Applied Thermal Engineering 113 (2017) 529–536

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Experimental investigation on fluid flow and heat transfer characteristics of a submerged combustion vaporizer

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HIGHLIGHTS

- Thermal performance analysis of submerged combustion vaporizer (SCV) was performed experimentally.
- Visualization study of shell-side flow field for SCV was carried out.
- The effects of various operational parameters on the overall system performance were discussed.
- Two new non-dimensional Nusselt correlations were proposed to predict the heat transfer performance of SCV.

ARTICLE INFO

Article history:
Received 30 June 2016
Revised 30 October 2016
Accepted 9 November 2016
Available online 10 November 2016

Keywords:
Submerged combustion vaporizer
Trans-critical
Flue gas
Heat transfer
New correlations

ABSTRACT

Submerged combustion vaporizer (SCV) occupies a decisive position in liquefied natural gas (LNG) industrial chain. In this paper, a visual experimental apparatus was established to have a comprehensive knowledge about fluid flow and heat transfer performance of SCV. Trans-critical liquid nitrogen (LN_2) was selected as alternative fluid to substitute LNG because of safety reason. Some unique experimental phenomena inside the SCV (local water bath freezes on the external surface of tube bundle) were revealed. Meanwhile the influences of static water height, superficial flue gas velocity, heat load, tube-side inlet pressure and tube-side mass flux on the system performance were systematically discussed. Finally, based on the obtained experimental results, two new empirical Nusselt number correlations were regressed to predict the shell-side and tube-side heat transfer characteristics of SCV. The maximum errors between predicted results and experimental data were respectively ±25% and ±20%. The outcomes of this paper were critical to the optimum design and economical operation of SCV.

1. Introduction

As the demand for natural gas (NG) in the world-wide continues to increase, a growing number of researchers have been focusing on the study of thermal performance analysis for liquefied natural gas (LNG) vaporizers [1–3]. Among commonly used vaporizers, submerged combustion vaporizer (SCV) is applicable to LNG receiving terminals as peak-shaving regasification facility because of its inherent advantages, such as excellent thermal efficiency, safety in water bath heating, uniform outer tube wall temperature and quick response capability [4]. It mainly uses water bath system as intermediate medium to achieve the heat exchange between the flue gas and cryogenic LNG. To the best of our knowledge, only limited numbers of published literature have been related to SCV [5–7]. However, these studies are mainly theoretical and cannot reflect actual physical process well as a result of some assumptions. Accordingly, to advance this novel technology, it is believed that the experimental investigation of fluid dynamic phenomena and thermal performance for the SCV is in urgent need of it.

In recent years, a large number of investigators had experimentally studied the so-called direct-contact heat transfer [8–10] and supercritical fluid heat transfer in the horizontal tube [11–13]. Ribeiro and Lage [14] experimentally investigated the transient liquid temperature, two-phase mixture height, system evaporation rate and local bubble size distributions in a direct-contact evaporator. The influences of both structural and operating parameters on the system performance were analyzed. Their experimental results revealed some important features for non-isothermal bubbling system. Dizaji et al. [15] investigated the dynamics of a heat exchanger by injecting air bubbles into the shell-side. The results demonstrated that the number of thermal units (NTU) and performance of heat exchanger could be significantly improved due to the bubbles injection. Abdulrahman [16] experimentally studied

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http://dx.doi.org/10.1016/j.applthermaleng.2016.11.075
1359-4311/

Nomenclature

K	heat transfer coefficient (W/m^2 K)
Nu	Nusselt number
T	temperature (K)
P	pressure (MPa)
U	superficial velocity (m/s)
Re	Reynolds number
D_o	outer diameter (mm)
D_i	inner diameter (mm)
H	static water height (mm)
Q	heat transfer rate (W)
A	area (m^2)
V	volume flow rate (N m^3/h)
n	number of tube
q	heat flux (W/m^2)
L	tube length (mm)
C_p	specific heat (J/g K)
h	enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
H_{we}	height of weir (mm)
R	diameter of bend tube (mm)
Pr	Prandtl number
S_L	longitudinal pitch (mm)
S_T	transverse pitch (mm)

Greek letters

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

Subscripts

s	shell-side
t	tube-side
in	inlet
out	outlet
ave	average value
fg	flue gas
f	fuel
b	water bath
w, out	outer wall
w, in	inner wall
o	overall

Abbreviations

SCV	submerged combustion vaporizer
LNG	liquefied natural gas
LN_2	liquefied nitrogen

the direct-contact heat transfer characteristics in a slurry bubble column reactor. Effects of operating parameters on the volumetric heat transfer coefficient of the reactor were systematically examined. Finally, the empirical correlation for the Nusselt number was proposed. Baqir and Mahood [17] carried out the experimental study to measure the average volumetric heat transfer coefficient of a direct-contact evaporator. Furthermore, the influences of operating and structural parameters of sparger on the heat transfer performance were examined. The results demonstrated that increasing fluid flow rates could lead to an enhancement on the heat transfer coefficient. On the other hand, Liao and Zhao [18] performed an experimental study of supercritical CO_2 in the vertical miniature and horizontal tubes. The influences of main factors including inlet pressure, tube diameter and heat flux on the heat transfer coefficient were reported. The axially-averaged Nusselt number correlations were developed for the convection heat transfer process to supercritical CO_2. Xu et al. [19] experimentally investigated the convective heat transfer of supercritical CO_2 in a serpentine vertical mini tube. The influences of inlet Reynolds numbers, heat fluxes and flow direction on heat transfer behavior were studied thoroughly. The heat transfer intensity of fluid inside the serpentine tube was also studied. Gu et al. [20] performed the studies of supercritical water flowing inside the circular tubes. Tube diameters, heat flux, inlet pressure, mass flux and bulk temperature on the heat transfer coefficient were experimentally investigated. The correlations of Cheng et al. and Jackson showed an agreement with the experimental data. Zhang et al. [21] performed an experimental study on the supercritical water flowing in a heated vertical tube. The experiment data included a relatively large range of some important operational parameters. Finally the obtained correlation was developed on the basis of the tested tube to predict the corresponding heat transfer coefficient.

Unfortunately, we find that the existing correlations are not suitable in respect of effective design of SCV, which owns unique structure features and complex heat exchange process between two-phase mixture and trans-critical fluid. For the sake of filling this tap, in this paper, a visual experimental apparatus is set up to investigate the coupled fluid flow and heat transfer characteristics inside the SCV. The effects of operational parameters on the overall thermal performance are experimentally investigated in details, and two new Nusselt number correlations are regressed to respectively predict the shell-side and tube-side heat transfer performance of SCV.

2. Experiments

2.1. Experimental apparatus

It was well known that using trans-critical LNG as the working medium of SCV was very dangerous in the laboratory. By the contrast, liquid nitrogen (LN_2) was often selected as excellent alternative media for the experimental investigation of vaporizers [22,23]. Fig. 1 illustrated the flowchart of the employed experimental facility which was improved based on our previous experimental work [24]. It could be mainly divided into four parts, i.e. (1) combustion system; (2) shell-side system; (3) tube-side system; (4) the data collection system. Four pieces of transparent glasses were respectively placed in the front and back sides of weir and water tank. A high speed camera (FASTCAM SA4) was employed for recording the corresponding pictures. The outer wall surface of water tank was thermally insulated to reduce the heat loss to the surroundings. Moreover, the pipelines located between the dewar and vaporizer were also thoroughly covered by the thermal insulation material to avoid the vaporization of LN_2 prematurely. Fig. 2 showed the actual photograph of experimental apparatus. The tested tube bundle consisted of five heat exchange tubes in the staggered arrangement, and the schematic view of tube bundle was shown in Fig. 3. Each tube was made of stainless steel (ss, Type 304), which could endure high-pressure and ultralow temperature experimental conditions. Additionally, they were marked as tube1 $\sim$ tube5. The detailed geometric parameters of SCV in the present study were summarized in Table 1.