# MODELING, DYNAMICS AND CONTROL OF HORIZONTAL TUBE FALLING FILM MULTIEFFECT DESALINATION PLANTS

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## Contents



## Summary

This article summarizes the state-of-the-art in dynamic modeling and control of horizontal tube, falling film, ME distillers with a steam jet ejector for thermal vapor compression using a case study approach. A dynamic first principle model has been constructed for a four-effect plant. Selected modeling issues, such as the heat transfer coefficient, carbon dioxide, and ejector modeling, are addressed.

The dynamics of the plant have been studied with non-linear simulation and by a linear controllability analysis. The analysis showed that there are no significant limitations to the achievable control performance inherent in the plant design.

Based on the linear analysis results a decentralized control structure has been suggested. The resulting structure corresponds to the structure commonly implemented on actual ME plants. PI-type controllers were used to implement the control structure. It has been shown in dynamic non-linear simulations that these controllers give satisfying control

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performance provided that they are properly tuned.

Finally, MPC technology was applied to the ME plant. MPC did not achieve better control performance than the decentralized control structure employing PI-type controllers in base control cases. However, it could be shown that the application of MPC to advanced control objectives such as control of a performance index is promising.

## 1. Introduction

Like multistage flash evaporation (MSF), multieffect (ME) evaporation is a thermal desalination process. There are many different design variants of ME desalination plants. Typically, the design features, such as effect design (vertical tubes, horizontal tubes, submerged tubes, etc.), flow sheet lay-out (parallel, feed forward brine distribution, etc.), and the use of thermal vapor compression and additional brine pre-heaters, are varied.

For this study a horizontal tube, falling film, four-effect distiller plant with a steam jet ejector for vapor compression has been considered (Figure 1a). This kind of design is typically chosen to provide potable water in remote areas due to its high reliability and low demand in labor. The high-pressure steam used to drive the steam jet ejector is provided by an external boiler unit. The make-up seawater is distributed equally to all four effects. Only the make-up to the first effect is pre-heated by condensing steam from the vacuum ejectors. Part of the condensate from the first effect is used to desuperheat the vapor entering the first effect. The boiler unit receives its feedwater from the first effect distillate. The brine and remaining distillate flows are passed from effect to effect for flashing. The distillate flow leaving the plant is cooled by the seawater flow entering the cooler. The first and second effects have internal vents while the third and fourth effects are vented to the condenser. From there the vent flow is drawn off by the vacuum ejectors

The study was carried out to assess possible improvements in the control performance relative to the state-of-the-art control structures, as depicted by broken lines in Figure 2. In this control structure, the levels of brine and distillate in the last effect and condenser are controlled by varying the brine outlet flow and the distillate outlet flow. The brine temperature in the first effect is controlled by adjusting the motive steam valve of the ejector. This brine temperature is controlled to avoid the precipitation of solid salts which occurs at brine temperatures higher than a certain allowable top brine temperature (TBT). The temperature of the vapor in the condenser is controlled by varying the seawater reject flow. If the condenser temperature is too low the vapor volume flow exceeds the capabilities of the vapor channel between the last effect and the condenser. The set point of the brine temperature controller is set by a cascaded controller to control the distillate flow.

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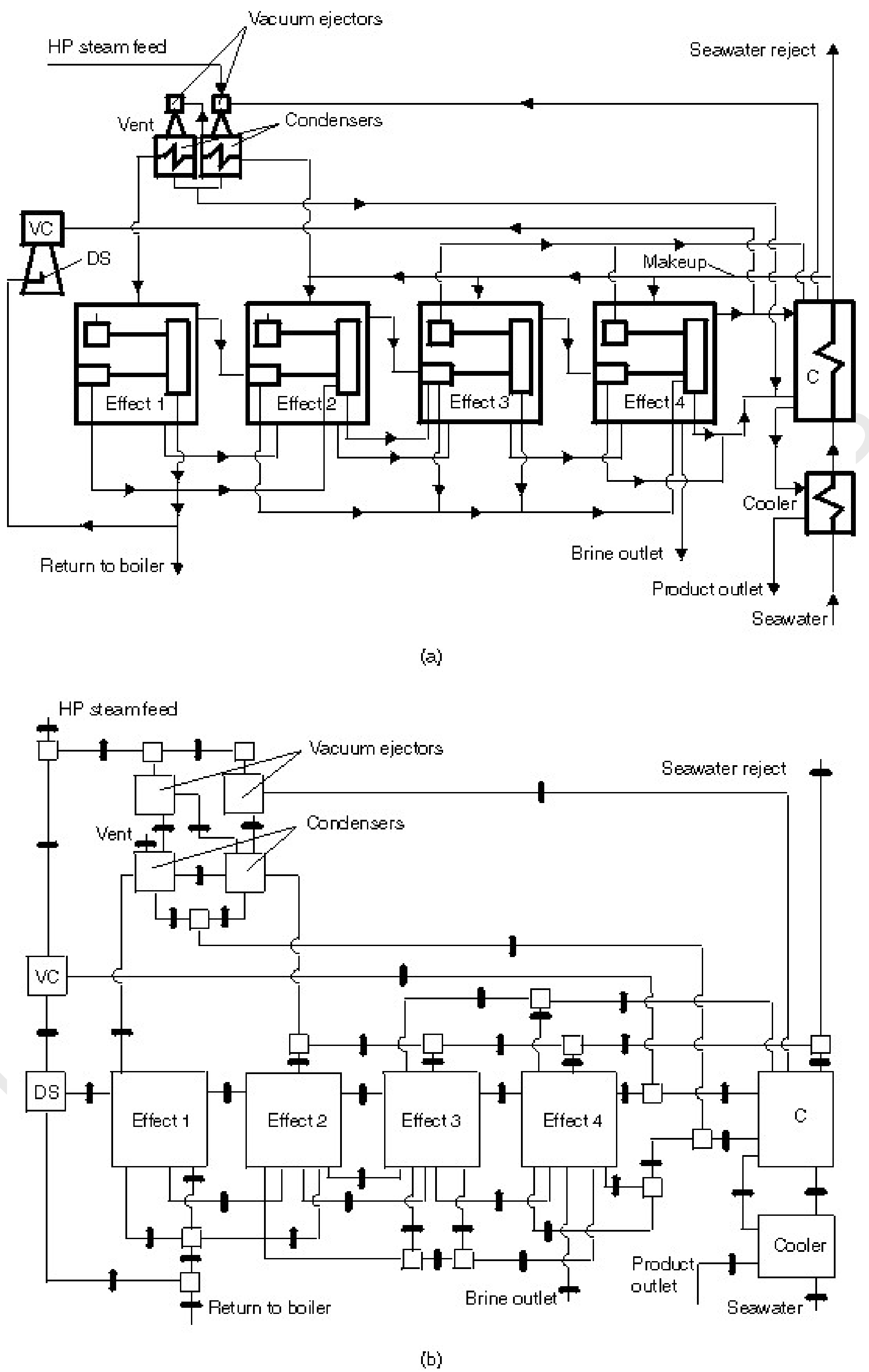


Figure 1. (a) Plant lay-out and (b) model structure. C, main condenser; VC, vapor compressor; DS, desuperheater.

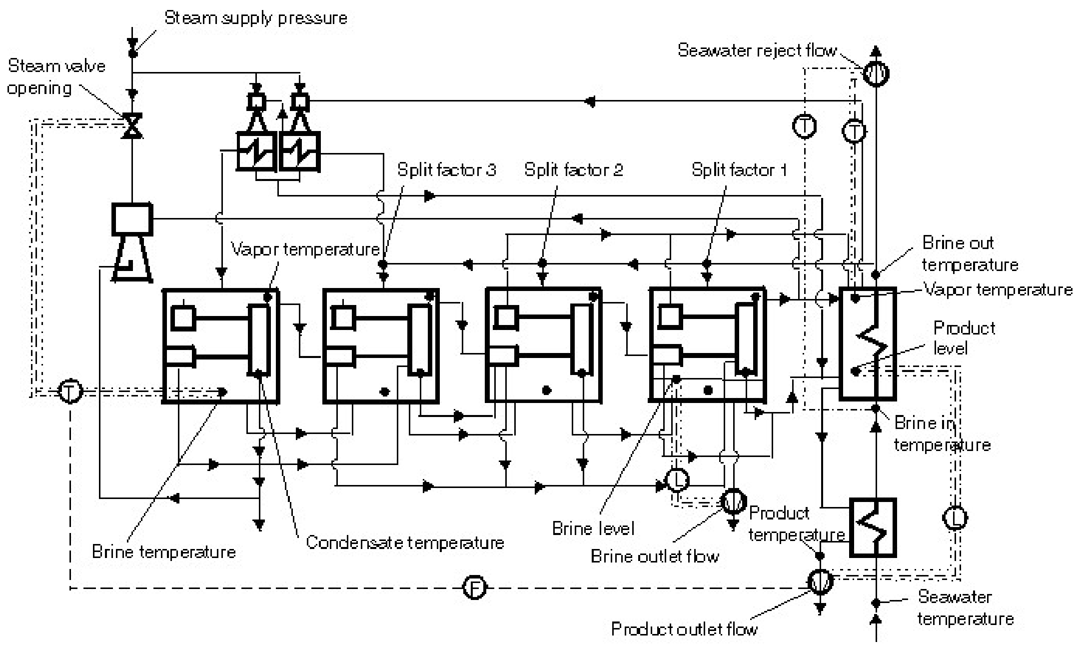


Figure 2. Control structures and measured, manipulated, and disturbance variables.

Our investigations confirmed the suitability of this common control structure for full load operation. However, the plant performance, as expressed by an efficiency factor (distillate flow divided by ejector motive steam flow), gets worse for partial load operation or if fouling is encountered. A model predictive control (MPC) scheme is therefore investigated for controlling the plant efficiency directly.

The study is based on a detailed first principles-based model of the plant. Such models have rarely been reported and only for special plant types. No reference to a dynamic model of an ME desalination plant with thermal vapor compression has been found in the literature.

In the general literature, Bolmstedt (1977) presented a detailed dynamic simulator for ME evaporation processes based on previous work (Bolmstedt and Jernqvist 1976). The simulator was designed to simulate general ME evaporation processes. Different flow sheet designs can be simulated because the simulator uses unit cells for the effects which can be connected arbitrarily. The simulator can be fitted to different configurations of an effect by supplying a special purpose subroutine for the heat transfer calculations. Bolmstedt (1977) also gave a review of earlier work on the dynamics and control of general ME plants. No reference to ME desalination plants has been reported.

In recent desalination literature the use of detailed first principles-based models for ME processes is reported for steady-state comparisons of different distillation processes in general (Darwish and El-Dessouky 1995), different flow sheet configurations of ME processes (Gregorzewski and Genthner 1995), and the effect of thermal vapor compression (Al-Najem et al. 1997). El-Dessouky et al. (1997) presented a very detailed steady-state model for studying the correlations between various design parameters of ME plants without vapor compression.

Recent studies on the dynamics of ME desalination plants only have been reported for a horizontal tube ME plant with a stack configuration of the effects. El-Nashar and Qamhiyeh (1990) used a model for this plant which included only dynamic energy balances to study the start-up. Reddy et al. (1997) discussed a model for the same plant which also included dynamic mass balances for the effects. Both models used correlations for the heat transfer derived from measured plant data.

Results on potential inherent limitations to controllability or on the application of advanced control schemes such as MPC to ME processes have not been reported.

## 2. Dynamic Modeling of ME Distillers

### 2.1. Model Overview

To model the plant in this study, a modeling methodology described in detail by Von Watzdorf and Marquardt (See: Dynamic Modeling and Simulation: Modeling Concepts and Model Overview). A feature of this methodology is that it distinguishes between model objects which can store extensive quantities (devices, as depicted in Figure 1b) and those which transport these quantities (connections, as depicted in Figure 1b as bold bars).

Figure 1(b) shows the chosen model structure for the four-effect plant. All submodels include lumped mass and energy balances. The behavior of all devices except the effects, condenser, and cooler is assumed to be in quasi-steady-state.

The brine and distillate flows between the effects are calculated from pressure drop correlations. The hydrostatic pressure of the liquid hold-up is taken into account. The distillate flow from the first effect is set to be equal to the actual high-pressure steam consumption. The flow through the motive steam valve is determined from a pressure drop correlation. All other flows, such as the steam to the venting system, the seawater feed, the seawater return, the distillate outlet, and the brine outlet are set directly to the desired flow rate. No models for valves and pumps are included for these flows.

The ejectors in the venting system are modeled by steady-state mass and energy balances only. The more detailed ejector model described below has not yet been used in plant simulations because no data was available on the vacuum ejectors. The desuperheater model also includes only mass and energy balances. The water feed rate to the desuperheater is assumed to be constant.

### 2.2. Effect Model

#### 2.2.1. Model Structure

The effects of the modeled plant are all assembled in line in a large cylindrical shell. Figure 3 shows one effect as a partial view of the whole shell. The previous and



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following effects are connected to the left and right, respectively.

The vapor enters the effect from the left side into the pre-chamber. The pre-chamber is the head space in front of the left tube plate. From there all vapor is forced through the first-pass tubes. At the end of the tubes a large water box collects the condensate and the remaining vapor flows through the second-pass tubes. The condensate from the second pass is collected in a small waterbox and guided to the large waterbox. The small box is either externally vented or an orifice allows a small vapor flow between the waterbox and the shell side for internal venting. The feed seawater is sprayed on the outside of the tubes where it is partly evaporated. The generated vapor can flow through demisters (not depicted in Figure 3) in the second tube plate around the large waterbox to enter the pre-chamber of the next effect.

Figure 3(b) shows the model structure of an effect. The vapor feed to the effect arrives in the pre-chamber model. Two additional interfaces provide connectibility to models describing the condensate flow from the pre-chamber to the condensate collection system or the hot condensate flow from previous effects to be flashed in the pre-chamber.

The first-pass tube bundle model and the pre-chamber model are connected by connections describing the vapor flow to the tubes and the condensate pouring from the tubes into the pre-chamber. Similarly, the first-pass model is connected to the waterbox model and the latter to the second-pass model.

The second waterbox is not modeled because of the negligible hold-up volumes. The condensate connection between the second pass and the waterbox accounts for the condensate pouring from both sides of the second-pass tubes. Like the pre-chamber, the waterbox model also has interfaces for in- and outflowing condensate.

All the device models mentioned so far include lumped dynamic mass and energy balances. They model a liquid and a vapor phase in phase equilibrium. The equilibrium temperature has been determined from steam tables corrected by a boiling point elevation accounting for the salts in the liquid phase. The vapor connections relate the pressure difference between the adjacent device models to the vapor flow rate by pressure drop correlations. The correlations used to calculate the condensate flow pouring from the tubes are presented in a subsequent section.

The brine side of the effect is modeled by three device models. The film model describes the brine film on the outer surface of the tubes. It includes stationary mass and energy balances according to the negligible hold-ups for energy and mass in the film. Since the flows at the brine feed interface and the vapor-liquid interface connection are given by other models, the connection describing the brine dropping from the tubes does not have to provide a correlation for the brine flow from the tubes' surface.

The brine model represents the brine collecting at the bottom of the effect. It includes dynamic mass and energy balances. The vapor device accounts for the vapor space around the tubes in the effects. It has also dynamic mass and energy balances.

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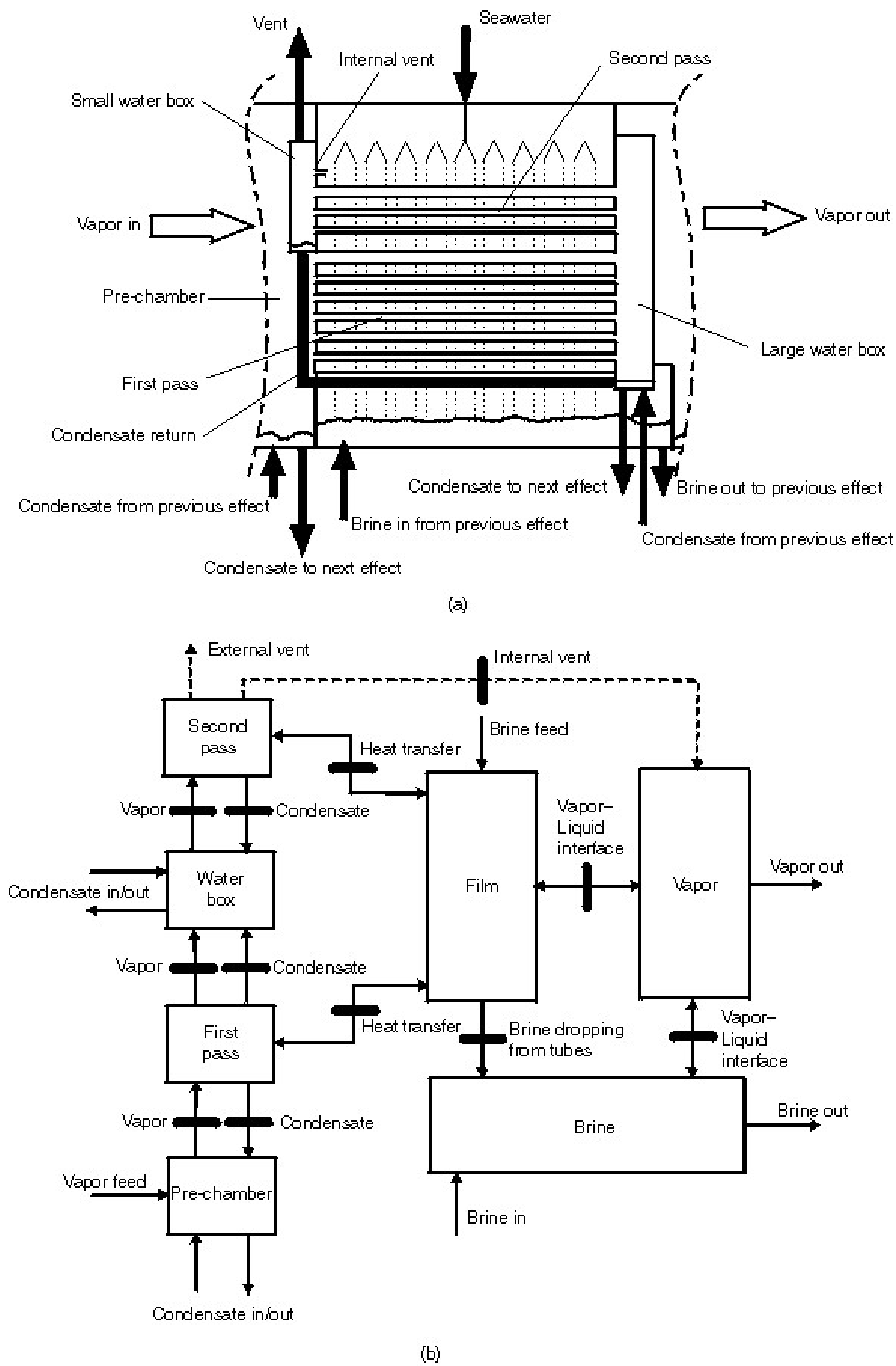


Figure 3. (a) Effect design and (b) model structure.

The vapor-liquid interface connections between film, vapor, and brine correlate the mass and energy flows between the adjacent phases to the molar concentration and temperature differences between them. A simplified version of the multicomponent mass transfer models described by Taylor and Krishna (1993) has been applied.

The heat transfer between the condensing vapor and the brine is modeled in the heat transfer connections between the pass and film devices. The heat transfer coefficient models used are discussed in a subsequent subsection.

Depending on the kind of venting of the effect, the second-pass model either provides an interface for access to external models or there is a vapor flow connection between the vapor space on the brine side and the second-pass model. The latter connection model relates the vent flow rate to the pressure drop between the devices.

Since water and the accumulated salts are considered as components of the liquid phases and water as the only component of vapor phases the total effect model includes 17 dynamic state variables.

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