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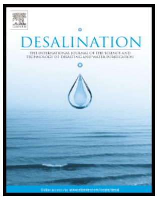

Numerical study of counter-current desuperheaters in thermal desalination units

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HIGHLIGHTS

- The performance of a counter-current desuperheater is investigated in this study.
- Numerical simulation is done by using the discrete phase model approach.
- Effective parameters on desuperheater performance improvement are considered.
- Numerical result of desuperheated steam is well approved by experimental data.

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ABSTRACT

One of the methods for decreasing the temperature of superheated steam is utilizing desuperheaters which by injecting a fine spray of cooling water and maximizing the evaporation surface, lead to reduce the superheated steam temperature. In this study, a counter-current desuperheater in a thermal desalination unit which is used to reduce the outlet steam temperature of a thermo-compressor is simulated by using the discrete phase model (DPM) and the Eulerian-Lagrangian approach. The effect of different parameters such as the vapor velocity, sprayed droplets size, cooling water mass flow rate, the location, and direction of cooling water injection on desuperheaters performance are considered. The results show that mentioned parameters have considerable influence on the performance of desuperheaters. Numerical results of desuperheater outlet steam temperature show good agreement with experimental data with an average error of 4.89%.

1. Introduction

Superheated steam has important advantages on certain applications such as power generation, steam engine, steam drying, steam oxidation, chemical, and food processing. However in many cases, to efficient use on heating applications, the steam must be controlled in the saturation point. Desuperheating is the process whereby superheated steam turns to its saturated state, or the superheated temperature is reduced. For this purpose, desuperheaters are used which regulate the temperature of superheated steam by injecting a spray of cooling water [1]. Several parameters such as cooling water mass flow rate, injection manner, temperature and pressure of inlet superheated steam and injected droplets diameter play lead roles in desuperheater design and selection.

Desuperheaters are found in many major industries [2] such as industrial heating system, thermal desalination units, food processing, shipboard service and turbine bypass steam temperature control. Due to the cost of experimental studies and their time-consuming aspects to design and optimization of desuperheaters performance numerical simulations have been desired in recent years [3]. An appropriate method for numerical simulation of particulate two-phase flows is discrete phase model, which is based on the Eulerian-Lagrangian approach.

Chrigui et al. [4] analyzed the interaction between evaporating droplets and the turbulent flow of the air stream using an Eulerian-Lagrangian approach. They studied the effect of the droplet evaporation on the mass and heat transfer processes and the influence of the turbulent fluctuations of velocity on the droplet evaporation rate. Ren and Yang [5] analytically studied heat and mass transfer in co-current and counter-current flow of an indirect evaporative cooler and investigated effects of sprayed water evaporation and the temperature and enthalpy changes of water during the surface heat transfer.

Ebrahimian and Gorji [6] simulated the cooling water sprayed to the same direction superheated steam with discrete phase model and investigated the influences of temperature, pressure and velocity of the superheated steam on the evaporation rate of the cooling water. Kouhikamali et al. [2] simulated the heat transfer of water droplets and superheated steam, as a two phase drop flow in co-current

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desuperheaters, by using a discrete phase model. They studied the effects of water droplets diameter, water mass flow rate and tube diameter on the required length for droplets evaporation.

Nomenclature

a_1, a_2, a_3	constant experimental parameters
A_p	particle area (m^2)
C_D	drag coefficient
C_m	momentum exchange coefficient
c_p	specific heat capacity (J/kg K)
$c_{p,\infty}$	heat capacity of the vapor bulk flow (J/kg K)
C_s	thermal slip coefficient
C_t	temperature jump coefficient
D	tube diameter (m)
$D_{T,P}$	thermophoretic coefficient
d_p	particle diameter (m)
F_x	additional acceleration force (N/kg)
F_{saff}	Saffman lift force (N/kg)
F_v	virtual mass force (N/kg)
F_T	Thermophoretic force (N/kg)
g	gravitational acceleration (m/s^2)
h	convective heat transfer coefficient (W/m^2K)
i_{fg}	latent heat (J/kg)
k	fluid thermal conductivity based on translational energy only = (15/4) μR
k_p	particle thermal conductivity (W/m K)
k_∞	thermal conductivity of the vapor bulk flow (W/m K)
Kn	Knudsen number
Kr	the ratio of thermal conductivity (k/k_p)
$\dot{m}_i$	inlet mass flow rate (kg/s)
m_p	particle mass (kg)
Nu	Nussult number
P	pressure (Pa)
Pr	Prandtle number
Re_d	relative Reynolds number
t	time (s)
T	temperature (K)
T_p	particle temperature (K)
T_∞	temperature of continuous phase (K)
u	fluid velocity (m/s)
u_p	particle velocity (m/s)
z	location of injection

Greek letters

ε	turbulent kinetic energy dissipation rate (m^2/s^3)
κ	turbulence kinetic energy (m^2/s^2)
ρ	density (kg/m^3)
ρ_p	particle density (kg/m^3)
μ	dynamic viscosity (kg/m s)
ν	kinematic viscosity (m^2/s)
ω	specific dissipation rate (1/s)

Subscripts

i, o	inlet and outlet of tube, respectively
bp	boiling point
cw	cooling water
p	particle (water droplet)
Saff	Saffman's lift force
s	superheated steam
ref	reference
T	thermophoretic
vap	vaporization
0	initial state

Lee and Lee [7] experimentally studied a counter flow regenerative evaporative cooler with finned channels and examined influence of water vapor mass flow rate, inlet temperature and pressure changes in their experiments. Alkhedhair et al. [8] numerically studied air pre-cooling with water sprays in natural draft dry cooling tower. They simulated a 3-D model of a test channel with a single spray nozzle along the air direction. They studied the effects of droplets size, air velocity and gravity. The results showed that non-uniform temperature distribution existed and air was cooled mostly in the lower half-region due to gravitational effect. Thus it was seen that air velocity played a significant role in evaporation. Lower air velocity causes longer traveling time, therefore better evaporation.

Sadafi et al. [9] investigated the performance of saline water, compared to pure water as the coolant in spray cooling by using the discrete phase model. They studied a practical spraying application which the air stream was cooled using an array of water spray nozzles and showed that the use of saline water can lead to a number of benefits, such as reduced water costs (compared to pure water) and improved cooling efficiency. Furthermore full evaporation was observed substantially earlier compared to the pure water case.

In this study, a counter-current flow desuperheater in a thermal desalination unit which is used to reduce the temperature of a thermo-compressor outlet steam to the saturation point is simulated by using a discrete phase model and the influence of injected droplets size, vapor velocity, cooling water mass flow rate, the location, and direction of cooling water injection on desuperheating process have been investigated.

2. Basis of numerical simulation

2.1. Numerical method

The discrete phase model formulation is used to simulate desuperheaters operation in present work. DPM implements the Eulerian approach for continuous phase and the Lagrangian approach for second phase. Second phase consists of spherical particles (droplets) dispersed in the continuous phase. It should be noted that the discrete phase formulation includes the assumption that the second phase is sufficiently dilute. While the continuous phase always impacts the discrete phase, the impact of the droplets on the continuous phase is considered as source terms to the governing equations of mass, momentum and energy. Due to turbulency of the flow, the shear stress transport $\kappa-\omega$(SST) model [3] is used in computational fluid dynamics (CFD) model. The selection was based on test among other models, including different $\kappa-\varepsilon$models and standard $\kappa-\omega$model, and for accessibility of best results with selective $\kappa-\omega$model as compared to experimental results. Fig. 1 shows the reverse flow type axial desuperheater, where z is the location of cooling water injection.

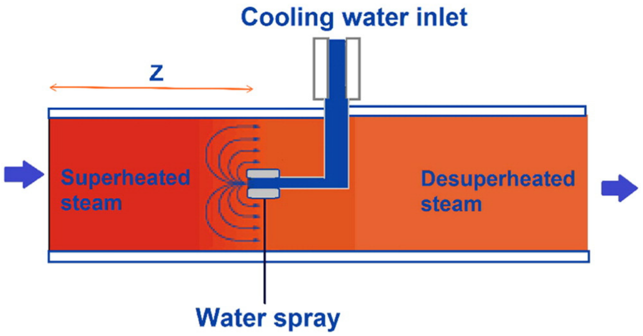

Fig. 1. The Reverse flow type axial desuperheater (counter-current flow).