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Experimental studies of shell-side fluid flow and heat transfer characteristics in a submerged combustion vaporizer

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ABSTRACT

In this paper, an experimental apparatus was set up to study the two-phase mixture flow and heat transfer over a horizontal tube bundle on the shell-side of the submerged combustion vaporizer (SCV). The influences of the static water height, superficial flue gas velocity and heat load on the heat transfer characteristics were systematically examined. The experimental results revealed some interesting observation of the SCV, such as the circulation flow of water bath accompanying a great deal of gas bubbles and the highly thermal efficiency due to the direct-contact heat transfer between the highly turbulent two-phase mixture and staggered tube bundles. Finally, based on the experimental data, a new dimensionless, semi-theoretical empirical correlation was developed for two-phase mixture convection heat transfer over the staggered tube bundle on the shell-side of SCV. The discussion and correlation provided a framework for designing the SCV.

1. Introduction

With the ever-consuming of energy sources, high reliability and economic efficiency vaporizers for LNG receiving terminals are becoming more important. Four types of LNG vaporizers are mainly used in the LNG import terminal, namely, open rack vaporizer (ORV), superORV, submerged combustion vaporizer (SCV) and intermediate fluid vaporizer (IFV) [1]. Among them, SCV has been most frequently applied for the peak-shaving regasification because of its inherent ability of higher thermal efficiency and safety in water bath heating [2]. The fundamental principle of SCV is the exploit of the water bath as the intermediate working medium to achieve the heat transfer between the flue gas and the process fluid. It is believed that high thermal efficiency of water bath unit is vital for the whole SCV system. Meanwhile, owing to most of heat transfer behaviors in the shell-side of the SCV usually occur at the gas–water interface or two-phase mixture and tube bundle wall interface, the available heat transfer area may vary dramatically with its operating conditions over traditional shell-and-tube heat exchangers. Consequently, to advance this technology, the mixture-to-wall heat transfer coefficient is important in respect of effective design of SCV.

In recent years, many investigators have focused on the heat transfer processes based on the superheated gas and liquid in the direct-contact heat exchanger, in which a gas is dispersed into a liquid, involves a relatively complex fluid dynamics of bubbles motion. The equipment exhibits many advantages including high heat transfer rates, great simplicity of construction and the capacity to operate at small temperature difference [3]. Thus, it has been recommended for the applications of the water desalination [4], cooling tower [5], bubble column [6], crystallization [7] and power generation [8]. Related review article was given by Ribeiro and Lage [9]. Ghazi [10] performed the experiments on direct-contact heat transfer of air injected through an orifice and bubbling through a pool of water. The Nusselt number which based on an average overall heat transfer coefficient between the air and water was correlated. Kawasaki and Hayakawa [11] carried out the experimental study on direct-contact mass and heat transfer between vapor and liquid with change of phase, volumetric coefficients of vapor phase mass transfer were measured and the effects of some specified operating conditions on condensation and evaporation rates were made clear. Mahood et al. [12] experimentally measured the transient temperature distribution and volumetric heat transfer coefficient during the inception of flooding in a three-phase bubble type direct contact condenser. The transient temperature distribution, phase maps identifying flooding conditions and the volumetric heat transfer coefficient associated with flooding were estimated. Abdulrahman [13] experimentally investigated the direct contact heat transfer for a helium gas at 90 °C injected through a slurry of water at 22 °C and alumina solid particles in a slurry bubble column reactor. The effects of superficial

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Nomenclature

H_0	two-phase mixture overall height, (cm)
H	static water height, (cm)
Q	heat exchange rate, (W)
m	mass flow rate, (kg/s)
C_p	heat specific, J/(kg·K)
U	superficial velocity, (m/s)
T	temperature, (K)
h	enthalpy, (kJ/kg)
K	heat transfer coefficient, W/(m·K)
N	number of tube
l	tube length, (mm)
d	tube diameter, (mm)
q	heat flux, (W/m^2)
u	mean velocity of flue gas through the orifice, (m/s)
d_{or}	orifice diameter of gas distributor, (mm)
V	volume flow rate, (Nm^3/h)
Re	Reynolds number
Nu	Nusselt number
Pr	Prandtl number

Greek symbols

ε_g	gas hold-up
ρ	density, (kg/m^3)
μ	dynamic viscosity, kg/(m·s)
λ	thermal conductivity, W/(m·K)

Subscripts

t	tube-side
s	shell-side
f	fuel
gs	flue gas
o	outer
i	inner
b	water bath
w	tube wall
in	inlet
out	outlet
v	steam
gs,v	flue gas without steam

gas velocity, static liquid height and solid particle size on the volumetric heat transfer coefficient and slurry temperature of the slurry bubble column reactor were studied. Finally these effects were formulated in forms of empirical equations. Ribeiro and Lage [14] experimentally measured the transient liquid temperature, bubbling height, evaporation rate, gas hold-up and bubble size distributions in a DCE. The effects of both the sparger and the gas flow rate upon the equipment performance were analyzed. The results revealed the temporal evolution of bubble size distributions and gas hold-up values. They also obtained the experimental bubble size distributions and bubble mean diameters by means of a photographic technique [15]. Other studies on this subject include Jacobs [16], Campos and Lage [17], Kandlikar and Steinke [18] and Boulama et al. [19].

Based on the above review, although there are amounts of literature concerning the characteristics of the direct-contact heat transfer, the underlying two-phase mixture flow and heat transfer over the staggered tube bundle occurred on the shell-side of SCV has not comprehensively been well studied. Therefore, the use of previous correlation to describe this process can be risky. In order to fill the gap, in this study, the effects of the static water height, superficial flue gas velocity and heat load on the hydrodynamic and heat transfer in the SCV are discussed, and a new Nusselt number correlation is proposed to predict the shell-side heat transfer performance of the SCV.

2. Experimental work

2.1. Experimental setup

Fig. 1 showed a schematic diagram of the laboratory-scale SCV applied for studying the shell-side fluid flow and heat transfer characteristics. The test apparatus mainly consisted of combustion part, heat exchanger part, measuring instruments and data acquisition device. The combustion part included an air blower, LPG tank, burner and rotameter. The heat exchanger part consisted of water tank, gas distributor, tube bundles and the measurement sensors. The experiment was equipped with appropriate flow rotameters for the air, fuel gas and cold water flow rate measurement and control. All experiments were carried out in a water tank made of stainless steel, with wall thickness of 10 mm and with 940 mm length, 655 mm width and 520 mm height. It should be noticed that four transparent visualization windows in total were placed in the front and back sides of the water tank and weir in order to enable a clear vision for the bubbles behavior. The water tank wall was thermally insulated to minimize heat losses from the wall.

Fig. 2(a) showed the schematic drawing of the heat exchanger part, in which hot gas dispersed through a gas distributor made of stainless steel, which has 22 orifices on each branch pipe, totaling 242 orifices and left from the exhaust stack across the tube bundle that submerged in the water bath. The configuration of staggered tube bundle layout, as shown in Fig. 2(b) was used for experiments. The tubes were marked as Tube 1–Tube 5. The testing heat exchange tube bundle presented a 90° rotated square arrangement. The space between two tandem tubes was defined by longitudinal pitch S_L and the space between side-by-side tubes was defined by transverse pitch S_T. In the current work the longitudinal pitch ratios and the transverse pitch ratio were also 1.78. The detailed geometric parameters of the testing SCV were shown according to Table 1.

Pt 100 resistance temperature sensors were used for measuring the water temperatures at the inlet and outlet of the tube-side. All

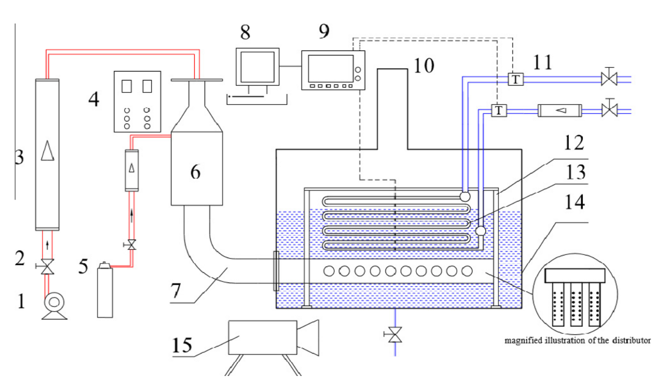

Fig. 1. Schematic illustration of the experimental setup: (1) air blower (2) ball value (3) flow rotameter (4) ignition panel (5) LPG tank (6) burner (7) gas distributor (8) computer (9) data acquisition system (10) exhaust stack (11) temperature sensor (12) weir (13) tube bundle (14) water tank (15) high-speed camera.