Applied Thermal Engineering 112 (2017) 585–594

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Numerical simulations on the effect of sloshing on liquid flow maldistribution of randomly packed column

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HIGHLIGHTS

- A model for randomly packed column under sloshing conditions is developed.
- The model predictions are validated with the experimental data.
- Both static and sloshing conditions are considered.
- Effect of tilt angles and aspect ratios are discussed.

ARTICLE INFO

Article history:
Received 6 February 2016
Revised 1 August 2016
Accepted 9 October 2016
Available online 11 October 2016

Keywords:
Randomly packed column
Numerical simulation
Sloshing
Liquid distribution

ABSTRACT

Randomly packed columns are key equipment for natural gas pre-treatment process of the FLNG (Floating Liquefied Natural Gas). It is of great importance to study on the effect of sloshing on liquid flow maldistribution at the column tray under severe sea state. A three-dimensional CFD model for randomly packed column under sloshing conditions was developed and the inter-phase drag force, porous resistance force, liquid dispersion and radial variation of volume porosity were incorporated into the volume averaged equations. Then the simulation results were validated with the experimental data. Both static and sloshing simulations have been carried out with varying angles and aspect ratios to map the distortion of liquid distribution. Quantitative analysis of liquid volume fraction, liquid velocity and maldistribution factor affected by tilt angles and aspect ratios were provided. The duration time of the dry area occupies about 40% of the period in the wall region and the total dry area occupies about 10% of the cross-sectional area. The maximum tilt angle should be less than 3° to prevent severe liquid flow maldistribution of the column with the aspect ratio of 3 (L/D = 3).

1. Introduction

Growing global demand for natural gas is pushing the industry to consider the development of remote offshore fields. Floating Liquefied Natural Gas (FLNG) offers a cost effective alternative, and is expected to be the next technological breakthrough for monetizing remote, offshore natural gas resources [1]. Packed columns have been used in acid gas removal, NGL recovery, and natural gas fraction on the FLNG vessel. However, these highest and heaviest equipment in natural gas liquefaction process (especially the pressure of feed gas is high) are easily influenced by the movements of hull [2].

In typical sloshing conditions under the severe sea state, there are three angular motions (roll, pitch and yaw) and three linear motions (surge, sway and heave). Angular motions divert the liquid from the vertical and cause liquid maldistribution close to the column wall especially with periods longer than 12 s. Horizontal accelerations affect the liquid distribution necessary to obtain the maximum column efficiency due to inertia effects, whereas vertical accelerations have a greater influence on the maximum capacity of the packed column. Static tilt causes liquid maldistribution similar as angular motions due to weather conditions or unbalanced product storage or offload conditions [3]. However, Cullinane et al. [4] illustrates faster motion dampens liquid maldistribution until inertial effects are more important than gravity and the gravity offset by inertia effects help to get the minimum liquid maldistribution of packed column.

Up to now, many researchers such as Yin et al. [5,6], Sun et al. [7] and Liu et al. [8] have done studies on liquid flow maldistribution of randomly packed columns by experimental and CFD simulation study, which can predict the liquid flow distribution,

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http://dx.doi.org/10.1016/j.applthermaleng.2016.10.049
1359-4311/

Nomenclature

a_s	specific surface area (1/m)
$\mathbf{B}$	body force vector (N/m^3)
C_1	constants in Robbins's correlation (dimensionless)
C_2	constants in Robbins's correlation (dimensionless)
C_μ	empirical constant in Eq. (17) (dimensionless)
D	column diameter (m)
d_p	nominal diameter of packing particles (m)
d_e	equivalent diameter of the packing (m)
$\mathbf{F}_{gl}$	inter-phase drag force (N/m^3)
$\mathbf{F}_{ls}$	porous resistance by the porous medium to the liquid phase (N/m^3)
$\mathbf{F}_{gs}$	porous resistance by the porous medium to the gas phase (N/m^3)
F_{pd}	packing factor (1/m)
F_{factor}	gas kinetic factor (Pa$^{0.5}$)
G_f	gas loading factor (kg/(m^2 s))
G_g	gas superficial flow rate per unit cross-sectional area (kg/(m^2 s))
G_l	liquid superficial flow rate per unit cross-sectional area (kg/(m^2 s))
$\mathbf{g}$	gravitational vector (kg/(m^2 s))
h	holdup (dimensionless)
K_c	constant in Eq. (14) (m^2 s)
k	turbulence kinetic energy (m^2/s^2)
L	packed bed height (m)
L_f	liquid loading factor (kg/(m^2 s))
M	maldistribution factor (dimensionless)
m_{static}	mass flux under static conditions (kg/s)
$m_{sloshing}$	mass flux under sloshing conditions (kg/s)
P_0	operating pressure (Pa)
∇p	pressure drop (Pa/m)
∇p_d	dry pressure drop (Pa/m)
∇p_w	wet pressure drop (Pa/m)
R	radius of the column (m)
$\mathbf{R}_z$	axial resistance component (N/m^3)
r	radial coordinate (m)
T	period (s)
T_0	operating temperature (K)
t	time (s)
$\mathbf{U}$	interstitial velocity vector (m/s)
$\mathbf{U}_{slip}$	slip velocity vector (m/s)
u	liquid local superficial velocity (m/s)
u_g	gas superficial velocity (m/s)
u_{av}	liquid average superficial velocity (m/s)

Greek symbols

ε	turbulence dissipation rate (m^2/s^3)
ε_b	bulk porosity of the column (dimensionless)
ε_p	porosity (dimensionless)
γ	volume fraction (dimensionless)
β	the variation of flux ratio (dimensionless)
ϕ	volume averaged variable
ϕ_q	intrinsic phase averaged variable
ρ	density (kg/m^3)
ω	angular velocity (1/s)
$\mathbf{\Gamma}$	dispersion coefficient for volume fraction (kg/(m s))
θ	deviation angle of the column axis from the vertical axis (°)
θ_{max}	the amplitude of the angular motion (°)
μ	molecular viscosity (kg/(m s))
μ_e	effective viscosity (kg/(m s))
μ_t	turbulent viscosity (kg/(m s))
σ_t	turbulent Prandtl number (dimensionless)

Subscripts

g	gas phase
l	liquid phase
q	phase index
s	solid phase
t	turbulent flow

pressure drop, concentration profile and column efficiency. Duss et al. [3] summarized the factors that influence liquid maldistribution and mass transfer: column diameter, bed height, packing type, hydraulic loads, physical properties, liquid distribution design, static tilt, motion conditions and the location of the column on the vessel. Jafari et al. [9] carried out numerical study on flow behavior through random packing of non-overlapping spheres. Dimensionless pressure drop was studied at different Reynolds numbers through randomly packed bed based on pore permeability and interstitial fluid velocity. Liu et al. [10] predicted the concentration and liquid velocity distribution as well as the turbulent mass transfer diffusivity in an industrial scale randomly packed distillation column based on $\overline{c^2} - \varepsilon_c$ numerical model. Fourati et al. [11] proposed a gas-liquid porous media CFD model incorporated with the porous resistance, inter-phase momentum transfer and liquid dispersion. Pham et al. [12] developed the gas-liquid porous media CFD model integrated with mass transfer and chemical reaction in an amine absorber with Mellapak 500.X.

TOTAL, PROSERNAT and IEPEN at Heriot-Watt University [13] built an early model of an absorption column subjected to motion based on theoretical approach and presented a summary of experimental measurement of liquid distribution with 5° at different heights of packing in the 0.6 m column. Pham et al. [14] developed a gas-liquid Eulerian porous media CFD model for an absorber with structured packing to remove CO_2 from natural gas by mono-ethanol-amine (MEA). As tilt angle increased, the liquid holdup and effective interfacial area decreased and CO_2 removal efficiency was lowered. The uniformity of liquid holdup deteriorated by 10% for a 3° static tilt, and a rolling motion with 4.5° amplitude and 12 s period, respectively. CFD modeling generally confirms that same angle static tilt is the most severe design condition with the highest maldistribution factors [1,14]. Li et al. [15] investigated the effect of sloshing orientations, angles, frequencies and displacements on sloshing resistance and gas-liquid distribution performance in plate-fin heat exchangers. A mathematical model of FLNG spiral wound heat exchangers under rolling conditions was developed and the effect of rolling amplitude on the heat transfer performance was analyzed [16]. Experimental and theoretical studies of single-phase natural circulation flow and heat transfer under a rolling motion condition were performed [17].

However, there is still limited information and industrial experience available related to hydrodynamics and maldistribution of columns subjected to sloshing. It is necessary to do further research on the effect of sloshing on liquid flow distribution in randomly packed column to obtain critical conditions for column design to guarantee column performance under severe sea state.

The gas-liquid porous media CFD model was developed to study on the effect of sloshing on liquid maldistribution of the randomly packed column. Under static conditions, effect of tilt angles and aspect ratios on gas-liquid distribution performance were