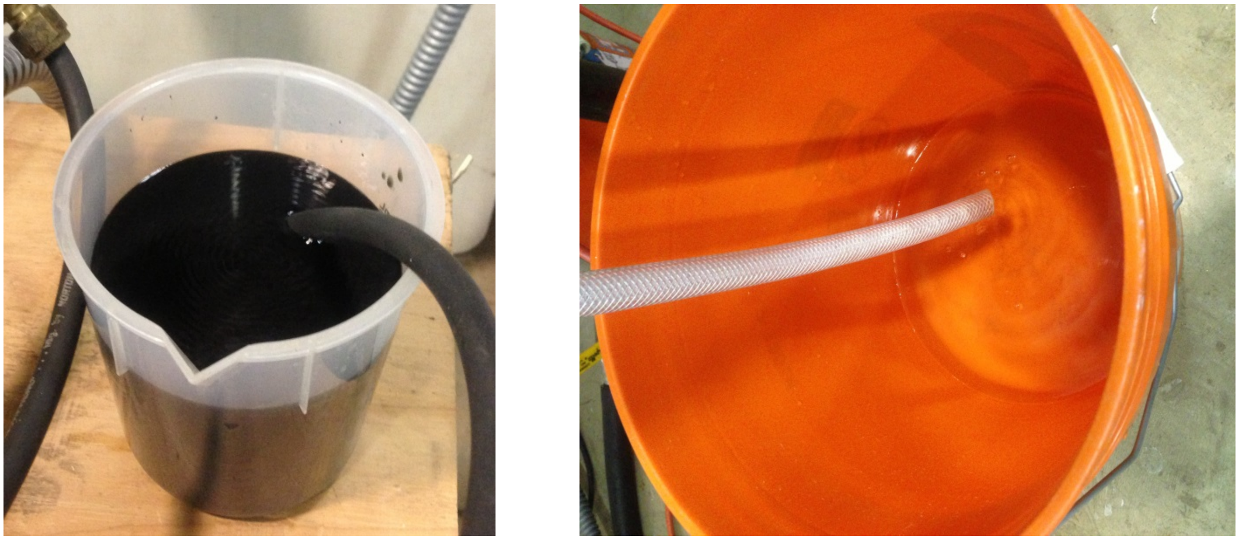
Table 4 shows the test results for the laboratory-scale water distillation unit. As shown in the table's rightmost column, the highest system efficiency (distillation rate) is achieved when hot water at a temperature of 140°F (60°C) is used for moist air re-humidification. The highest distillation rate achieved during the experiments was 55 percent of evaporated water. The distillation rate can be substantially increased, potentially to 100 percent, by developing the proposed concept and optimizing the process variables.

Table 4: Laboratory-Scale Unit Test Result

Inlet air flow rate, SCFM	150	200	200	268
Exhaust air flow rate, SCFM	75	150	150	255
Inlet air temperature, °F	68	69	65	79
Inlet air relative humidity RH, %	22	23	33	69
Air temperature after evaporating channel, °F	n/a	59.5	83.2	115
Air relative humidity after evaporating channel, %	n/a	89	100	100
Exhaust air temperature, °F	58	69	94	101
Exhaust air relative humidity, %	87	78	90	100
Wastewater flow rate, lb/hr	75	120	120	150
Wastewater temperature, °F	64	64	90	140
Evaporated water flow rate, lb/hr	28	35	54	78
Distilled water flow rate, lb/hr	0	3.5	22	43
Estimated distillation rate, %	0	10	41	55

Figure 17 shows photographs of (a) wastewater before the distillation (recovery), and (b) condensate (distillated water) collecting from the condensing channel. The experiments showed that more condensate is produced when the air flow rate is higher.

Figure 17: Wastewater (a) and Condensate (b)



(a) **(b)**

2.6 Conclusions

The project evaluated different distillation techniques available on the commercial and development markets for wastewater reuse via heat recovery. The evaluated techniques included reverse osmosis, atmospheric distillation, mechanical vapor compression, vacuum distillation, multi-stage flash distillation, and multi-effect distillation with thermal vapor compression, vacuum distillation with a heat pump, and evaporative reduction and solidification with a water separation membrane.

A novel distillation technique for wastewater recovery via waste heat utilization was developed and experimentally evaluated. The main component of the new wastewater and waste heat recovery system is a plate heat-mass-exchange module that has been successfully used for evaporative air conditioning applications. For the tests, a commercial HMX module with rearranged air and water flow streams was used in the distillation system. The HMX module has a multilayer design composed of parallel perforated plastic plates that create an air counter flow/cross flow thermodynamic design between the air streams in dry, evaporating, and condensing channels.

During testing of the new distillation technique, wastewater was evaporated at a low temperature (up to 140 °F [60 °C]) and co
module at ambient pressure and without boiling. Waste heat was used to preheat the wastewater in order to increase efficiency of the distillation process.

The following conclusions can be made from the test results:

- A high distillation rate of 55 percent of wastewater was achieved. The distillation rate can be substantially increased, potentially to 100 percent, by developing the proposed concept and optimizing the process variables.

- The distillate production rate is substantially increased when waste heat is used to preheat wastewater.
- The distillate production rate is also increased with a higher air flow rate. Increasing the air flow rate through the HMX module would also allow the distillation unit to operate more efficiently due to more uniform condensate flow in the HMX module channels.
- Visual observation of distilled water (condensate) showed no signs of dirt or coloring in the condensate.

GLOSSARY

Term	Definition
EPIC	Electric Program Investment Charge
Smart Grid	Smart Grid is the thoughtful integration of intelligent technologies and innovative services that produce a more efficient, sustainable, economic, and secure electrical supply for California communities.

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APPENDIX A:
Acronyms List

AD	Atmospheric distillation
BOD	Biochemical oxygen demand
BT	Brine tank
Btu	British thermal unit
COD	Chemical oxygen demand
DCFB	Direct contact floating bed
DOME	Dew-Out Multi-channel Evaporator
DOE	Department of Energy
DWT	Distilled water tank
ED	Electrodialysis
GPD	Gallons per day
GPM	Gallons per minute
GTI	Gas Technology Institute
HMX	Heat-mass-exchange
HTL	Heat transfer liquid
IMED-TVC	Integrated multi-effect distillation with thermal vapor compression
kg	Kilogram
kWh	Kilowatt
MSF	Multi-stage flash distillation
MVC	Mechanical vapor compression
NAICS	North American Industry Classification System
NF	Nanofiltration
NFP	Not-for-profit
psi	Pounds per square inch
RO	Reverse osmosis

SCFM	Standard cubic feet per minute
TES	Thermal energy storage
TDS	Total dissolved solids
TOC	Total organic carbon
TSS	Total suspended solids
VD	Vacuum distillation
VDHP	Vacuum distillation with heat pump
VOC	Volatile organic compound
WSM	Water separation membrane
WT	Wastewater tank

APPENDIX B:
Example of Wastewater Effluent Quality for California Food Processing Plant

Figure B-1: Aerobic Wastewater Treatment Plant Effluent Assay Results

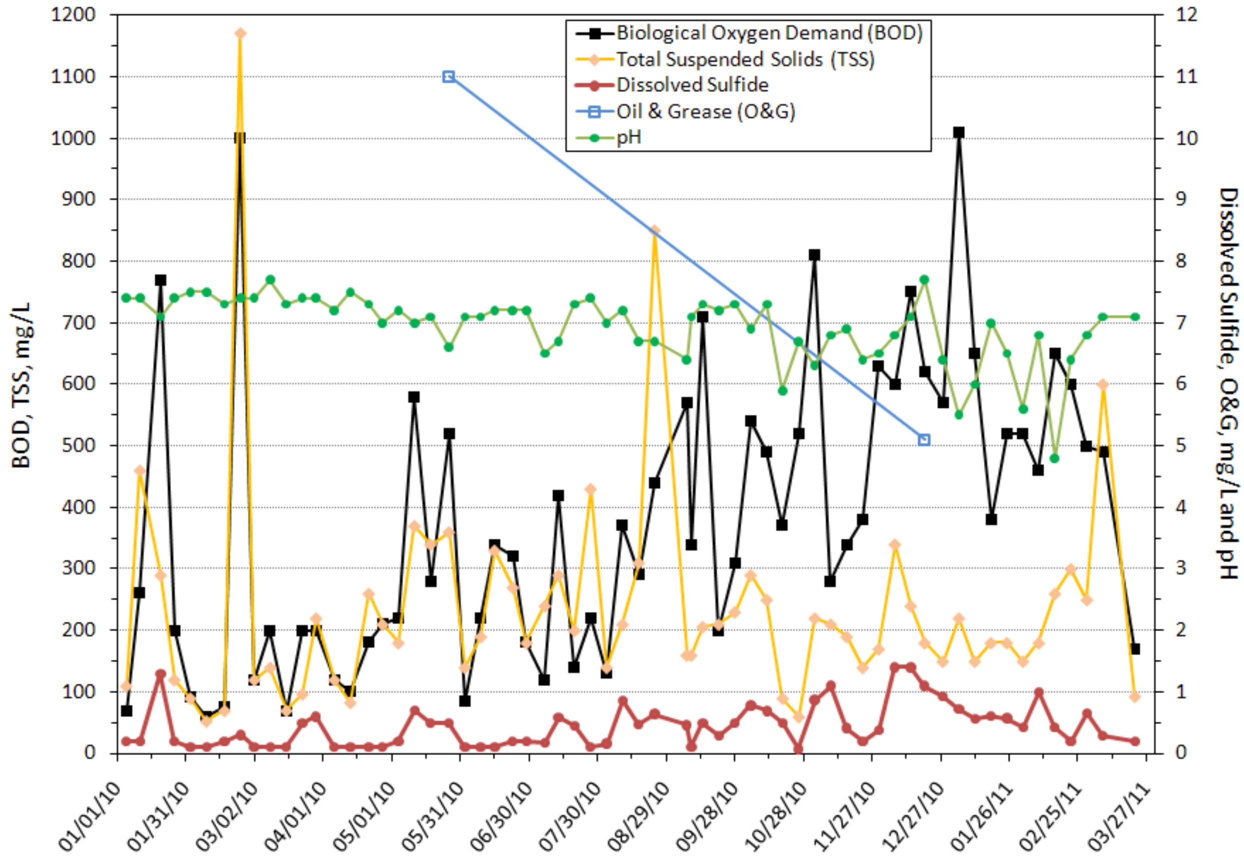


Table B-1: Wastewater Treatment Plant Effluent Assay Results Data used for Figure B-1

Date	Biological Oxygen Demand (BOD)	Total Suspended Solids (TSS)	Dissolved Sulfide	pH	Oil & Grease (O&G)	Ca	Mg	Na	Total Dissolved Solids (TDS)	Total Alkalinity (as CaCO3)
	City of Oxnard Maximum Limit									
	800 mg/L	1000 mg/L	0.5 mg/L	6-10	350 mg/L					
	mg/L									
01/05/10	69	110	0.20	7.4						
01/11/10	260	460	0.20	7.4						
01/20/10	770	290	1.30	7.1						
01/26/10	200	120	0.20	7.4						
02/02/10	92	90	0.10	7.5						
02/09/10	60	53	0.10	7.5						
02/17/10	75	70	0.20	7.3						
02/24/10	1000	1170	0.30	7.4						
03/02/10	120	120	0.10	7.4						
03/09/10	200	140	0.10	7.7						
03/16/10	69	70	0.10	7.3						
03/23/10	200	97	0.50	7.4						
03/29/10	200	220	0.60	7.4						
04/06/10	120	120	0.10	7.2						
04/13/10	100	83	0.10	7.5						
04/21/10	180	260	0.10	7.3						
04/27/10	210	210	0.10	7.0						
05/04/10	220	180	0.20	7.2						
05/11/10	580	370	0.70	7.0						
05/18/10	280	340	0.50	7.1						
05/26/10	520	360	0.50	6.6	11					
06/02/10	84	140	0.10	7.1						
06/09/10	220	190	0.10	7.1						
06/15/10	340	330	0.10	7.2						
06/23/10	320	270	0.20	7.2						
06/29/10	180	180	0.20	7.2						
07/07/10	120	240	0.17	6.5						
07/13/10	420	290	0.59	6.7						
07/20/10	140	200	0.45	7.3						
07/27/10	220	430	0.11	7.4						
08/03/10	130	140	0.16	7.0						
08/10/10	370	210	0.86	7.2						
08/17/10	290	310	0.47	6.7						
08/24/10	440	850	0.64	6.7						
09/07/10	570	160	0.46	6.4						
09/09/10	340	160	0.10	7.1						
09/14/10	710	206	0.49	7.3						
09/21/10	200	210	0.29	7.2						
09/28/10	310	230	0.49	7.3						
10/05/10	540	290	0.78	6.9						
10/12/10	490	250	0.69	7.3						
10/19/10	370	90	0.50	**5.9**						
10/26/10	520	60	0.07	6.7						
11/02/10	810	220	0.87	6.3						
11/09/10	280	210	1.10	6.8						
11/16/10	340	190	0.41	6.9						
11/23/10	380	140	0.19	6.4						
11/30/10	630	170	0.38	6.5						
12/07/10	600	340	1.40	6.8						
12/14/10	750	240	1.40	7.1						
12/20/10	620	180	1.10	7.7	5.1					
12/28/10	570	150	0.93	6.4						
01/04/11	1010	220	0.72	5.5						
01/11/11	650	150	0.56	6.0						
01/18/11	380	180	0.61	7.0						
01/25/11	520	180	0.57	6.5						
02/01/11	520	150	0.43	5.6						
02/08/11	460	180	1.00	6.8						
02/15/11	650	260	0.43	4.8						
02/22/11	600	300	0.20	6.4						
03/01/11	500	250	0.65	6.8						
03/08/11	490	600	0.29	7.1						
03/22/11	170	93	0.20	7.1		78	26	130	970	430

Table B-2: Aerobic Wastewater Treatment Plant Effluent Assay
Case 2006

Dumping Area 6092707-01 (Water)

Anions by EPA Method 300.0/300.1

Analyte	Result	Units	Reporting Limit	Dilution Factor	Method	Batch Number	Date Prepared	Date Analyzed	Data Qualifiers
Chloride	**52**	mg/l	5.0	10	EPA 300.0	W6J0225	10/05/06	10/06/06 ac	
Sulfate as SO4	**420**	mg/l	5.0	10	EPA 300.0	W6J0225	10/05/06	10/06/06 ac	

Conventional Chemistry/Physical Parameters by APHA/EPA/ASTM Methods

Analyte	Result	Units	Reporting Limit	Dilution Factor	Method	Batch Number	Date Prepared	Date Analyzed	Data Qualifiers
Alkalinity as CaCO3	**200**	mg/l	2.0	1	SM 2320B	W6I1113	09/28/06	09/28/06 mac	
Carbonate Alkalinity as CaCO3	ND	mg/l	2.0	1	SM 2320B	W6I1113	09/28/06	09/28/06 mac	
Bicarbonate Alkalinity as HCO3	**250**	mg/l	2.0	1	SM 2320B	W6I1113	09/28/06	09/28/06 mac	
Hydroxide Alkalinity as CaCO3	ND	mg/l	2.0	1	SM 2320B	W6I1113	09/28/06	09/28/06 mac	
Total Hardness as CaCO3	**540**	mg/l	1.0	1	EPA 200.7	W6J0252	10/06/06	10/11/06 pl	
Nitrate as NO3	**20**	mg/l	0.50	1	EPA 353.2	W6I1027	09/27/06	09/27/06 tl	
pH	**7.95**	Units		1	SM4500 H+ B	W6I1035	09/27/06	09/27/06 cc	
Residual Chlorine, Total	**1.6**	mg/l	0.50	10	SM 4500 Cl G	W6I1013	09/27/06	09/27/06 cc	
Total Dissolved Solids	**720**	mg/l	10	1	SM2540C	W6I1143	09/29/06	09/30/06 cc	
Total Suspended Solids	ND	mg/l	1	1	EPA 160.2	W6I1028	09/27/06	09/28/06 cc	
Soluble Sulfide	ND	mg/l	0.10	1	SM 4500S2 D	W6I1045	09/27/06	09/27/06 tl	
Total Organic Carbon	**1.0**	mg/l	0.30	1	SM5310C	W6I1122	09/28/06	09/28/06 jl	
Turbidity	**0.12**	NTU	0.10	1	EPA 180.1	W6I1081	09/28/06	09/28/06 mac	

Metals by EPA 200 Series Methods

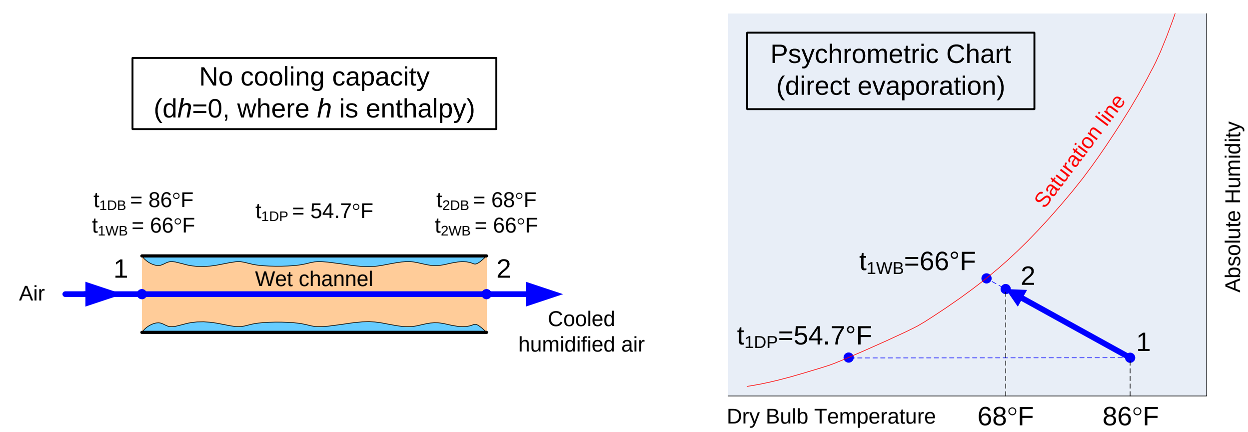
Analyte	Result	Units	Reporting Limit	Dilution Factor	Method	Batch Number	Date Prepared	Date Analyzed	Data Qualifiers
Total Barium	**0.033**	mg/l	0.0020	1	EPA 200.7	W6I1062	09/28/06	09/29/06 PL	
Calcium	**140**	mg/l	0.10	1	EPA 200.7	W6I1062	09/28/06	09/29/06 PL	
Total Copper	**0.053**	mg/l	0.010	1	EPA 200.7	W6I1062	09/28/06	09/29/06 PL	
Total Iron	ND	mg/l	0.020	1	EPA 200.7	W6I1062	09/28/06	09/29/06 PL	
Magnesium	**47**	mg/l	0.10	1	EPA 200.7	W6I1062	09/28/06	09/29/06 PL	
Total Manganese	**0.017**	mg/l	0.010	1	EPA 200.7	W6I1062	09/28/06	09/29/06 PL	
Sodium	**95**	mg/l	0.50	1	EPA 200.7	W6I1062	09/28/06	09/29/06 PL	
Total Silica (SiO2)	**27**	mg/l	0.10	1	EPA 200.7	W6I1062	09/28/06	09/29/06 PL	
Total Zinc	ND	mg/l	0.050	1	EPA 200.7	W6I1062	09/28/06	09/29/06 PL	

APPENDIX C
Fundamentals for Dew Point Evaporative Cooling

I. Direct Evaporative Cooling

Direct evaporative cooling is quite simple and a cheaper, simpler alternative to vapor compression cycles. Used in so-called "swamp coolers" for air conditioning, warm and dry air is passed by a wetted surface, and the latent heat required by evaporation water cools the air. As it is defined, the theoretical cooling limit is the wet bulb temperature t_{wb} of the incoming air stream (Figure C-1). This is an adiabatic process, in which there is a direct energy swap of the latent heat of vaporization of water evaporated for sensible cooling of the gas stream. While a simple process, often cooling *and* humidifying the air is not desirable.

Figure C-1: Direct Evaporation (Adiabatic Cooling)



Subscripts: DB – dry bulb, WB – wet bulb, DP – dew point

Pro: Simple, effective, used throughout history.

Con: No cooling capacity since sensible heat is transferred from latent heat. Cooling is limited to the incoming t_{WB} and cooled air leaves saturated.

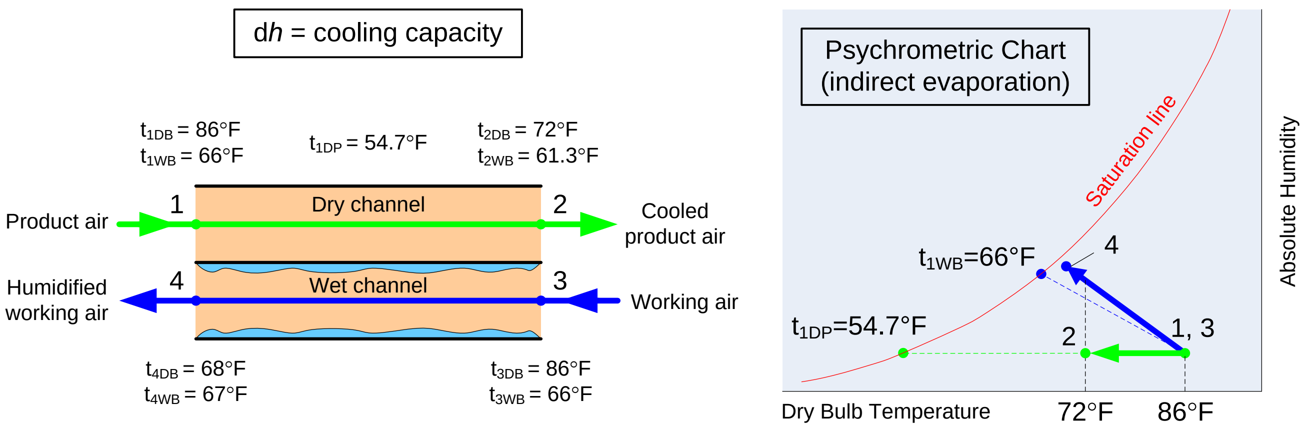
II. Basic Indirect Evaporative Cooling

Indirect evaporative coolers do not humidify the product air through use of a dual-channel heat exchanger. Like Direct Evaporative Cooling, it is limited by the wet bulb temperature of the incoming fluid. This is also a direct swap of latent for sensible energy, however the heat exchanger prevents the product (dry) gas from being humidified. Using the example in the diagram (Figure C-2), the outside air at (1, 3) is split into two channels:

- The wet channel is effectively a Direct Evaporative Cooler, which humidifies the air ideally to its wet bulb temperature t_{1WB} =66°F. On the chart below this is the dashed line of constant wet bulb temperature from (3) to 66 °F on the saturation line. In reality, the air is humidified to higher wet bulb temperature t_{4WB} (4) because of heat supply from the dry channel.

- The dry channel is cooled through the heat exchanger to 72 °F at (2). On the chart this moves horizontally (i.e. no change in absolute humidity) from a dry bulb of 86 °F to 72 °F

Figure C-2: Indirect Evaporation



Pro: There is cooling capacity in the process. Benefits of Direct Evaporative Cooling without product air humidification.

Con: Cooling is limited to the incoming wet bulb temperature and humid working air must be rejected. Additional material without cooling benefit is often not justifiable.

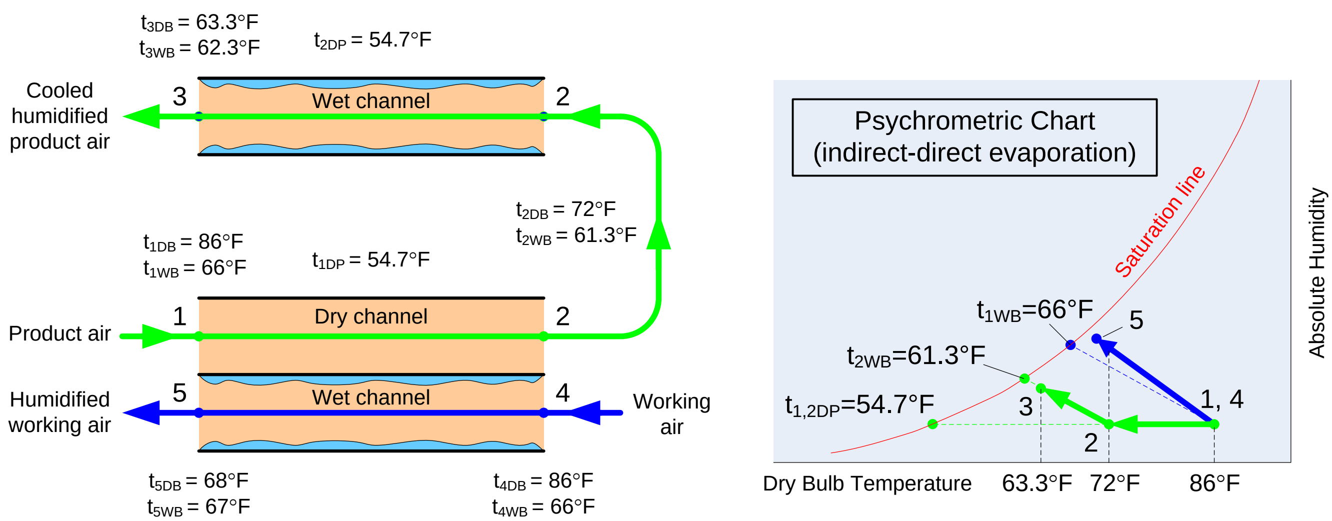
III. Indirect-Direct Evaporative Cooling

With a simple rearrangement, Indirect-Direct Evaporative Cooling reroutes the dry channel through a second wet channel. It takes advantage of the fact that when a parcel of air is sensibly cooled, the saturated water vapor pressure decreases, thus reducing the wet bulb temperature. Note that in the previous chart this occurred as well; as the wet bulb temperature at (2) was lower than (1).

Examining Figure C3 and psychrometric chart, it is apparent how through this staged sensible [(1) to (2)] *then* latent cooling [(2) to (3)] we arrive at dry bulb temperatures t_{3DB} below the incoming wet bulb temperatures t_{1WB}, from (1) to (3). The limit for cooling now is the dew point temperature $t_{1,2DP}$, which is indicated by the horizontal dotted line extending from (2) to the saturation line.

One could add another dry channel on top of the wet channel from (2) to (3) and perform a second latent for sensible energy swap, which could facilitate cooling without humidification. This process of adding dry/wet channels could repeat until the theoretical dew point cooling limit is reached. This is both inefficient with energy and space however, as each dry/wet channel pairing must be separate to remain adiabatic, thus increasing the flow path and pressure drop. Additionally, with each additional dry/wet channel pairing a fraction of the incoming air is humidified and rejected, as done at point (5).

Figure C-3: Indirect-Direct Evaporation



Pro: Cooling is not limited to incoming wet bulb temperature.

Con: Air is humidified which means that air quality is reduced. Dry-to-wet channels must be separate increasing material/space requirements and humid working air must be rejected for each dry/wet channel pairing.

IV. M-Cycle for Indirect Evaporative Cooling

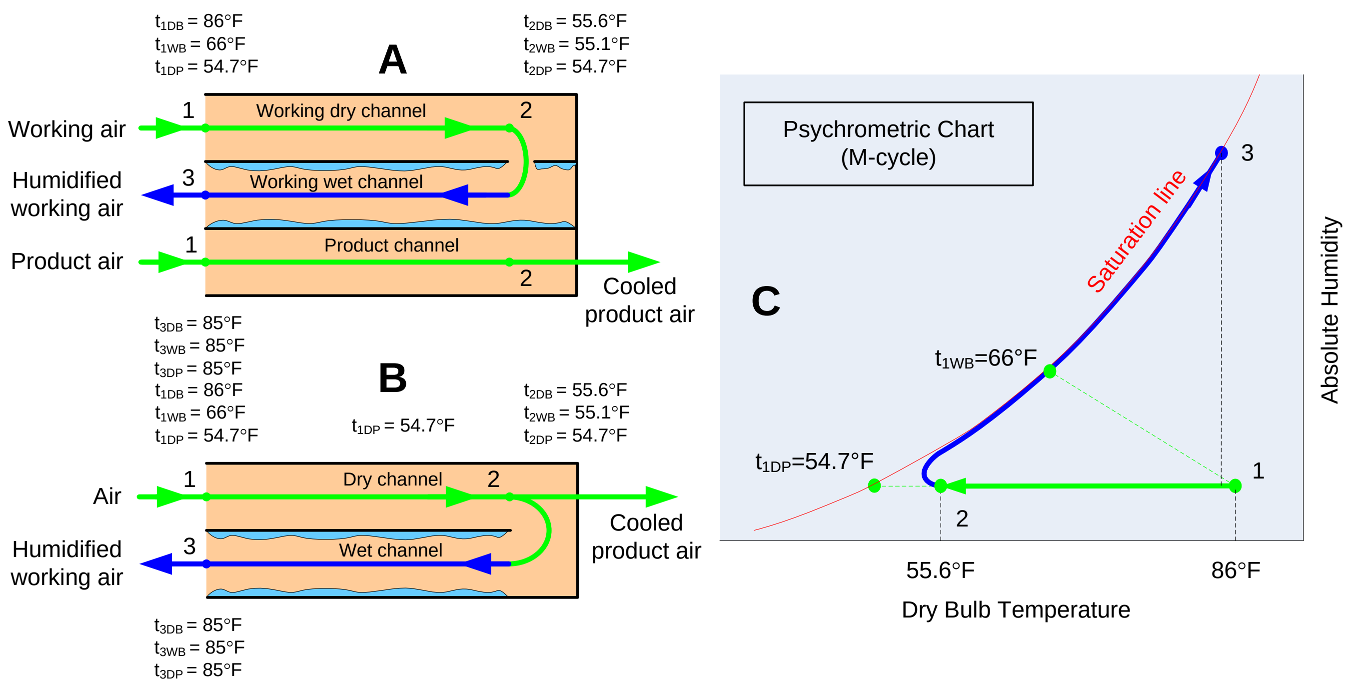
While achieving sub-wet bulb cooling, Indirect-Direct Evaporative Cooling is problematic in practice, as the more cooling stages employed require several separate wet/dry channel chambers. The M-cycle uses the same wet side and dry side of a plate as described in the above indirect evaporative cooler but with different airflow arrangement creating a different thermodynamic cycle (Figure C-4). The M-cycle utilizes the air potential energy available from latent heat of water evaporating into the air.

Two manifestations of the M-Cycle for Evaporative Cooling are shown below: (A) is a Product Air Cooling arrangement, as employed by Coolerado ® air conditioners, which keeps working and product dry channels separated and (B) is a Partial Extraction of Air arrangement, which fractions a portion of the dry channel as usable product. Both arrangements are psychrometrically identical while arrangement (A) with product channel has essential advantages as compared to arrangement (B). Thus, any gas or liquid matter (for example hot waste product) can be used as a product flow in arrangement (A) while arrangement (B) is limited to the same gas for both channels. Moreover using the product channel allows reducing pressure drop in the system. Another advantage of arrangement (A) compared with (B) would be a possibility to use the product channel as a condenser for gas dehumidification.

Similar to Indirect-Direct Evaporative Cooling, the dew point temperature is now the theoretical limit. The two key characteristics of the M-Cycle which facilitate its effective and simple design are:

1. At steady state, the coolest point throughout the M-Cycle is always near the transition from working dry to wet channels, at state 2 in the working dry channel.
2. Saturation is reached rapidly and maintained in the working wet channel.

Figure C-4: Variations of M-cycle with (A) Product Air Cooling and B) Partial Extraction of Air



Pro: Cooling is not limited to incoming wet bulb temperature, more effective with hotter and humid air than other methods, compact and efficient design relative to other methods. Cooling capacity is increased when air temperature is increased as opposed to other methods.

Con: The process has being developed well for air conditioning only but requires further development for other applications.

V. Conclusions

The indirect dew point evaporative cooling (M-Cycle) is a theoretically sound method of reducing a fluid to dew point temperature which is lower than its wet bulb temperature. The M-cycle utilizes the psychrometric energy (or the potential energy) available from the latent heat of water evaporating into the air. While its current manifestation is as the Idalex/Coolerado HMX for air conditioning, through engineering design this cycle could be applied as a heat and moisture recovery device for combustion devices, cooling towers, condensers, and other processes involving humid gas streams. The M-Cycle has transitioned into the Coolerado Air Conditioner from the conceptual stage to commercial applications which offers up to a 90 percent reduction of power for air conditioning of homes, commercial, and industrial buildings.

APPENDIX D
Fiber and Fiber Characteristics for Idalex's HMX

Background: The Idalex's HMX is a very high efficient heat and mass exchanger. The key to the HMX evaporating process is a unique method for transporting and evaporating water, along with special geometry and heat transfer. The key material in the process is a synthetic fiber material that wicks water out of a reservoir and allows that water to evaporate into an air stream. The wicking fiber material is coated on one side to act as a moisture barrier and heat transfer surface.

The primary fabric characteristics needed are described below. Individual fibers, or fibers grouped into a yarn, may not necessarily have the desired characteristics. However, when bound into a fabric they must have and retain the characteristics even after years of continuous water flow:

1. Wetting: the fabric should absorb water without the use of a surfactant. The fibers that make up the fabric may or may not absorb water.
2. Wicking: the fabric must be able to wick water 2 inches (50 mm) high.
3. Evaporation: the fabric must readily allow water to evaporate. This is key to the thermodynamic process and achieving colder temperatures.
4. Wicking Release: water wicked out of a reservoir (up 2 inches) and over a lip, must release water droplets on the opposite side of the reservoir. The test is with a piece of fabric draped between a full cup of water and an empty cup of water should transfer water from the full cup to the empty cup without the fabric touching the empty cups sides or bottom.
5. Wicking Speed: the fabric must wick water fast enough to replace water being evaporated away in the HMX process. Largely a function of material thickness. Tested by wicking colored water out of a reservoir and down a slope of an already wet fabric.
6. Smoke and Flame: the fabric must pass smoke and flame tests to UL standards for an air filter.
7. Coating: the fabric will be coated (typically under a separate process) on one side with a moisture barrier. Currently use a 1.5 mil (.0015 inches, 40 micrometers) thick extruded plastic coating (as opposed to laminated) that adheres to and encapsulates the surface fibers on one side of the fabric.
8. Biological Resistance: fiber must be naturally resistant to mold (cannot use cellulose for example).
9. Cost: less than $0.40 per square yard at quantities of a million square yards for year 2011.
10. Other characteristics:

11. Fabric Thickness: minimal needed to wick water to replace evaporation. Currently use fabric 0.010 inches (250 micrometers).
12. Fabric Stiffness: prefer stiffer fabric for ease in manufacturing.
13. Fiber Size: any
14. Multi-component Fiber: open
15. Multi-layered Fabric: open
16. Moisture Expansion: minimal
17. Thermal Expansion: minimal
18. Recyclability: yes

APPENDIX E
Distillation Unit Design and Fabrication

Figure E-1: HMX Unit with Rearranged Flows Around the Unit

Figure E-2: Fan and Motor with Motor Controller

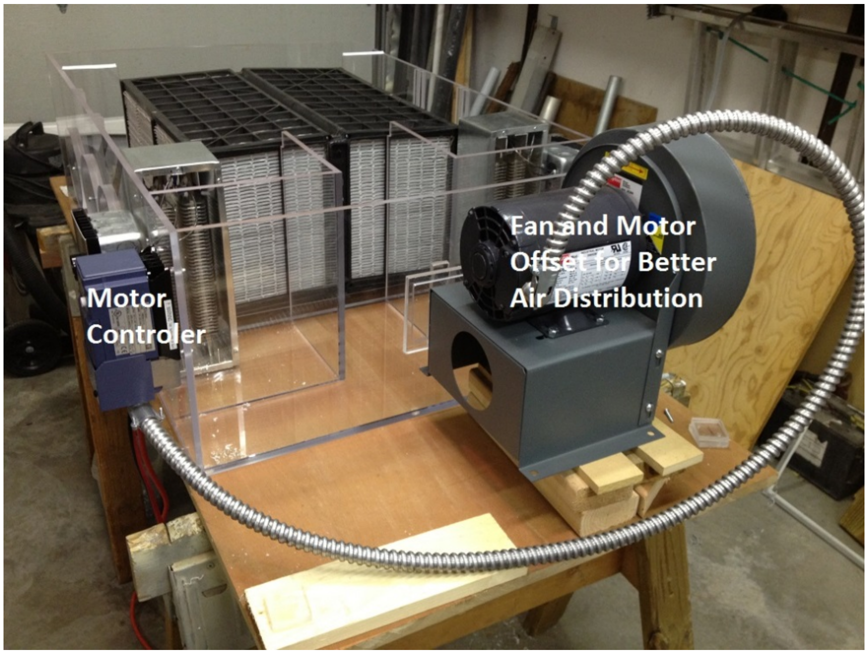


Figure E-3: Electrical Air Heaters with Heat Control and Water Control Board