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Stochastic evolution of regulation errors in a boundary-actuated desalination plant

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ABSTRACT

A desalination plant – considered in two configurations (once-through and brine recirculation) – is modelled and controlled using a system of coupled PDEs that describe the desalination processes. The analysis is conducted in two separate parts. First, the operating point of the plant is obtained based on the deterministic process models of the plant. The steady-state distillate production is optimized with respect to a reference pressure head (operating point) that is achieved by applying relatively simple boundary controls. Both deterministic plant configurations are compared in term of characteristic numbers that evaluates the energy-efficient operation of the plant. In particular, those are the thermal ratio and the specific flow rate, where gains of roughly 5.5% and 21.5% are obtained in favour of the brine recirculation plant. The pressure head is subject to turbulence phenomena that disturb its surface so that a deterministic model is an insufficient representation of the real-case scenario. Concerning the second part of the paper, the effects of turbulence are incorporated through stochastic elements given as generalized and cylindrical Wiener processes located on the boundaries and throughout the plant (subdomain), respectively. The pressure head residual is defined as the difference between the deterministic and stochastic system. As both systems are actuated by the same type of boundary controls, the residual field is interpreted as a measure of a regulation error. It is statistical characterization is done spatially by means of the first four statistical moments (sampled) and temporarily with the autocorrelation function. It is found that the applied boundary controls are robust enough to keep the regulation error within tight bounds throughout the whole subdomain of the plant. Throughout the plant, the spatial standard deviation (std) is less than 0.3.

1. Introduction

Many parts of the world suffer from shortage of potable water supplies due to reasons such as increase of population and uneven distribution of water resources [1]. The aforementioned trend of water stress has been steadily increasing over the past and is not expected to subside in the future. Having reliable solutions for potable water supplies are an essential objective in that regard. On an industrial level, the multi-stage desalination plant (MSF) has been one of the most popular solutions for large-scaled production capacities [2]. These type of plants are mainly implemented along the shore lines of the Gulf states and USA [3,4]. When it comes to small-scaled production, desalination plants are also utilized on ships during cruises for on-board drinking water production [5].

The desalination plant is characterized by numerous interconnected subsystems and their associated dynamic processes. Safe and efficient operation relies on the design of control systems for which a comprehensive overview is provided in [6,7]. The development of accurate static and dynamic models is one of the most crucial aspect prior to designing the real-time control system. During the dimensioning phase, static models are usually used in order to tune parameters and obtain the operating points of the plant that involves components such as brine heater, mixing tanks and evaporation stages, etc. [8–10]. Regarding the design of the control system, dynamic models of the desalination processes are required as reported in [11–13]. All the processes have been considered as a system of coupled ODEs covering the most relevant dynamics that are the pressure head, brine salinity and the brine temperature inside each tank. The desalination plant has a cascaded structure by connecting each single evaporation stage via a submerged orifice.

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Nomenclature

Acronyms

BR	brine-recirculating configuration
CFD	computational fluid dynamics
OT	once-through configuration
pdf	probability density function
TBT	top brine temperature

Greek symbols

α	spatial correlation coefficient
η	thermal performance ratio
$\gamma(x)$	spatial skewness
$\kappa(x)$	spatial kurtosis
κ_{cv}	control valve parameter
$\lambda_s(x)$	latent heat at saturation condition, J/kg
ν	specific flow rate
ω	random element from the sampled space, where the stochastic processes are defined
ρ	brine density, kg/m^3
$\sigma(x)$	spatial standard deviation
σ_0	noise intensity at the inlet boundary
σ_d	noise intensity in the subdomain
σ_L	noise intensity at the outlet boundary
τ	time lag, s
$\varepsilon_H(t, x)$	pressure head residual
ζ_0	noise intensity of the ingoing mass flux
ζ_L	noise intensity of the outgoing mass flux

Latin symbols

$\bar{A}_{bh}$	averaged heat transfer area in brine heater, m^2
$\bar{A}_{ct}$	averaged heat transfer area of condenser tubes, m^2
$\mathbf{z}(t, x)$	vector of process variables
A	bottom cross section of single evaporation stage (in ODE representation), m^2
a	cross section of orifice perpendicular to flow velocity vector (in ODE representation), m^2
a_j	polynomial coefficients of latent heat $\lambda_s(x)$
B	unit operator ($B = I$) or functional operator in coloured noise realization
$c(t, x)$	salinity, mol/m^3
c_p	specific heat capacity of the brine, J/kg K
c_{max}	upper limit of discharged brine salinity, mol/m^3
D_0	maximum diffusion coefficient, m^2/s
D_j	diffusivity coefficient of species j, m^2/s
e	regulation error, m
E_A	activation energy for diffusion, J/mol
$F(t, x)$	distillate production, m^3/s
g	gravitational constant, m/s^2
$H(t, x)$	pressure head, m
$H_x(t, x)$	pressure head gradient
K	parameter representing the back pressure from the cumulated pressure head located downstream of location x, m
k	Boltzmann constant
K_I	integral gain
k_j	advection coefficient of species j, m/s
K_P	proportional gain
L	length of desalination plant, m
m	number of spatial samples
$m(x)$	spatial mean
n	number of time samples
$p(x)$	pressure distribution, Pa
p_x	pressure gradient, Pa/m
p_{atm}	atmospheric pressure, Pa
Q	flow rate, m^3/s
$q_{ev}(t, x)$	relative evaporation rate, 1/s
R	orifice resistance, s/m^2 $\sqrt{\mathrm{m}}$
$R(x, \tau)$	autocorrelation function
R_g	universal gas constant, J/kg K
r_j	reaction term of species j, 1/s
S_{cyl}	equivalent cross section area of all condenser tubes, m^2
T	terminal time instant, s
t	time variable, s
$T(t, x)$	brine temperature, K
$T_s(x)$	saturation temperature, K
$T_{ct}(t, x)$	condenser tubes temperature, K
U	overall heat transfer coefficient, W/m^2 K
V	volume, m^3
$W(t, x)$	Wiener process
x	spatial coordinate, m

Sub- and superscripts

*	reference condition
0	initial condition
∞	steady-state condition
ref	control reference
bd	blow-down
bh	brine heater
ct	condenser tubes
ext	external
in	ingoing
mix	mixing tank
out	outgoing
rec	recirculation
S	shell-side
s	saturation condition
sea	seawater
st	steam
T	tube-side

In [14], the established ODE process models – from aforementioned authors – have served as a starting point for a different perspective on the modelling task of a desalination plant. An equivalent PDE model has been derived for the relevant dynamics by parametrizing the submerged orifices in a way that it accounts for the physical separation of the walls, flow resistance and mass hold-up. The PDE model has been represented as diffusion-advection-reaction equations and the dynamics were shown to be in good agreement with the existing ODE models.

1.1. Contribution of the paper

The paper is structured in two distinct parts that is outlined next. First, the process models of the desalination plant are presented in deterministic form and are utilized during the design phase, which is outlined as follows.

1.1.1. Deterministic analysis

- A distributed parameter model is presented for the basic desalination dynamics in the form of diffusion-advection-reaction equations. The resulting system of coupled PDEs is provided for two typical plant configurations: (A) once-through (OT) plant and (B) brine recirculating (BR) plant.
- The operating point of the plant is obtained as a reference pressure head distribution inside the plant that aims at efficient distillate production in steady-state conditions. The pressure