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The development of a dynamic single effect, lithium bromide absorption chiller model with enhanced generator fidelity

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ABSTRACT

Single effect, lithium bromide absorption chillers offer the ability to utilize low-pressure steam to produce chilled water for satisfying various comfort cooling needs. Previous attempts have been made to characterize dynamic and steady-state absorption chiller operation. Though these models perform adequately, they are based on hot water driven absorption chillers. Commercially available absorption chillers often can run on both hot water and low-pressure steam. In this paper, the mathematical framework for a dynamic single effect, lithium bromide absorption chiller model capable of using low-pressure steam is presented. The transient thermodynamic FORTRAN model is grounded on mass, energy, and species balances, and builds on prior modeling efforts. Well-known correlations for heat transfer coefficients are used to describe both tube-side and shell-side heat transfer rates in each primary chiller component. To account for the absorption chiller unit receiving steam, a heat transfer model for condensation inside horizontal tubes based on distinct internal condensation flow regimes is incorporated within the generator. This heat transfer model is used with two-phase flow pressure drop equations to establish steam temperature, quality, and pressure along the generator tube bundle. Steam consumption trends are established as a function of fluctuating external conditions. These trends reasonably align with information made available online by the manufacturer, though some deviation does occur at low chiller capacities and cooling water temperatures. Additionally, the transient response of internal and external parameters from a step increase in heat input supplied to the generator mimics results of other dynamic absorption chiller models found throughout literature.

1. Introduction

Electric chillers have been predominantly used to produce chilled water for satisfying cooling demands due in large part to inherent high vapor-compression cycle Coefficients of Performance (COP), flexible unit placement, and fast transients. Fundamentally, compressing a vapor necessitates a large energy input, which electric chillers receive in the form of electricity. Single effect, lithium bromide (LiBr) absorption chillers, on the other hand, harness energy from hot water or low-pressure steam less than 205 kPa (15 psig) and the affinity between an absorbent and a refrigerant to create a chilling effect. Though COPs of single effect absorption chillers are significantly less than those of equivalent size electric chillers, absorption chillers offer a niche in that they can utilize low-pressure steam or hot water that might otherwise be rejected to a low-temperature sink or the environment.

The miniscule electrical power requirement relative to the heat input necessary to drive absorption chillers makes them particularly attractive in waste heat and solar thermal applications, especially given present-day concerns of carbon emissions. This heightened interest has spurred a plethora of analyses predicated on the steady first and second laws of thermodynamics. For example, Pongtornkulpanich et al. [1] applied basic relations to design solar-driven LiBr absorption chillers for buildings. Agyenim et al. [2] conducted a similar study on solar-driven LiBr absorption chillers. Chen et al. [3] designed the framework of a LiBr absorption chiller powered via a supercritical CO_2 solar collector. Gomri [4] performed a second law of thermodynamics comparison of single effect and double effect, LiBr absorption chillers. Lastly, Bakhtiari et al. [5] developed a steady-state model of a 14-kW single effect, LiBr absorption chiller. A comparison of the steady-state simulation results and experimental measurements revealed good agreement [5].

While these studies reveal important steady-state absorption chiller trends, understanding part-load and dynamic operation is vital for describing real absorption chiller performance. Large absorption chiller thermal masses coupled with temperature-driven mass transfer and deposition translate into long absorption chiller transients compared to

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Nomenclature

Latin variables

T	temperature (°C)
M	mass (kg)
c_p	specific heat (kJ kg^{-1} K^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
t	time (s)
UA	overall heat transfer coefficient (kW K^{-1})
ΔT_{lm}	log mean temperature difference (°C)
h	specific enthalpy (kJ kg^{-1})
X	water-LiBr mass fraction (%)
H	height between upper and lower shell components (m)
P	pressure (kPa)
C_d	discharge coefficient (–)
y	fluid level in heat exchanger level (m)
g	gravity (m s^{-2})
$\dot{Q}$	heat transfer rate (kW)
D	diameter (m)
R''	thermal resistance (m^2 K kW^{-1})
k	thermal conductivity (kW m^{-1} K^{-1})
Re	Reynolds number (–)
Pr	Prandtl number (–)
Nu	Nusselt number (–)
Ga	Galileo number (–)
Ja	Jakob number (–)
z	axial distance (m)
L	length (m)
n	number of tubes (tubes)
N	number of (–)
$\dot{V}$	volumetric flow rate (m^3 s^{-1})
x	quality (–)
f	friction factor (–)
G	mass flux (kg s^{-1} m^{-2})
X_{tt}	Lockhart-Martinelli parameter (–)
c_1, c_2	constants (–)
C	correction factor (–)
r	radius (m)
g_c	gravitational constant (kg m N^{-1} s^{-2})
A	area (m^2)
V	volume (m^3)
NR	average number of tubes per row (tube row^{-1})
NTU	number of transfer units (–)

Greek variables

ε	effectiveness (–)
ρ	density (kg m^{-3})
ζ	loss coefficient (–)
μ	dynamic viscosity (kg m^{-1} s^{-1})
Γ	film flow rate (kg s^{-1} m^{-1})
α	heat transfer coefficient (kW m^{-2} K^{-1})
Δ	difference (–)
$\varnothing^2$	two-phase flow multiplier (–)
θ	angle from top of tube to condensate level in bottom of tube (Ra)
σ	vapor void fraction (–)

Subscripts

i	inner tube surface
o	outer tube surface
in	inlet
out	outlet
eva	evaporator
con	condenser
abs	absorber
gen	generator
w	wall
l	liquid
v	vapor
IHX	intermediate heat exchanger
strat	stratified
f	friction
lo	liquid only
ct	cooling tower
ch	chilled water
st	steam
fo	fouling
nom	nominal
calc	calculated
weak	dilute water-LiBr solution mixture
strong	concentrated water-LiBr solution mixture
fi	film
x	cross-sectional
atm	atmospheric
wb	wet-bulb
db	dry-bulb
tot	total
met	metal
recirc	recirculation
pan	condenser pan
avg	average
t	tube
sol	solution
vo	vapor only
ls	superficial
no	nodes
max	maximum
min	minimum
air	air

their mechanical-driven vapor-compression cycle counterparts; thus, it is advantageous to accurately depict dynamic absorption chiller behavior. However, the mass, temperature, and species transport phenomena within the chiller dictates establishing and solving a highly non-linear system of time-dependent conservation equations at each time-step, which can be computationally expensive.

Several models aim to characterize dynamic single effect, LiBr absorption chiller performance while implementing significant steady-state simplifications. Anand et al. [6] led early absorption chiller research efforts in which they modeled isolated absorption chiller components as well as an entire 10.55-kW chiller in order to gain insight on unit warmup and shutdown procedures. Later, Kohlenbach and Zielger [7] developed an absorption chiller model based on external and internal steady-state enthalpy balances. Despite assuming constant water-LiBr properties, constant overall heat transfer coefficient (HTC) values, and that evaporation and solution enthalpy are constant, simulation results reasonably agreed with experimental data obtained from a 10-kW absorption chiller [8]. Borg and Kelly [9] modeled dynamic absorption chiller behavior using a series of interrelated control volumes with lumped heat exchanger masses and experimentally calibrated performance maps. Li et al. [10] simulated dynamic absorption chiller performance in tropical climates using local energy and mass balances