INFLUENCE BEND RADIUS ON MULTIPHASE FLOW INDUCED FORCES ON A BEND STRUCTURE

S.P.C. Belfroid  
TNO  
The Netherlands

E. Nennie  
TNO  
The Netherlands

M. Lewis  
Xodus Group  
UK

ABSTRACT
Multiphase flow induced forces can result in large amplitude vibrations in flexible piping. In single phase, elongating the bend radius is a valid strategy to reduce the forces. In this paper, multiphase induced forces on a 1.5D and 3.3D bend are compared for near-atmospheric conditions in a 0.15m diameter bend. In contrast to the single phase, the larger bend radius has equal to slightly higher forces. On average, the measured forces in the 3.3D bend are 25% higher than in the 1.5D bend.

NOMENCLATURE
f  
frequency  
[Hz]

p  
pressure  
[Pa]

\( u_{lm} \)  
mixture velocity  
\( u_{lm} = u_g + u_l \)  
[m s\(^{-1}\)]

\( u_{SG} \)  
superficial gas velocity  
[m s\(^{-1}\)]

\( u_{SL} \)  
superficial liquid velocity  
[m s\(^{-1}\)]

\( v_i \)  
transport velocity  
[m s\(^{-1}\)]

A  
pipe cross sectional area  
[m\(^2\)]

ID  
pipe inner diameter  
[m]

F  
force  
[N]

Fr  
liquid Froud number  
[-]

\( R_{Cm} \)  
modified gas Reynolds number  
[-]

\( R_{El} \)  
liquid Reynolds number  
[-]

We  
Weber number (\( We = \rho_l \frac{u_m^2}{\sigma} \))  
[-]

\( \alpha_l \)  
liquid holdup  
[-]

\( \lambda \)  
no slip liquid holdup  
\( U_a/U_m \)  
[-]

\( \mu_G \)  
gas viscosity  
[Pa s]

\( \mu_L \)  
liquid viscosity  
[Pa s]

\( \rho_G \)  
gas density  
[kg m\(^{-3}\)]

\( \rho_L \)  
liquid density  
[kg m\(^{-3}\)]

\( \sigma \)  
surface tension  
[N m\(^{-1}\)]

INTRODUCTION
Multiphase flow induced forces can lead to large amplitude vibrations in flexible piping structures for the complete range of flow regimes. A common method to reduced flow induced forces on bend structures is to increase the bend radius. In this paper a comparison is made between the multiphase flow behavior and flow induced forces in a 1.5D bend and 3.3D bend radius horizontal bend. The 1.5D bend results are discussed in detail in [1].

EXPERIMENTAL SETUP AND EXPERIMENTS
A schematic of the measurement section of the 3.3D bend experiments is given in Figure 1. The ID of the measurement section is 0.15m with the bend radius of 3.3D (0.495m with a straight section of 85 mm). The setup consist of a long horizontal inlet (11.9 m) followed by the instrumented section. For more details of the upstream and downstream sections it is referred to [1]. In the same reference, the details of the 1.5D bend setup is given including details of the used instrumentation. The bend was fully instrument with upstream and downstream video and a two plane ERT [2] system (accuracy approximately ± 0.02). In the bend, 11 dynamic pressure sensors, two absolute and a pressure drop sensor were installed to monitor the pressures. The forces have been measured by force rings at the flanges (2*8 sensors, accuracy ± 6% or ± 10N whichever is higher), strain gauges and piezo strain gauges (accuracy ± 2% or ± 2N whichever is higher). The force sensors and strain gauges were all statically and dynamically calibrated when installed in the bend. The bend was clamped-in closely to ensure a high enough natural frequency such that the measured forces are directly the fluid forces. For reference, the y-direction is the direction in the inflow direction. The flows are measured with an accuracy of 1% except at very low liquid rates (\( u_l < 0.01 \) m/s) at which the liquid rate is measured with 10% accuracy.

FIV2018-91
 Measurements were taken at a large range of gas and liquid flows covering all flow regimes except bubbly flow. Special attention was given to low liquid fraction measurements. An overview of the measurement conditions is given in Table 1 and Figure 2. Each measurement run was 180s with a sample rate of 5kHz. With respect to this paper, the attention is given to the dynamic part of the force. That means for the measured forces, the mean values are ignored and only the dynamic part of the forces is plotted. This is defined as the root-mean-square (rms) value of the dynamic part which is the standard deviation of the total signal. As it is customary to call these forces still the rms force, this practice is continued in this paper.

### BASE RESULTS – SINGLE PHASE RESULTS

For single phase conditions, the increase of the bend radius has a positive effect on the dynamic forces. In Figure 3, the dynamic force (standard deviation of the measured force) is plotted as function of the Reynolds number, normalized with the flow momentum \( \rho u^2 A \) for the gas and liquid flow. For both the gas and liquid flow, the forces in the 3.3D bend are 0.4 - 0.5 times the forces in the 1.5D bend with a 10-30% higher pressure drop (Figure 4). Therefore, for single phase conditions, elongating the bend is advantageous with respect to the dynamic forces.

### BASE RESULTS – HOLD-UP

In addition to the forces, also the hold-up upstream and downstream of the bend have been measured. For both systems, the upstream conditions were similar which was also measured in the holdup data. Across the bend, the development of the multiphase flow did differ. In Figure 6, the ratio of the upstream to downstream average hold-up is plotted as function of the mixture velocity. For both systems, the downstream measured hold-up is reduced in comparison to upstream. This is due to mixing, aeration of the film and possible entrainment. This all reduces the effective slip.
For a set of specific conditions where the flow conditions were almost identical (taken across the whole range of low and high liquid fraction and high and low velocities), the data is also plotted in Figure 5. At higher liquid rates, the downstream hold-up is less reduced in comparison to the 1.5D bend. This seems to hint at that in the 3.3D bend the liquid is less mixed than in the 1.5D bend. At lower liquid rates, this effect is less and the hold-up reduction is reversed or not present.

Also in terms of the dynamics of the wave structures, the effect between the two bends is limited. In Figure 7, the downstream peak Strouhal number of the hold-up (based on Fast Fourier Transform of the cross-sectional averaged hold-up) is plotted. The dominant frequency components of the multiphase flow coming out of the bend are very similar between two systems.

**BASE RESULTS – FORCES**

For the 1.5D bend cases, it has been demonstrated that a quasi-steady approach is valid [1]. That is, all effects occurring in the bend itself such as the transport time of waves/slugs through the bend and any centrifugal forces in the bend, are neglected. That means the bend radius is not directly included. For steady state, the force (in one direction) in a 90° bend is given by a pressure \( \rho \) and momentum effect (with \( A \) the pipe cross sectional area):

\[
F = (p + \rho u^2)A \quad (1)
\]

For the transient analysis the transient pressure and density are used:

\[
F(t) = (p(t) + \rho(t) u^2_{\text{wave,slug}})A \quad (2)
\]
The density variations are, of course, due to the holdup variations due to slugs and waves. For the pressure we use the upstream absolute pressure sensor. In Figure 8, the comparison between the reconstructed and measured force is plotted for both the 1.5D and 3.3D bend experiment. In general, the comparison is well for both systems, with more spread at the higher forces for the 3.3D bend experiments. This does mean that the dynamic forces are dominated by the incoming conditions and less by turbulent effects in the bend itself.

A direct comparison for the selected conditions, between the dynamic forces (rms) between the two sets is given in Figure 9. In general, the two sets are very comparable to each other. For equal conditions the force in the 3.3D bend is, on average, slightly higher than in the 1.5D bend (Figure 10) but if we compare the power Spectral Density (PSD) of the force for the selected cases (Figure 11) the differences are minor. In addition, also in the crest factor (ratio peak-to-peak force to rms force) the differences are minimal (Figure 12). The similarities between the two data sets is very large.

Therefore, based on the multiphase experiments, the effect of elongating the bend to reduce the dynamic forces does not work as well as for the single phase cases.
FIGURE 11: COMPARISON OF PSD OF FORCE (Y-DIRECTION) BETWEEN 1.5D AND 3.3D BEND EXPERIMENTS AT (NEAR) SIMILAR FLOW CONDITIONS.

CONCLUSIONS - DISCUSSION

The data sets for the two bends are compared to literature data in Figure 13. In this figure, the total (combined x and y direction) force is made dimensionless according:

$$F_{\text{rms (total)}} = C \rho l u m^2 A_{\text{tube}} W e^{-0.4}$$  \hspace{1cm} (3)

This scaling is based on the work of Yih, Riverin and Pettigrew ([10],[11]). In addition, a low and high hold-up correction are introduced. For 0.01 < \( \lambda < 0.2 \), the force is corrected with:

$$F_{\text{rms (total)}} = 5 \cdot \lambda_1 \cdot C \rho l u m^2 A_{\text{tube}} W e^{-0.4}$$  \hspace{1cm} (4)

For 0.8 < \( \lambda < 0.99 \), the force is corrected with:

$$F_{\text{rms (total)}} = 5 \cdot (1 - \lambda_1) \cdot C \rho l u m^2 A_{\text{tube}} W e^{-0.4}$$  \hspace{1cm} (5)

FIGURE 12: COMPARISON OF CREST FACTOR (RATIO OF PEAK-TO-PeAK TO RMS) AS FUNCTION OF NO-SLIP LIQUID HOLD-UP.

FIGURE 13: COMPARISON OF MEASURED FORCES (TOTAL RMS) WITH LITERATURE DATA. BELFROID 25 mm [4], CARGNELUTTI 6 mm [5], NENIE 100 mm [6], GIRAUDEAU [7], LIU [8], TAY [9]. THE WEBER NUMBER IS DEFINED AS We = \( \rho l u m^2/\sigma \).

This results in an almost constant C value for the complete range of liquid fractions. This C value is determined for the different literature cases and for the two data sets. For the current two sets the values are:

1.5D bend: \hspace{1cm} C = 24 \pm 14
3.3D bend: \hspace{1cm} C = 30 \pm 16
As indicated, the C value for the 3.3D bend data is, on average, slightly larger than for the 1.5D bend. In Figure 14 the C values as plotted as function of bend radius and as function of diameter. From this, it can be concluded that for the multiphase cases, the effect of bend radius is minimal but that a clear transition is present in the diameter. For diameters less than 50mm, the C value is approximately 15, whereas for the larger diameters, a value of 30 is more appropriate.

![Graph of C factor as function of bend radius and diameter](image)

**FIGURE 14:** C FACTOR AS FUNCTION OF BEND RADIUS (TOP) AND AS FUNCTION OF DIAMETER (BOTTOM). IN RED THE CURRENT 1.5D BEND DATA AND IN GREEN THE 3.3D DATA. THE BLUE DATA HAS BEEN DERIVED FROM: BELFROID [4], CARGNELUTTI 6 mm [5], NENNIE 100 mm [6], GIRAUDEAU [7], LIU [8], TAY [9].

**ACKNOWLEDGEMENT**

This work is done within the JIP Multiphase Flow Induced Vibration. TNO carried out the test work, while Xodus managed the program and performed CFD validation. Authors would like to acknowledge Xodus and the sponsors BP, Shell, Statoil, Total, Lundin, AkerSolutions, and FMC Technologies for the possibility to publish these results.

**REFERENCES**