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Changing the World's Energy Future

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Desalination Multi-Effect Evaporator Model in Support of Integrated Energy Systems

Emily Solis*, Logan Williams*, Stephen Terry*, Joseph Doster*, Daniel Mikkelson†

*Department of Mechanical and Aerospace Engineering, North Carolina State University, 1840 Entrepreneur Dr, Engineering Building III, Raleigh, NC, 27695-7909, eesolis@ncsu.edu, ldwill10@ncsu.edu, sdterry@ncsu.edu, doster@ncsu.edu

†Idaho National Laboratory, 2525 Fremont Ave, Idaho Falls, ID 83402, Daniel.Mikkelson@inl.gov

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INTRODUCTION

The purpose of this work is to contribute to the Integrated Energy Systems (IES) modeling efforts from the U.S. Department of Energy (DOE) with Idaho National Laboratory (INL). The DOE is working on a plug-and-play set of models in an open-source repository called HYBRID, available at https://github.com/idaholab/HYBRID/, that can be used to improve IES modeling capabilities.

Nuclear Energy and Desalination

Nuclear desalination is the coupling of a desalination plant with a nuclear energy plant and has been of heightened interest since the 1990s according to the International Atomic Energy Alliance [1]. 60% of water desalination installations are reverse osmosis (RO) [2], a membrane-based technology where high-pressure systems are electrically driven to generate fresh water. An RO model already exists within the NHES repository. Thermal desalination technologies constitute at least 35% of installations and are primarily either multi-stage flash (MSF) or multi-effect distillation (MED) [2]. A multiple effect evaporator (MEE), of which MED is a subtype, can use low grade heat as initial steam input for its system.

Moreover, according to a systematic review and meta-analysis of desalination life cycle assessment (LCA) publications, the operation and maintenance phase of life, in RO, MED, and MSF technologies, is the primary contributor within the LCA impact analysis. Across many scopes within the study, the energy generation process required to run the desalination plants was largely responsible for increasing negative environmental impacts in the indicator categories, including, among others, global warming potential, acidification potential, and eco toxicity. [3]

The ability to potentially use waste heat to partially drive an MED plant presents many IES opportunities while also reducing the environmental impact of a desalination plant. Aligned with similar IES concepts, the coupling of these systems can provide cogeneration of potable water and electricity while reducing costs and inefficiencies in each process compared to stand alone plants.

Multi-Effect Evaporator Theory

MEEs are used in a variety of industries to gradually concentrate a liquid as it separates water from an impure feed. The desired product from the process can be the concentrated liquid or, in the case of desalination MEEs, the clean water that has been boiled off from the feed.

Within an MEE, each effect acts as a dual phase change heat exchanger with two streams in and three streams out. All streams are at or very near saturation conditions so the temperature in each stream stays reasonably consistent throughout phase change alongside correlating losses. The incoming hot stream is steam that condenses in the heat exchange and leaves as liquid condensate. The incoming cold stream is an impure feed that leaves in two streams; one liquid stream with a final higher impurity concentration and one clean water vapor stream that has evaporated off the cold stream. By accomplishing phase changes in both streams, MEEs are designed to capitalize on the large heat of vaporization of steam during the heat exchange.

To create an MEE system, the streams from different effects are connected; many feed and product flow configurations are possible. Each effect utilizes a different saturation temperature and corresponding pressure in order to match the incoming streams. The outgoing higher concentrated liquid stream is typically the feed for a new effect and will undergo a heat absorption to evaporate more pure water from the stream. Similarly, the outgoing clean water vapor, having just absorbed energy from the heat exchange, enters a new effect as the incoming hot stream in order to boil off more fresh water and generate more vapor. This cascades down until the temperatures and pressures are less than what can be economically used or until a feed reaches a desired design concentration. The effects are self-feeding in this way through the system so that an MEE has two primary feeds that drive the whole system, an initial motive steam and the lowest concentration impure feed.

METHODOLOGY

The model is developed as a single effect evaporator and then multiple evaporators are chained together to create a full system. Each effect is a system of equations derived from the conservation equations (1-20) listed below and constitute a fully transient model. These equations were written into Modelica, an acausal, inherently dynamic, and object-oriented development language. Dymola is a commercial Modelica compiler and was used to run the simulations.

Mass Balances

(1)

(2)

Energy Balance

(3)

Salt *Concentration Balance*

(4)

State Equations

(5)

(6)

(7)

(8)

Brine

(9)

(10)

(11)

(12)

Vapor

(13)

(14)

(15)

(16)

Mixture

(17)

(18)

(19)

The *mixture* set of equations contains a bubble rise velocity correlation, equation (19), which accounts for mass transfer between the brine liquid and generated vapor.

Equilibrium Equation

(20)

RESULTS

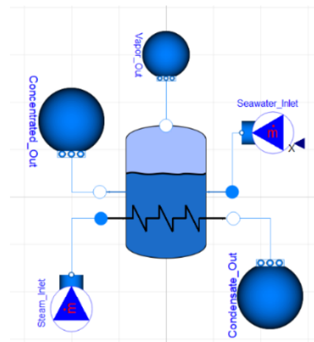

Fig. 1. Visual of developed evaporator model.

The first model created, shown in Fig. 1, was a single evaporator with water on both sides of a vectorized heat exchange and a phase change in both streams. Multiple single effect models were then linked to create an eight effect MED system, seen in Fig. 2. This configuration has a parallel brine feed where the brine only passes through one effect. System values of interest are reported in Table I and specific effect values are called out in Tables II and III. Salt concentration values are an external calculation and carried out between each evaporator. This evaporator model does not account for the boiling point rise that occurs within a brine solution that is increasing in solute concentration.

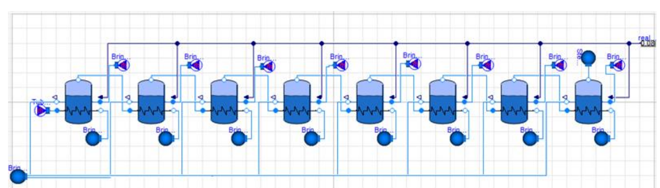

Fig. 2. An Eight Effect System Model

TABLE I. Eight Effect MED System Parameters

Variable	Value	Unit
Brine Inlet Temperature	80	ºC
Brine Inlet Concentration	0.08	kg/kg
Motive Steam Flowrate	1	kg/s
Motive Steam Pressure	100	kPa

A brine media package was then developed and modeled through a single effect evaporator configuration identical to Fig. 1. This media package accounts for the brine's enthalpy, pressure, temperature, and boiling point rise according to its salinity concentration.

TABLE II. Eight Effect MED System Input Values

Inputs

Variable	Pressure	Brine Flow In
Unit	kPa	kg/s
Effect Number:		
1	70	4
2	65	4
3	60	4
4	55	4
5	50	4
6	45	4
7	40	4
8	35	4

TABLE III. Eight Effect MED System Results Values

Results			
Variable	Steam Production	Heat Transfer Rate	Exit Salinity
Unit	kg/s	MW	kg/kg
Effect number:			
1	0.960	2.297	0.105
2	0.924	2.189	0.104
3	0.904	2.112	0.103
4	0.898	2.067	0.103
5	0.901	2.038	0.103
6	0.914	2.041	0.104
7	0.952	2.076	0.105
8	0.982	2.099	0.106
Totals	7.435	16.919	-

TABLE IV. Heat Transfer Area Between Models

Units	Water	Brine	Delta
m^2	26,800	35,400	8,600

Due to the boiling point rise of the solution, there is an anticipated reduced rate of heat transfer in the water-brine evaporator when compared against the water-water evaporator. The water-brine single effect model was run with a parameter sweep on the heat transfer area variable until the vapor flowrate output value was equal with the water-water single effect model. The final heat transfer area values can be seen in Table IV and is representative of the heat transfer reduction that brine carries. Table V compares the heat transfer rate, exit vapor temperature, and condensed steam exit enthalpy.

TABLE V. Variable Comparison Between Models

Variable	Water	Brine	Unit
Heat Transfer Rate	2.306	2.32	MW
Exit Vapor Temp	89.93	91.69	ºC
Condensed Steam Exit Enthalpy	419	406	kJ/kg

CONCLUSION

A transient evaporator model was developed that has a vectorized heat exchange and a phase change in both streams. Modeling water in both sides of the evaporator, an MED system can be created by easily connecting singular evaporators together. When modeling an evaporator with an incoming brine stream a single effect can be used. Efforts are ongoing to build up an MED system that incorporates the brine media.

These models are developed to be incorporated into the NHES repository for INL's IES program. While the focus of this paper is desalination, MEEs are used across a variety of industries, including medicinal, food, and paper manufacturing. This is especially pertinent where small modular reactors are anticipated to provide cogenerate electricity and thermal resources to industrial process as an SMR model already exists within the NHES repository. These MEE models would be quickly adaptable to simulate an IES that incorporates industrial MEE processes outside of desalination.

NOMENCLATURE

= Mass
= Volume
= Enthalpy
Q = Heat Rate
= Acceleration due to gravity
= Temperature
= Energy
= Salt Mass
= Concentration
= Void Fraction
= Density
= Specific Gibbs Free Energy of Water Vapor
= Relative Specific Chemical Potential of Salt Water
= Surface Tension
= Mass Flow Rate
= Cross Sectional Area
= Pressure
= Specific Eternal Energy
= Bubble Rise Velocity Correlation

Subscripts

= Brine
= Mixture
= Vapor
= Transfer
= Feed
= Concentrate

REFERENCES

1. INTERNATIONAL ATOMIC ENERGY AGENCY, Introduction of Nuclear Desalination, Technical Reports Series No. 400, IAEA, Vienna (2000)

2. S. U. D. Khan, S. U. D. Khan, S. N. Danish, J. Orfi, U. A. Rana, and S. Haider, “Nuclear Energy Powered Seawater Desalination,” *Renewable Energy Powered Desalination Handbook: Application and Thermodynamics*, pp. 225–264, Jan. 2018, doi: 10.1016/B978-0-12-815244-7.00006-4.

3 . K. Lee and W. Jepson, “Environmental impact of desalination: A systematic review of Life Cycle Assessment,” *Desalination*, vol. 509, p. 115066, Aug. 2021, doi: 10.1016/J.DESAL.2021.115066.

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