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Numerical simulation and experimental validation of a helical double-pipe vertical condenser

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ABSTRACT

A predictive model is developed to describe heat transfer and fluid dynamic behavior of a helical double-pipe vertical condenser used in an absorption heat transformer integrated to a water purification process. The condenser uses water as working fluid connected in countercurrent. Heat transfer by conduction in the internal tube wall is considered; in addition the change of phase is carried out into the internal tube. The dynamic model considers equations of continuity, momentum and energy in each flow. The discretized governing equations are coupled using an implicit step by step method. Comparison of the numerical simulation over range of experimental data presented in the heat device is applied to validate the model developed. The model is also evaluated of form dynamic to determine the principal operation variables that affect the condenser with the main objective to optimize and control the system. A variation of mass flow rate in the internal pipe induces important changes on the heat flux that the pressure and temperature.

1. Introduction

Condensation is a important phenomenon that occurs in many applications [1]. Helical coiled tubes are extensively used in steam generators, refrigerators, nuclear reactors and chemical plants, etc., due to their practical importance for high efficiency heat transfer, compactness in structure, ease of manufacture and arrangement [2].

The condensers and evaporators devices model have been studies by different authors. Wang [3] presented a numerical method to analyze the two-phase condensing flow in a double-pipe condenser using a semi-implicit finite-difference scheme used to solve the governing equations. Morales et al. [4] presented a numerical study of the thermal and fluid-dynamic behavior of the two-phase flow in ducts under condensation or evaporation phenomena. The authors discretized governing equations and solved using the semi-implicit method for pressure linked equations. Colorado et al. [5] developed a predictive model to describe heat transfer and fluid-dynamic behavior of a helical double-pipe vertical evaporator for a heat transformer. Ali [6] performed analytically a design of a compact plates-and-frames absorber possessing a hydrophobic microporous membrane contactor at the aqueous solution water vapor interface. The absorber is a component of a 5 kW cooling capacity single-effect lithium bromide-water absorption chiller that incorporates a hot water thermally driven generator and a water-cooled absorber and condenser. Voyiatzis et al. [7] developed a transient one-dimensional model, capable of describing the performance of a newly introduced adsorption chiller with continuous operation. Gao et al. [8] carried out the numerical and experimental assessment of thermal performance of vertical energy piles. Lee and Lu [9] evaluated empirically models for predicting energy performance of vapor-compression water chillers. Li et al. [10] developed and experimentally validated a special simulation module for variable refrigerant flow system with a water-cooled condenser (water-cooled VRF). Also, the flow patterns of two-phase condensation flow in tubes have been studied experimentally by Wang [11].

Helical double-pipe vertical condenser is also used in the absorption heat transformer integrated to a water purification process. The water purification process used in the absorption heat transformer is a simple distillation process where impure water is heated to obtain vapor which is immediately condensed. The condenser releases heat and pure water. The absorption heat transformer is a system that consists of a thermodynamic device capable of producing useful heat at a thermal level superior to the one at the source [12,13]. This integration of both systems enables to increase the temperature of the impure water system, and thus obtain pure water and useful heat. Thermodynamic models to absorption system have been studied by different authors. Sencan et al. [14] presented a thermodynamic and exergy analysis for single-effect lithium bromide/water absorption system for cooling

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Nomenclature

A	cross area section [m^2]
AB	absorber
b	coil pitch [m]
CO	condenser
COP	coefficient of performance [dimensionless]
Cp	specific heat at constant pressure [J/kg °C]
CV	control volume
D	helical diameter [m]
Dn	Dean number $\left[Dn = Re\left(\frac{d}{D}\right)^{\frac{1}{2}}\right]$
d	diameter [m]
EV	evaporator
Fr	concentration relation [dimensionless]
f	friction factor [dimensionless]
g	acceleration due to gravity [m/s^2]
GE	generator
G	mass velocity [kg/m^2 s]
H	height of helical coils[m]
h	enthalphy [J/kg]
He	Helical number $\left[He = \frac{Dn}{[1+(b/2\pi(d/2))^2]^{\frac{1}{2}}}\right]$
$\dot{m}$	mass flow rate [kg/s]
L	length of helical coil [m]
m	mass [kg]
n_z	number of control volumes
Nu	Nusselt number $\left[Nu = \frac{\alpha \cdot d}{\lambda}\right]$
p	pressure [bar]
P	perimeter [m]
Pr	Prandtl number $\left[Pr = \frac{Cp\mu}{\lambda}\right]$
$\dot{q}$	heat flux per unit of area [W/m^2]
Q	heat flux [W]
%RSD	relative standard deviation
Re	Reynolds number $\left[Re = \frac{Gd}{\mu}\right]$
s	deviation standard
t	time [s]
T	temperature [°C]
v	velocity [m/s]
X	solution concentration in %wt
X_{tt}	Martinelli parameter $\left[X_{tt} = \left(\frac{1-x_g}{x_g}\right)^{0.9}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\mu_g}{\mu_l}\right)^{0.1}\right]$ [dimensionless]
x_g	vapor mass fraction [dimensionless]
z	axial coordinate

Greek letters

θ	angle [rad]
ρ	density [kg/m^3]
δ	convergence criterion [dimensionless]
σ	superficial tension [N/m]
Φ	two-phase frictional multiplier [dimensionless]
α	heat transfer coefficient [W/m^2 °C]
τ	shear stress [Pa]
λ	thermal conductivity [W/m °C]
μ	dynamic viscosity [Pa s]
ϵ_g	void fraction [dimensionless]
Δt	temporal discretization step [s]
Δz	axial discretization step [m]

Subscript

Anu	annulus
c	coiled
exp	experimental
g	vapor
Int	internal pipe
l	liquid
s	straight
sim	simulation
tp	two-phase flow

Superscripts

$\circ$	previous instant
$*$	previous iteration

and heating applications. Sozen and Serder Yucesu [15] showed a mathematical model of absorption heat transformer operating with the aqua/ammonia coupled to a solar pond and used a special ejector. Therefore, these thermodynamic models are considered to estimate the Coefficient of Performance (COP), which are based on some assumptions that might be to difficult fulfill in practice. The heat flux to condenser is calculate under steady-state conditions. Nevertheless, it is necessary to calculate heat flux in dynamic state to control the on-line system.

According to Sozen and Arcaklioglu [16] for an ejector-absorption heat transformer, increasing condenser temperature increases evaporator temperature for working heat transformer and decreased COP. The heat flux of the condenser is key to the performance of the evaporator in a heat transformer. Consequently, the objective of this paper is to develop a physical model to describe heat transfer and fluid-dynamic behavior inside a helical double-pipe vertical condenser (CO). Therefore, study of helical condenser is important because is a part of absorption system and influence COP.

2. Experimental data

Experimental database provided by Huicochea and Siqueiros [17], consist of different COP values with energy recycling, obtained from a portable water purification process coupled to an absorption heat transformer. The experimental data set was the result of different initial concentrations of LiBr + H_2O in AB and GE, different temperatures in AB, GE, EV, CO and different pressures in AB and GE. In addition to the experimental data of each component, the steady-state is taken into account for each initial concentration used in the process. From this database only the experimental database of the condenser (CO) is considered in this work.

The condenser has a design of helical double-pipe heat exchanger. The whole system was built with stainless steel tubes and was well isolated by foam insulation. Table 1 describes the dimensions of the helical condenser. In the internal pipe, working fluid flow (water), which changes from vapor phase to liquid phase, reached the heat to the cooling water (annulus).

Table 1
Dimensions of the helical double-pipe condenser.

	Internal pipe (mm)	External pipe (mm)
External diameter (d)	17.1	26.67
Internal diameter (d)	13.8	22.45
Helical diameter (D)	194	194
Turns	5	5
Length (L)	3000	3000
Height (H)	330	330
Coil pitch (b)	60	60