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Experimental investigation of wet flue gas condensation using twisted tape insert

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A B S T R A C T

In the present study, the effect of twisted tape insert on the wet flue gas condensation in a horizontal tube, as a widely used application of condensation in the presence of non-condensable gas are examined experimentally and numerically. Four different tapes were evaluated under various range of combustion excess air. Several parameters of heat and mass transfer, such as convection/total heat transfer coefficient, friction factor, condensation ratio, latent heat proportion and total performance were investigated. As shown in the results, any kind of the tape insert causes the heat transfer enhancement and this improvement is not uniform for investigated range of excess air (5–30%). A wall film condensation model is used to simulate the vapor condensation. To validate the numerical model, the experiments of ambient air at same inlet Reynolds number is used to ensure that the trend of numerical data is acceptable. The numerical data demonstrates friction factor has two different trends before and after a complete combustion process (excess air = 10%). But the variation of friction factor is not more tangible under investigated range of inlet mass flow. The increase of condensation ratio is more considerable for lower values of excess air. Meanwhile, the greatest effect of twisted tape on latent heat proportion was achieved at excess air = 30%. The best improvement of condensation ratio and latent heat proportion were 24 and 25%, respectively. The calculation of total performance shows that, under investigated range of excess air, the higher twist ratio is preferred. Finally, the correlation of condensation ratio was reported and compared with experimental results.

1. Introduction

In the recent years, the use of natural gas in various expenditures is extended considerably. Due to environmental safety, the natural gas as a source of clean energy has found various applications in different areas, such as the flue of gas fired boilers/chillers. The exhaust flue gas temperature is more than 200 °C in conventional hot water boilers [1]. Although for preventing of corrosion in the conventional boiler, this temperature should be higher than flue gas's dew point, but it causes a large amount of heat loss. Condensation of vapor, which is a part of combustion product, causes the retrieval of the vapor latent heat. Since the other constituents of flue gas (such as SO_x, NO_x, and soot) could be absorbed by the condensed vapor, the environmental pollution of the gas fired boiler could be partially reduced noticeably [2]. The vapor condensation of flue gas is one of the most widely applied in the area of vapor condensation in the presence of non-condensable gas (NCG). There are various studies in the area of condensation in the presence of NCG which could be divided into two general parts: low concentration of NCG and high concentration of NCG.

Tang et al. [3] carried out the double boundary layer model to study the behavior of film condensation in the presence of air as an NCG outside of a horizontal tube numerically. The local mass transfer, velocity and temperature distribution in boundary layer were investigated and observed that a small concentration of NCG in a bulk mixture leads to a considerable reduction of average heat transfer coefficient. Li [4] provided a CFD model to estimate the thermal analysis of vapor condensation in vertical tube turbulent flow and evaluated a various range of inlet vapor portion from 0.66 to 0.98 and resulted that the axial velocity of the gas mixture at the interface between main flow and the condensed film is significant and cannot be ignored. Szijarto et al. [5] used RELAP5, a thermal-hydraulic system code, to evaluate rapid wall condensation process and predicted the temperature, pressure and void fraction of vapor along the vertical flow.

Ambrosini et al. [6,7] compared a numerical model with the benchmark results of CONAN experimental facility and suggested the experimental correlations for Nusselt number and Sherwood number of wall condensation resulting from a vertical flow on a flat

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Nomenclature

A	area (m^2)
C_i	constant
d	diameter (m)
e	twist length (m)
E_g	discrepancy (%)
f	friction factor
Ga	Galileo number
h	heat transfer coefficient (W/m^2 K)
L	length (m)
m_{cond}	condensation rate (kg/s)
$\dot{m}_{cond}$	condensation flux (kg/m^2 s)
Nu	Nusselt number
Pr	Prandtl number
Q	heat transfer quantity (W)
q''	heat flux (W/m^2)
Re	Reynolds number
T	temperature (°C)
U	mean velocity of flue gas (m/s)
U_e	overall heat transfer coefficient (W/m^2 K)
V	mean velocity of cooling water (m/s)
x	local quality
z	Cartesian coordinate along the channel (m)

Greek symbols

α	thermal diffusion (m^2/s)
β	fraction of the perimeter over the condensed film occurred
γ	condensation latent heat (J/kg)
ε	latent heat proportion (%)
η	performance
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (kg/ms)
ν	kinetic viscosity (m^2/s)
Ω	half stratification angle
ρ	density (kg/m^3)
φ_v	volume fraction of water vapor (%)
ω	condensation ratio (%)
Γ	total mass flow rate (kg/s)

Subscripts

bot	bottom
cond	condensation
conv	convection
cw	cooling water
f	condensed film
g	flue gas
i	interface
in	internal
inl	inlet
l	latent
nc	non-condensable
o	outlet
p	plain tube
s	sensible
sat	saturation
t	total
tc	thickness of the tube
v	vapor
w	wall

plate. Jia et al. [8] extended the numerical model of the annular thin film condensation in a vertical tube for a small amount of vapor mass fraction. In their major study, it was claimed that the fog formation in a wet flue gas has a tangible effect on condensation process and the influence of latent heat proportion was discussed. In the same study, Rao et al. [9] used a numerical model to predict the thermal and hydrodynamical characteristics of vapor condensation for a laminar regime of humid air. The local/average Nusselt number, condensate Reynolds number and gas-liquid interface temperature were estimated for different values of inlet conditions (Reynolds number, relative humidity and bulk temperature). Vyskocil et al. [10] developed a CFD model for both of compressible and incompressible air-steam mixture. They focused on the simulation of wall condensation for a situation that the influence of volume condensation is not sensible. Based on the comparison with the CONAN experimental facility, they reported condensation rate for various inlet conditions. Likewise, Zschaeck et al. [11] modeled a validated CFD simulation for studying the wall condensation in the presence of non-condensable multicomponent gas. Their numerical study showed that an increase of turbulent intensity and eddy viscosity ratio causes more condensation which is in good agreement with the results of CONAN experimental facility. Su et al. [12] tested the vapor condensation over an external surface of the vertical tube for various ranges of air/helium mass fraction from 0.1 to 0.8 and the total pressure in the range of 2×10^5–5×10^5 Pa, experimentally. It was shown that the wall condensation process has no influence on the local concentration of helium in the gas phase and the stratification phenomena did not occurred.

One of the fundamental research on condensation of vapor-air mixtures inside a horizontal tube was done by Wu and Vierow [13]. They studied several portions of the vapor-air mixture at different Reynolds number and calculated the local heat transfer coefficient along the tube and reported that the average heat transfer coefficient is much greater on the top side of the tube. Chantana and Kumar [14] modeled air-steam condensation for a low steam mass fraction (3–12%) in a vertical tube for the turbulent regime of the gas mixture in a wide range of Reynolds number (4600–14,000). They measured the film Reynolds number and found that the high Reynolds number of bulk gas mixture causes the wavy and rippling surface on condensed film. Also, it was shown that the suction of condensation leads to improvement of heat transfer rate which was effective even for low concentration of vapor. Saraireh and Thorpe [15] applied ANSYS FLUENT commercial CFD software to evaluate the numerical results of humid air wall condensation under investigation of condensed vapor rate and heat flux. In order to make a comprehensive study on condensation of vapor in the presence of NCG, Huang et al. [16] categorized previous studies into dropwise and filmwise condensation and investigated semi-theoretical and theoretical models of wall condensation in the presence of NCG under several parameters such as: condensate film thickness, surface waves, interfacial shear strength and suction effects.

Dobson and Chato [17] examined the condensation of different refrigerant in horizontal tube experimentally and investigated the influence of heat transfer coefficient on two-phase flow regimes under two dominated categories: gravity-dominated and shear-dominated. In a comprehensive study, El Hajal et al. [18] focused on two-phase flow pattern for condensation in horizontal tubes and present a new flow map which is in accure agreement with the recent flow map observations. In the second part of this study, Thome et al. [19] predict the local condensation heat transfer coefficient for several flow regimes: annular, intermittent, stratified-wavy, fully stratified and mist flow. They compared the mentioned