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Droplet entrainment analysis of three-phase low liquid loading flow

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ABSTRACT

Most of the commonly used multiphase flow models neglect the amount of droplets entrained in stratified wavy flow. However, the experimental data presented in this study show high entrainment values, exceeding 50% in some cases. This shows that neglecting entrainment phenomenon can introduce a major source of discrepancy into multiphase flow modeling predictions. This study improves the entrainment fraction predictions in three-phase stratified flow.

The droplet entrainment in three-phase stratified flow in horizontal pipelines is experimentally investigated using a 0.152-m ID facility. The experiments are conducted under low liquid loading conditions, which is very commonly observed in wet gas pipelines. The oil-aqueous-gas flow experiments are initially performed without mono-ethylene glycol (MEG), and then repeated with 50 wt% of MEG in the aqueous phase to analyze the effects of MEG presence on entrainment. MEG is a commonly used inhibitor in oil industry, applied to avoid hydrate formation in offshore systems. Its impacts on multiphase flow droplet entrainment are investigated.

The experimental range of this study covers superficial gas velocity (v_{Sg}) values from 17 to 23 m/s, superficial liquid velocity (v_{SL}) values of 0.01 and 0.02 m/s, and inlet liquid stream aqueous phase fraction (APF_{in}) values between 0 to 100%. Similar test matrix is completed for both water and water and MEG solution as the aqueous phase. An isokinetic probe system is used to measure the entrained droplet flux at different vertical positions in the gas phase. Liquid entrainment fraction is then estimated by means of volumetric averaging. The trends of the data with respect to input parameters are investigated.

The two and three-phase entrainment fraction data are used for a correlation evaluation study. Performances of ten correlations for two-phase entrainment fraction are compared to the experimental data, and best performing correlations are identified. The correlation of Pan and Hanratty (2002) is modified in an effort to improve the entrainment fraction estimations. The predictions of the modified correlation are compared with the acquired data and datasets from the literature. In addition, a simple empirical correlation is proposed to predict liquid phase entrainment fraction for three-phase flow systems.

1. Introduction

One of the most common phenomena in wet gas pipelines is low-liquid loading three-phase flow. Low liquid loading flow is a flow condition wherein the liquid flow rate is very small compared to the gas flow rate (LGR values less than 1100 $m^3/MMsm^3$, defined by Meng et al. 2001). Even though the pipeline is fed with single phase gas, the condensation of the heavier components of the gas phase along with traces of water can results in three-phase flow. Mono-ethylene glycol (MEG) is used continuously in deep water gas production systems as a hydrate inhibitor. However, MEG mixing in multiphase flow and its effects on flow parameters are not well understood.

In stratified wavy flow pattern, the interfacial shear is generated by the large velocity difference between gas and liquid phases. Once the interfacial shear becomes large enough, liquid droplets can be sheared off the waves at the interface and travel with the gas phase. At sufficiently high gas flow rates, the fraction of liquid phase traveling as entrained droplets increases significantly. This means that neglecting entrainment phenomenon can introduce a major source of uncertainty into the modeling of stratified wavy flow. Several models and correlations such as Wallis (1968), Oliemans et al. (1986); Ishii and Mishima (1989), and Sawant et al. (2009) are available in the literature to predict the droplet entrainment fraction for annular flow in vertical pipelines, where the entrainment is uniform across the pipe cross section.

Andreussi (1983) measured droplet entrainment in annular flow by tracer method, and observed that entrainment rate is proportional to liquid film rate and gas velocity squared.

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Nomenclature

A_{probe}	Probe cross-sectional area, m^2
APF	Flowing aqueous phase fraction, /
APF_{in}	Inlet stream aqueous phase fraction (WC for cases with no MEG, WC_{MEG} for cases with MEG in the aqueous phase), /
d_p	Pipeline inner diameter, m
$e_{Overall} =$	Overall correlation discrepancy with experimental data, %
E_X	Entrainment rate of phase X, kg/m^2s
$f_{E,Aqu}$	Aqueous phase entrainment fraction, /
$f_{E,L}$ or f_E	Liquid phase entrainment fraction, /
$f_{E,\max}$	Maximum droplet entrainment fraction, /
$f_{E,Oil}$	Oil phase entrainment fraction, /
$f_{ES,Aqu}$	Superficial aqueous phase entrainment fraction, /
$f_{ES,Oil}$	Superficial oil phase entrainment fraction, /
f_I	Interfacial friction factor, /
Fr_g	Gas phase froude number, /
H_L	Liquid holdup, /
k'_A	Droplet atomization constant, /
N_L	Liquid phase velocity number, /
P	Pipeline inner periphery, m
R^2	Coefficient of determination, /
Re_f	Liquid film reynolds number, /
S_a	Interface droplet atomization length, m
t_s	Iso-kinetic probe sampling time, s
u_τ	Entrained droplets terminal velocity, m/s
v_L	Liquid phase actual velocity, m/s
v_{Sg}	Gas phase superficial velocity, m/s
$v_{Sg,Atom}$	Onset of entrainment gas phase superficial velocity, m/s
v_{SL}	Liquid phase superficial velocity, m/s
WC	Water cut in the liquid phase, /
WC_{MEG}	Inlet stream aqueous phase fraction (with MEG), /
We	Gas phase Weber number, /
We_{SL}	Superficial liquid phase Weber number, /
σ	Liquid phase surface tension, N/m
$\sigma_{O,Aqu}$	Oil-aqueous phase interfacial tension, N/m
ε_1	Average percent error, %
ε_2	Absolute average percent error, %
ε_3	Percent standard deviation, %
ε_4	Average error, /
ε_5	Absolute average error, /
ε_6	Standard deviation, /
θ	Pipeline inclination angle, Rad
μ	Fluid viscosity, Pa.s
ρ	Fluid density, kg/m^3

Barbosa et al. (2002) used isokinetic probes to measure entrainment flux of liquid droplets at transition of annular and churn flow in vertical pipes and observed a minimum entrainment at the transition region. They observed significant errors in predictions of correlations, based on equilibrium between deposition and atomization rates at high liquid rates and in transition region. Alekseenko et al. (2012) investigated the effects of three-dimensional wave structure on droplet entrainment in vertical annular flow. Also, Zadrazil and Markides (2014) used particle image velocimetry methods to investigate droplet entrainment mechanism in vertical downwards annular flow. They observed significant impacts of large recirculating waves within the liquid film on mass and momentum transfer and droplet entrainment phenomena.

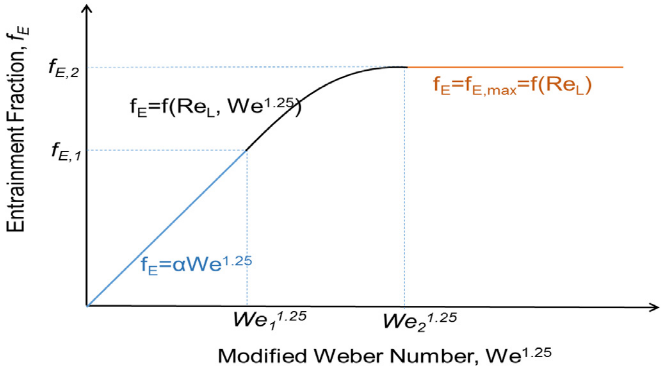

Fig. 1. Three different entrainment regions of Sawant et al. (2008).

Pan and Hanratty (2002) developed a correlation for entrainment in horizontal pipelines including gravitational effects. The concept of maximum entrainment, which was initially proposed by Ishii and Grolmes (1975), is used in Pan and Hanratty correlation. Ishii and Grolmes argued that there will be no interaction between the gas and liquid phases, while the liquid film thickness is lower than a minimum critical value. This critical value is the thickness of the buffer sub-layer of the turbulent velocity profile. Therefore, the maximum entrainment is close to unity, but slightly lower. Later, Gawas (2013) proposed some modifications to Pan and Hanratty's correlation. He suggested to use interfacial perimeter instead of pipe perimeter for stratified wavy flow pattern, and the model proposed by Mantilla et al. (2009) to calculate the maximum entrainment fraction.

Mantilla et al. (2009) developed a mechanistic model to predict onset of liquid entrainment, maximum entrainment fraction, and the amount of liquid entrainment. Onset of entrainment was defined as the point where drag forces become greater than the combination of surface and gravity forces. The concept of maximum entrainment from Ishii and Grolmes (1975) was applied. However, the correlation of critical liquid film thickness was modified using superficial liquid Reynolds number. They predicted entrainment fraction using a force balance on the wave crest. Several correlations were developed for wave characterization. Model predictions were compared with the experimental data obtained under low liquid loading conditions, and a fair agreement was observed.

Sawant et al. (2008) proposed an entrainment fraction correlation for vertical upward flow based on two dimensionless numbers; modified gas Weber number, We, and liquid film Reynolds number, Re_f. They divided droplet entrainment into three regions. The droplet entrainment is a unique function of Weber number in the first region, and a function of We and Re_f in the second region. It reaches the maximum value in third region. Fig. 1 shows the entrainment fraction regions of Sawant et al. (2008), for vertical annular flow. Al-Sarkhi et al. (2012) accepted this theory and developed a correlation for the second and third regions of entrainment, based on experimental data from different inclinations.

The number of studies conducted on three-phase droplet entrainment is very limited. Gawas (2013) developed a model to predict the entrainment fraction of oil and aqueous phases in three-phase low liquid loading flow. A source of uncertainty for this model is the assumption of a uniformly dispersed liquid phase resulting in similar droplet atomization rates for oil and water phases. However, terminal velocities of oil and water droplets in deposition rate measurements are different, which causes a difference between inlet and flowing water fraction in the liquid film. Consequently, different entrainment fractions are calculated for oil and aqueous phases. Gawas also conducted a set of experiments