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Hydrodynamic forces acting on pipe bends in gas–liquid slug flow

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ABSTRACT

In this paper, a one-dimensional, transient theoretical model, the Piston Flow Model (PFM), based on momentum analysis, is proposed to predict the time dependent forces acting on horizontal pipe bends in slug flow. Our experimental apparatus is described and results there from are presented. The PFM has been validated by comparing its predictions with our experimental results for air–water slug flow. The pressure traces, force traces and maximum force predicted agree well with our measurements.

Keywords: Hydrodynamics; Momentum transfer; Multiphase flow; Transient response; Force; Bend

1. Introduction

Slug flow is common in fixed and flexible riser systems in offshore oil production as well as more generally in process plants involving two-phase flow and in some pressure relief systems found in nuclear reactors. Bends in these systems are usually subjected to periodic hydrodynamic forces due to slug flow. It is important to know the forces so that the supports, in that they exist, or other restraining mechanisms such as friction with the sea bed can be properly designed to restrain the pipe against failure. In the case of a continuously slugging flow, the question of failure due to fatigue needs to be considered.

A survey of academic papers reveals an incomplete knowledge of the phenomena that can occur and great difficulty in measuring the forces on pipe bends due to slug flow in any experiment that has so far been devised. The only measurement of time-dependent force trace in accordance with liquid hold-up published in the open literature is that by Tay and Thorpe (2002). Other approaches taken in the literature are described in the next section.

The importance of understanding the hydrodynamic loads (forces) imposed on the flow line-riser structure is essential in designing piping support systems for offshore oil and gas production platforms.

In the next section, a transient (isothermal) model, based on unsteady-state momentum equation, to predict the time dependent force traces acting on horizontal pipe bends in slug flow is developed and subsequently the maximum forces on the bend are calculated. Section 3 describes the laboratory setup and experiments performed. A complete discussion and comparison of the calculated forces with our experimental data will be presented in Section 4.

2. Piston flow model

2.1. Previous studies and current industrial application: ‘Steady-state’ model

Most of the studies reported in the literature are based on pseudo steady state modelling; they take the bend filled with alternatively a slug or a bubble/film. This could be a significant flaw as there is suggestion of a peak force due to impact of the slug front within the bend as a result of the highly turbulent slug nose (Fairhurst, 1983; Lin and Hanratty, 1987; Hargreaves and Slocombe, 1998). This impact is a transient phenomenon. A multiplication factor of ‘2’ which is applied to the momentum terms from the pseudo steady state analysis has been used in industrial design. However, Tay and Thorpe (2002) recorded the force trace of a slug ($u_s = 2.81\,\mathrm{m\ s^{-1}}$) and

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Notation

A	Area (m^2)
D	Pipe diameter (m)
Eo_D	Eötvös number, $Eo_D = \frac{\rho_L g D^2}{\sigma}$
e	Surface roughness (m)
F	Force (N)
$\underline{\mathbf{F}}$	Force (vector) (N)
f	Friction factor, $\frac{1}{\sqrt{f}} = -4 \log \left[\frac{0.27e}{D} + \left(\frac{7}{Re} \right)^{0.9} \right]$
g	Gravitational acceleration ($m\,s^{-2}$)
h	Liquid height (above pipe base) (m)
H	Hold-up, $H_k = (A_k/A)$ where k is the corresponding fluid phase
j	Superficial velocity (i.e. Q/A) ($m\,s^{-1}$)
k_{Bend}	Bend loss coefficient
l	Length (m)
L	Pipe length (m)
P	Absolute pressure (Pa)
ΔP	Pressure difference (Pa)
Q	Flow rate ($m^3\,s^{-2}$)
r	Radial co-ordinate from pipe axis (m)
R	Bend radius (centre line) (m)
Re	Reynolds number, $Re = \rho u D/\mu$
S	Perimeter (m)
t	Time (s)
t_{lag}	Lag-time (s)
Δt	Time difference (s)
u	Actual velocity ($m\,s^{-1}$)
x-	x-direction in Fig. 2 part I
y-	y-direction in Fig. 2 part I

Greek symbols

μ	Dynamic viscosity (Pa s)
π	≈ 3.142
ρ	Density ($kg\,m^{-3}$)
σ	Surface tension ($N\,m^{-1}$)
θ	Angular coordinate in polar coordinates (see Fig. 2 in part I) (rad)

Subscripts

a	Atmospheric condition
a'	Point a' in Fig. 2 part I
ave	Average
cv	Control volume
d	Downstream pipe after the bend
e'	Point e' in Fig. 2 part I
f	Liquid film
G	Gas phase
hyd	Hydrostatic
i	Inside pipe
$inlet$	Inlet to the bend
$interfacial$	Gas–liquid interface
L	Liquid phase
l	Length
mo	Momentum term
o	Outside pipe
$outlet$	Outlet to the bend
PA	Pressure-area term
PFM	Piston Flow Model
R	Resultant
s	Slug unit
x	x-direction in Fig. 2 part I
y	y-direction in Fig. 2 part I

the liquid hold-up, at a rate of once every 10 ms and did not find this peak force.

Fairhurst (1983) carried out an experiment on a 80° horizontal-to vertical bend. He tried to estimate the forces acting on his bend based on the well known steady state momentum equation for a fluid by taking $F_x = \rho A u_s^2 (1 - \cos\beta)$ and $F_y = \rho A u_s^2 \sin\beta$, where u_s is the speed of the slug was taken to be j_G/H_G and H_G is the average void fraction of the slug flow estimated from the correlation of Beggs and Brill (1973). β is the angle between the inclined riser and the horizontal pipe. However, his calculation did not calculate the peak force due to the impact of the highly turbulent slug nose.

In industry, the maximum and minimum forces acting on a bend are estimated by $\underline{F}_{max} = ((2\rho_L (j_G + j_L)^2 (\pi D^2/4); 2\rho_L (j_G + j_L)^2 (\pi D^2/4))$ and $\underline{F}_{min} = ((\rho_L u_f^2 A_f); (\rho_L u_f^2 A_f))$, where $(j_G + j_L)$ is the total superficial velocity. The factor '2' applied to the momentum terms equations is the impact factor as explained earlier.

Similar to the assumption made in industrial design, Fairhurst (1983) also has not allowed for the contribution to force on the pipe due to pressure. In his study, the riser discharged to atmosphere. One of his tests was done at $j_L = 0.209\,m\,s^{-1}$ and $j_G = 0.782\,m\,s^{-1}$. Beggs and Brill (1973) estimate an average rise void fraction of around 60%. Therefore, the pressure at the bend due to the weight of water in the riser would have been $P - P_a = (1 - H_G)\rho_L g(\text{height of riser}) = 0.4 \times 1000 \times 9.81 \times (8 \times \sin 80^\circ) = 31\,kPa$ and the contribution to the force on the bend would have about $\Delta P \times A = 71N$, where $D = 54\,mm$. In addition Fairhurst (1983) measured fluctuations in pressure of amplitude 60 kPa in this test, which confirmed the importance of understanding this term in the study of forces on pipe bends. This clearly shows that ignoring the pressure-area term in Fairhurst (1983)'s analysis is a significant flaw.

Hargreaves and Slocombe (1998) used the apparatus built by Marnell and Winn (1997) and studied the forces on a horizontal 45 mm pipe bend and through a 90° bend of radius of 0.106 m in air/water slug flow. They proposed that for flow round a horizontal bend in the laboratory, the force should be given by $F_y = (P_{out} - P_a)A + \dot{m}_{out} u_{out}$ and $F_x = (P_{out} + \Delta P - P_a)A + \dot{m}_{in} u_{in}$, where $\dot{m}$ is the mass flow rate, u is the average velocity, ΔP is the pressure drop round the bend and P_{out} is the pressure at the outlet from the bend. Hargreaves and Slocombe (1998) did not measure slug velocity. They were unsure of the likely flow rate and velocity in the film phase. They assumed that in the film phase u is negligible, and used the mixture velocity, j_s, for the flow velocity in the slug phase. They further assumed a gas hold-up in the slug of near to zero. No quantitative comparison of the forces acting on the bend with the above theory was reported.

Interestingly, at the same time as Hargreaves and Slocombe (1998), Sánchez et al. (1998) also considered pressure-area term in their analysis, which has so far had been ignored. Sánchez et al. (1998) reported a theoretical and experimental study of the time-dependent forces exerted by a two-phase slug flow on a 41 mm I.D. and 280 mm long radius 90° elbow. They developed their model based on 'global momentum analysis' by taking the pipe bend as their control volume and quoted the unsteady version of force-momentum equation, $\underline{F}_{surface} + \underline{F}_{Body} = \frac{\partial}{\partial t} \int_{VC} \underline{u}\rho\,dV + \int_{SC} \underline{u}\rho u\,dA$, they then proceeded quite reasonably (for a horizontal bend) to ignore the sum of all body forces, $\underline{F}_{Body}$ (gravity) and, erroneously, to ignore the