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Investigation of the condensation process of moist air around horizontal pipe

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ABSTRACT

The condensation process of water vapor from moist air flowing around horizontal pipe is investigated theoretically and experimentally. This process involved in many engineering applications, such as refrigeration and air conditioning. In the theoretical analysis, the flow is assumed to be laminar, steady and with constant physical properties. The condensation process is described by continuity, momentum, energy and mass in the form of dimensionless ordinary differential equations using similarity variables. The dimensionless governing equations are solved by Runge Kutta fourth order integration technique accompanied with shooting method. The boundary layer thickness of mass, thermal and hydrodynamic, in addition to Nusselt and Sherwood numbers are investigated at different Reynolds numbers, and condensation and position parameters. In the experimental work, the effects of air inlet conditions (i.e. relative humidity, and mass flow rate) are varied and examined on the condensation process. The findings show that the average heat and mass transfer coefficients increase with increasing air mass flow rate and air relative humidity, and decrease with increasing the temperature difference between the air dew point and pipe surface temperature. Comparisons between the present theoretical and experimental work with previous theoretical study are accomplished within accepted error.

1. Introduction

Condensation process from moist air is widely employed in heat exchanger devices such as desalination units, refrigeration units, petroleum refinery and food industries. The heat and mass transfer process associated with condensation over flat plate and around pipe is important for many industrial applications. Condensation process over flat plate and around horizontal pipe was studied by many researchers. The condensation from moist air (including mass transfer) has less attention and seems to need more effort seeking for good understanding of this process. Gaddis and Rose [1,2] studied the condensation of steam on horizontal pipe. Yaghoubi, Kazeminejad [3] studied the effect of inlet relative humidity of moist air over horizontal flat plate. Legay-Desesquelles [4] studied the effect of temperature difference between the inlet temperature of moist air and surface temperature over horizontal flat plate. Condensation of moist air on horizontal pipe is studied by Ref. [5], the study was unsteady state condition for flow under supersaturated frosting. Heat transfer with condensation of water vapor from moist air was investigated by Refs. [6–22]. Cheng and Junming [23] presented a numerical investigation for condensation of humid air along a vertical plate using mathematical model built on the full boundary layer equations and the film-wise condensation assumption. Wilson and Newell [24] performed an experimental investigation to examine the combined buoyancy driven heat and mass transfer in open cavities of different aspect ratios. Sakakura and Yamamoto [25] investigated a numerical study of condensate flows of moist air in a cooled pipe by using the preconditioning method for solving incompressible and compressible Navier–-Stokes equations with additional equations and source terms for condensate flows. Xiaojun et al. [26] illustrated that the indoor moisture distribution, especially for wall condensation, is very important for a healthy and energy-efficient environment. Zhixiang et al. [27] investigated ambient air condensation on a cryogenic horizontal tube using a newly built mathematical model, in which the liquid film and the vapor boundary layer are coupled together

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Nomenclature

A	surface area, m^2
a	pipe radius, m
d	pipe diameter, m
C_P	specific heat of moist air, kJ/kg °C
L	pipe length, m
h	heat transfer coefficient, kW/m^2 °C
h_m	mass transfer coefficient, m/s
$\dot{m}_a$	mass flow rate of moist air, kg/s
$\dot{m}_c$	rate of condensation, kg/s
Q	total heat transfer, kW
RH	relative humidity of moist air
i	specific enthalpy of moist air, kJ/kg
U_∞	air free stream velocity, m/s
u	velocity component in x-direction, m/s
v	velocity component in y-direction, m/s
T	temperature of air, K
P	air pressure, Pa
K	thermal conductivity, W/m °C
h_{fg}	latent heat of condensation, kJ/kg
w	humidity ratio, kg_w/kg_a
D	mass diffusivity, m^2/s
f	function ($f = u/U_\infty$)
ΔT	temperature difference between dew point and wall temperature, °C
TR	temperature ratio, $TR = \Delta T/(T_{in} - T_w)$

Greek symbols

α	thermal diffusivity, m^2/s
ρ	density, kg/m^3
μ	dynamic viscosity, kg/m s
δ	film thickness, mm
θ	dimensionless temperature
ϕ	dimensionless concentration
υ	kinematic viscosity, m^2/s
Ψ	stream function
ζ	condensation parameter
ξ	position parameter
β	position angle, degree
η	transform axis y
λ	constant; λ is equal zero in the case of no interaction between heat and mass transfer, while λ is equal one when interactions considered

Subscripts

a	air
in	inlet
o	outlet
h	hydrodynamic
t	thermal
m	mass
w	wall
∞	free stream
avg	average value
x	local value

dimensionless quantities

Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
Sh	Sherwood number
Sc	Schmidt number

with a major emphasis on the effect of buoyancy. Le et al. [28] derived an analytical solution for the governing equations of steady laminar film condensation from quiescent pure vapors on convex and concave curved vertical walls. Mass transfer of condensable gases and mixtures of laminar films on a flat plate were presented by Ref. [30]. Forced convection condensation in the presence of non-condensables and interface resistance were investigated by Ref. [31]. Heat and mass transfer with condensation of steam-air mixtures were presented by Refs. [32,33]. Forced convection condensation in the presence of a non-condensing gas on a flat plate and horizontal tube was studied by Ref. [34].

According to authors' review, the influence of air mass flow rate, air relative humidity, and temperature difference between air dew point and pipe surface temperature on the heat and mass transfer coefficients of moist air condensation process on the outer surface of horizontal pipe is approximately not fully studied. Consequently, the present work is carried out to investigate the condensation process of moist air on the outer surface of horizontal pipe. In the theoretical study, the influence of Reynolds number and condensation and position parameters on the boundary layer thickness of mass, thermal and hydrodynamic, in addition to Nusselt and Sherwood numbers, are investigated. In other side, the effects of air inlet conditions (i.e. relative humidity and mass flow rate) are examined during condensation process. The experimental results are presented at two different values of temperature difference between air dew point and pipe surface temperature of 5 °C & 10 °C. Finally, numerical and experimental correlations for Nusselt and Sherwood numbers are investigated and presented in terms of all studied parameters within accepted error.

2. Theoretical study

The system physical model which is considered in this analysis is illustrated in Fig. 1. In the theoretical analyses of this work, the flow is assumed to be laminar, steady and with constant physical properties, moreover the thicknesses of water vapor layer is small compared with pipe radius. The condensation process is described by continuity, momentum, energy and mass partial differential equations that expressed in Cartesian coordinates system. According to the nature of the studied problem and to proper transformation of the dependent and independent problem variables, the governing equations are transformed to a set of ordinary differential equations (ODE). Therefore, the well-known numerical method, Rung Kutta is applied to solve the set of ODE. In consequence, the boundary layer thickness of mass, thermal and hydrodynamic, in addition to Nusselt and Sherwood numbers at different Reynolds numbers are investigated, Condensation and position parameters are well defined. The physical problem can be described as a humid air flow with inlet velocity (U) and uniform temperature (T) passes around constant surface temperature horizontal pipe. The physical description of the problem and coordinate system is shown in Fig. 1a, and the model in orthogonal curvilinear coordinates is depicted in Fig. 1b.

2.1. Governing equations

According to the foregoing assumptions, the continuity, momentum, energy and mass equations in Cartesian coordinates can be written as: