Estimation of Slug Forces in Pipe Bends

A first Analytical Approach

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Presentation at Aker Solutions FADS Seminar

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Overview of presentation

L. Ernstsen:

- Introduction / background
- Slug force calculation based on OLGA
- Wish for a verification

G. Jensen:

- Analytical approach: Including the bend length
- Worst case with 100% liquid slug
- Excel spread sheet
- Unresolved challenges
- Conclusion

Background

- Spin-off from Statoil's Sture project. Refer previous presentation, “Slugging phenomena in a flare header” by Runar Sæther
- Most of the Sture project work has been done by L. Ernstsen, as hired-in consultant from Petrosim AS
- Some slug force peaks found could be very high and of short duration, and one could question, if they were realistic

Employed Calculation Procedure

- **Based on the bend angle and the impulse momentum of the 4 OLGA flow fields: Gas, drops, oil film and water film**
- **The following equation has been used:**

$$F = (WG*UG+WLHL*ULHL+WLWT*ULWT+WD*UD)*\pi*ID^2/4*DAF*(2*(1-\cos(\theta)))^{0,5}$$

where:

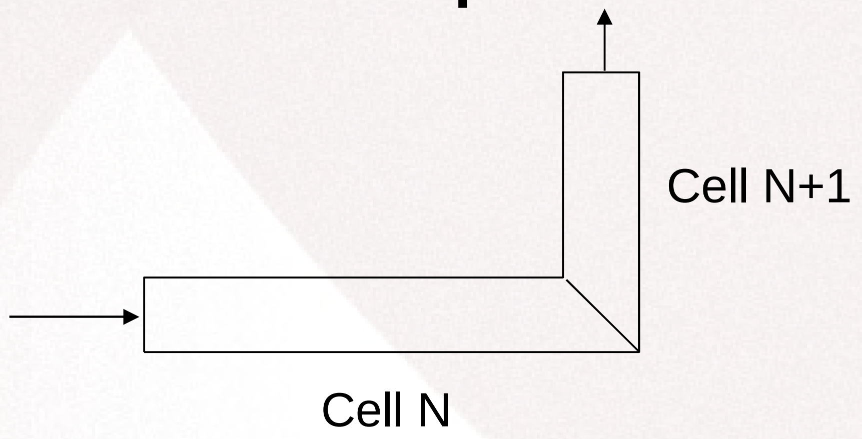
F =	Force on pipework [N]
WG =	Gas mass flux [kg/(s*m^2)]
WLHL =	Oil film mass flux [kg/(s*m^2)]
WLWT =	Water film mass flux [kg/(s*m^2)]
WD =	Droplet mass flux [kg/(s*m^2)]
UG =	Gas velocity [m/s]
ULHL =	Oil film velocity [m/s]
ULWT =	Water film velocity [m/s]
UD =	Droplet velocity [m/s]
ID =	Pipe inside diameter [m]
DAF =	Dynamic amplification factor, a constant in the range [1…2]
θ =	Angle of pipe bend [°]; θ=0 ~ a straight pipe ~ F = 0

Modeling in OLGA

- OLGA uses a one-dimensional sequence of cells to model a pipe
- Only flow direction changes, where elevation is changed, are taken into account
- Flow direction changes in the horizontal plane are not modeled. The user may, however, insert an arbitrary pressure loss at such locations.

Modeling in OLGA, cont'd

We will look at a 90° bend, where flow direction changes from horizontal to vertical-up as follows:

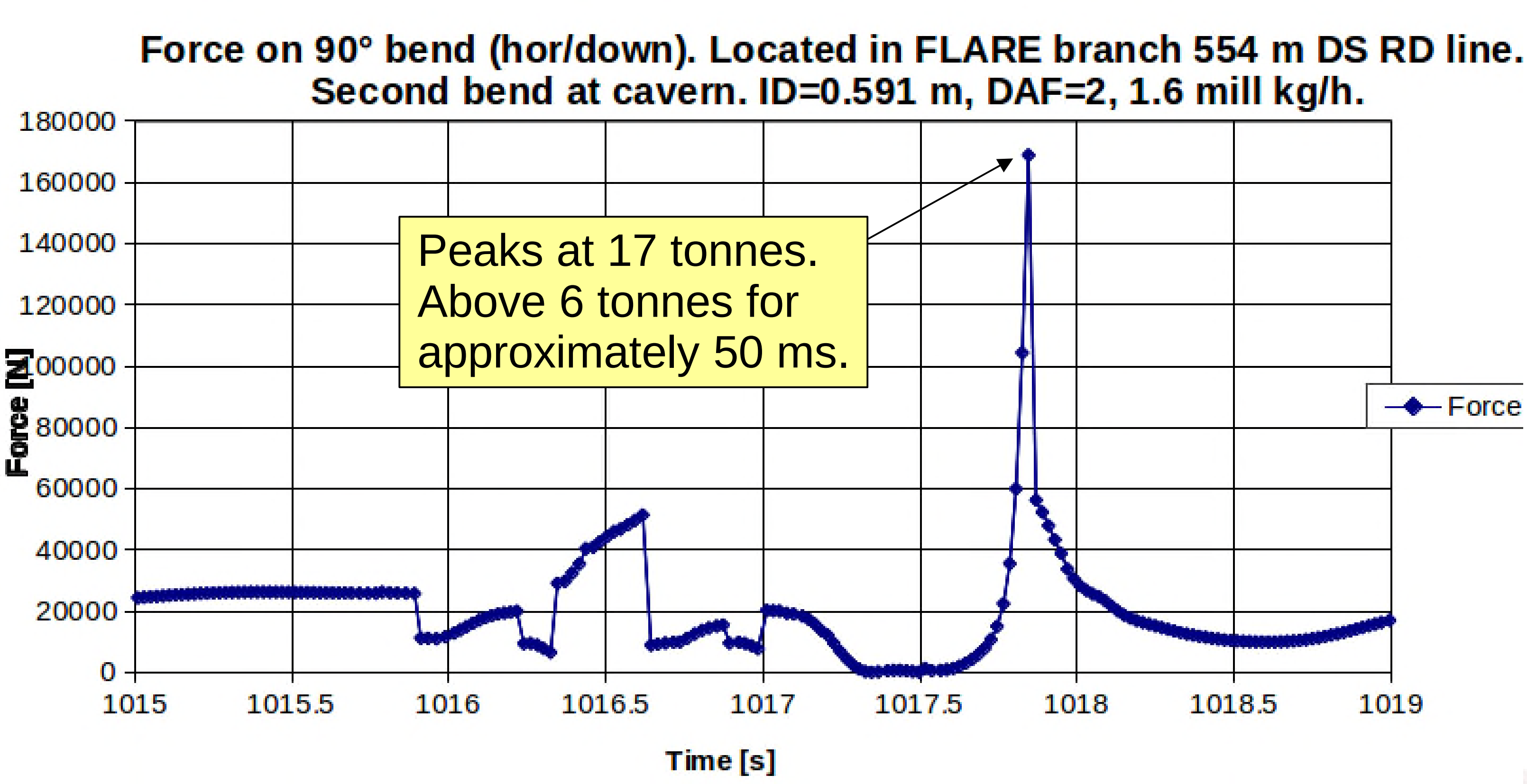


Fluid in cell N will make a "jump" to cell N+1 in one time step. The gradual flow direction change in a real bend is not modeled.

Slug Load in Pipe Bends

Questionable Force Peaks

An example from the Sture project:



Questionable Force Peaks, cont'd

Important to use sufficient fine resolution for OLGA results to be able to capture what is happening in the OLGA kernel.

Results time step: _|____|____|____|____|___

Calculation time step: _|_|__|___|__||_|__|___|____

Most of the suspicious force peaks have been caused by OLGA volume errors. Its a time consuming detective work to scrutinize such errors.

However, some force peaks could not be explained this way. There is therefore a wish to have such peaks verified.

Co-work with Gunnar Jensen

- Gunnar and I have known each other for many years
- Growing up at the time, when man entered space, implied a strong interest in technical and scientific issues
- Gunnar went the theoretical way and graduated from the University of Copenhagen as Cand Scient within chemistry and physics
- I followed the more practical engineering path and have a BS in chemistry and a MS in cybernetics, both from Denmark

Co-work with Gunnar Jensen, cont'd

- Over the years we have discussed / studied a wide range of technical / scientific issues. Neural networks and Coriolis force influence on flow in long pipelines can be mentioned.
- The present interest in modeling force on pipe bends was initiated during a winter vacation, February this year
- Gunnar's findings were considered so important, that Runar Sæther suggested we presented these for a wider audience

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… WITH THIS I WILL GIVE THE WORD TO GUNNAR --->

Slug Load in Pipe Bends

The formula used for calculation of the force on a pipe bend:

$$F = (WG*UG+WLHL*ULHL+WLWT*ULWT+WD*UD)*Pi*ID^2/4* DAF * (2*(1 – \cos(\theta)))^{0,5}$$

This formula is designed to work in short time intervals. It is therefore suited to work with the OLGA program, which delivers data e.g. every 20 ms at a given point.

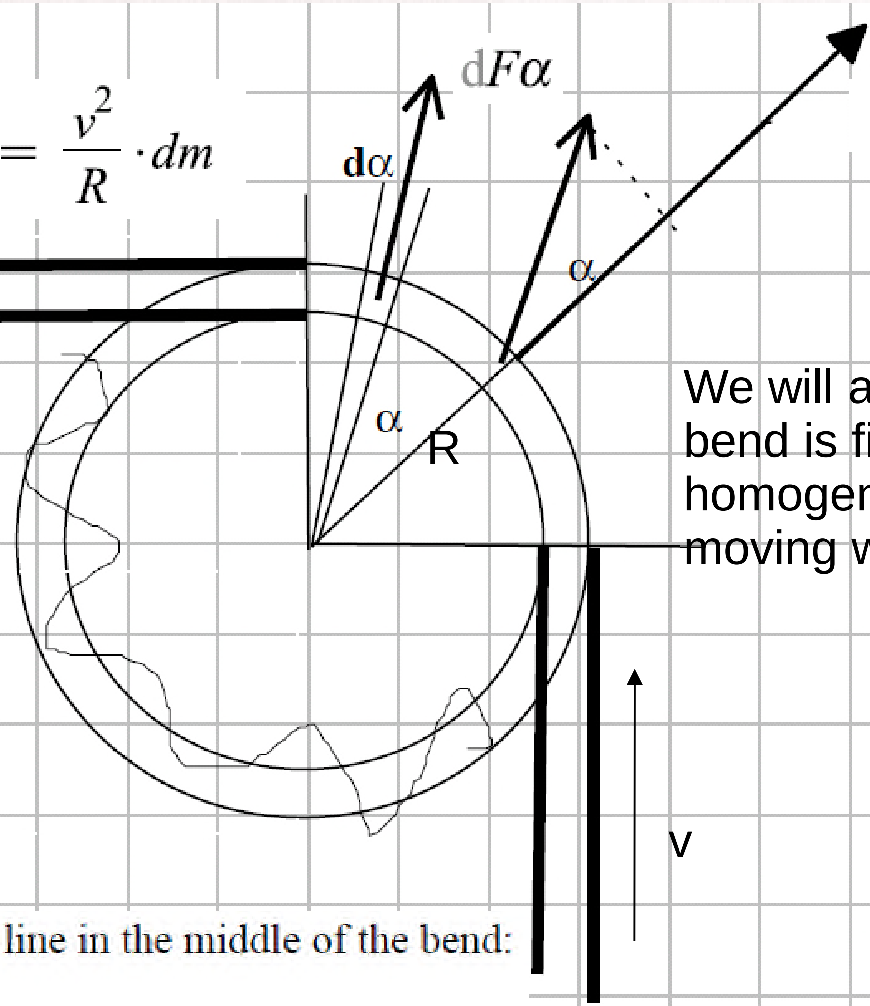
Slug Load in Pipe Bends

We will however question the use of the formula in the way this has generally been done.

In order to clarify the case, it will be appropriate with a short derivation of the formula:

Slug Load in Pipe Bends

A pipe bend in which material is passing



$$dF\alpha := \frac{v^2}{R} \cdot dm$$

$$dm := \frac{\pi \, ID^2 \, R \, d \, d\alpha}{4}$$

We will assume that the bend is filled with a homogeneous material, moving with a velocity v

the force is projected on the line in the middle of the bend:

$$\cos(\alpha) \cdot dF\alpha$$

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$$FC := 2\cdot\int_0^{\frac{\alpha b}{2}} \cos(\alpha)\, dF\alpha$$

αb is the angle of the bend

We insert dFα

$$FC := \frac{\pi\, ID^2\, d\, v^2}{4}\cdot 2\cdot\int_0^{\frac{\alpha b}{2}} \cos(\alpha)\, d\alpha = \frac{\pi\, ID^2\, d\, v^2 \sin\left(\frac{\alpha b}{2}\right)}{2}$$

this is only valid if the bend is filled with material

which can be transformed to

$$FC = Mf\cdot A\cdot v\cdot(2\cdot(1-\cos(\alpha b)))^{\frac{1}{2}}$$

Mf is the mass flux, *A* the area of a cross-section, *v* is the velocity.

This formula is the same as the previously mentioned.

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Slug Load in Pipe Bends

Resultant force $FC = Mf \cdot A \cdot v \cdot (2 \cdot (1 - \cos(\alpha b)))^{\frac{1}{2}}$

The formula contains instantaneous parameters, Mf and v. Nevertheless it is only valid, if the initial condition, which is that the bend is filled with the material in question, is fulfilled.

Slug Load in Pipe Bends

Example

Lets assume that we have a slug moving through a bend.
As a worst case we assume that the slug contains no gas (100 % liquid).
Further we assume that there is 'nothing' in front of and behind the slug. The slug is assumed so short that it does only 'fill' a fraction of the real bend; 0.40 m has been chosen. However, in OLGA the length of the bend is zero, and the slug passes the bend in one time step.

Angle of bend:	90º
Radius of circle describing the bend:	R= 1.80 m
Internal diameter of the pipe:	ID = 0.60 m
Velocity:	UD = v = 20 m/s
Slug density:	d = 780 kg/m^3
Time step:	dt = 0.020 s

Calculations:

Mass flux:	Mf = WD= $v \cdot d$ = 15600 $kg/(m^2 \cdot s)$
Length of the slug:	L = $v \cdot dt$ = 0.40 m
Mass of the slug:	$M = L \cdot A \cdot d = 0.40\ m \cdot \pi \cdot (0.30\ m)^2 \cdot 780\ kg/m^3 = 88\ kg$

Slug Load in Pipe Bends

Example, cont'd

At the entrance cell of the bend we calculate the force with our formula with DAF=1:

$F = WD*UD*Pi*ID^2/4 * (2*(1 - \cos(\theta)))^{0,5}$ = 124756 N or 12.7 tonnes,

(we have in mind that the mass moving is only 88 kg).

20 ms later the cell is empty, and the calculated force drops to zero! But in real life our slug is still in the bend, so there must be a force on the bend. The slug stays in the bend for 0.14 s where our calculated force is zero.

One can calculate a more correct* value of the force by calculating the angle the slug 'fills' in the bend, and use this with the formula above.

$\theta = L/R \cdot 180/\pi = 12.7^o$

F = 19563 N or 2.0 tonnes

***As I will mention later, it is still not entirely correct**

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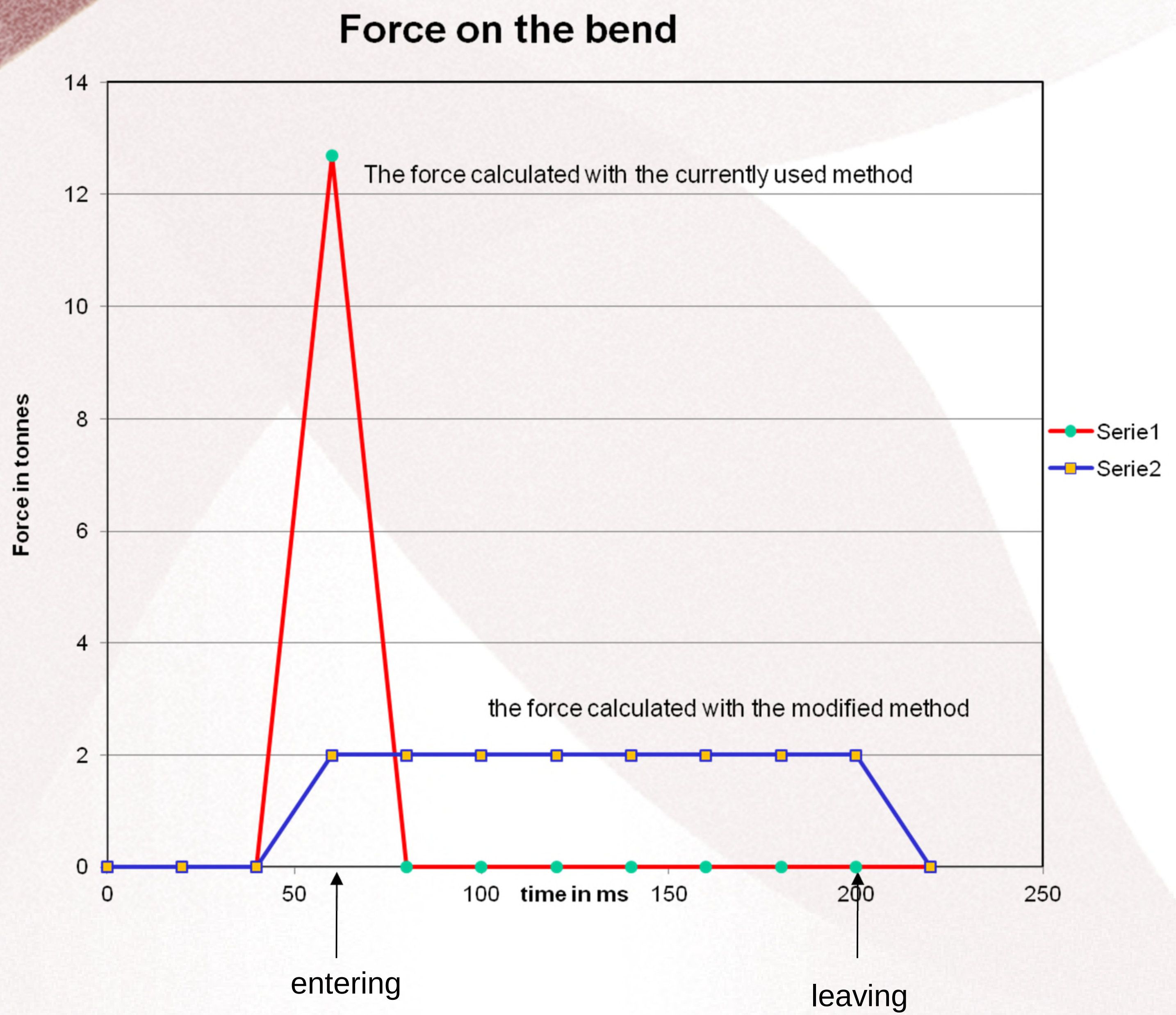
Slug Load in Pipe Bends



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Slug Load in Pipe Bends

	FORCE IN A BEND WHEN A LIQUID SLUG PASSES										
								input in yellow			
					Bend etc. definition:						
					ID=	0.6	m				
					angle	90		angle of mass in	12.7324		
					DAF	1					
Slug definition:					radius of bend	1.80	m				
d=	780	kg/m^3		total mass		88.22	kg				
L=	0.4	m		length of bend		2.83	m				
V=	20	m/s		length of actual mass in bend		0.40	m	mass in be	88.22	kg	
Mass pr. s pr.m^2 = V*d =			15600	kg/(s*m^2)		dt=	0.02	s is the time it takes the slug to			
								pass a given location			
F calculated from force				F calculated according to							
formula used by SPT				the actual mass in the bend							
	124756	N		19563	N						
	12.70	tons		1.99	tons						
							Received from G. Jensen, 23.04.2013				

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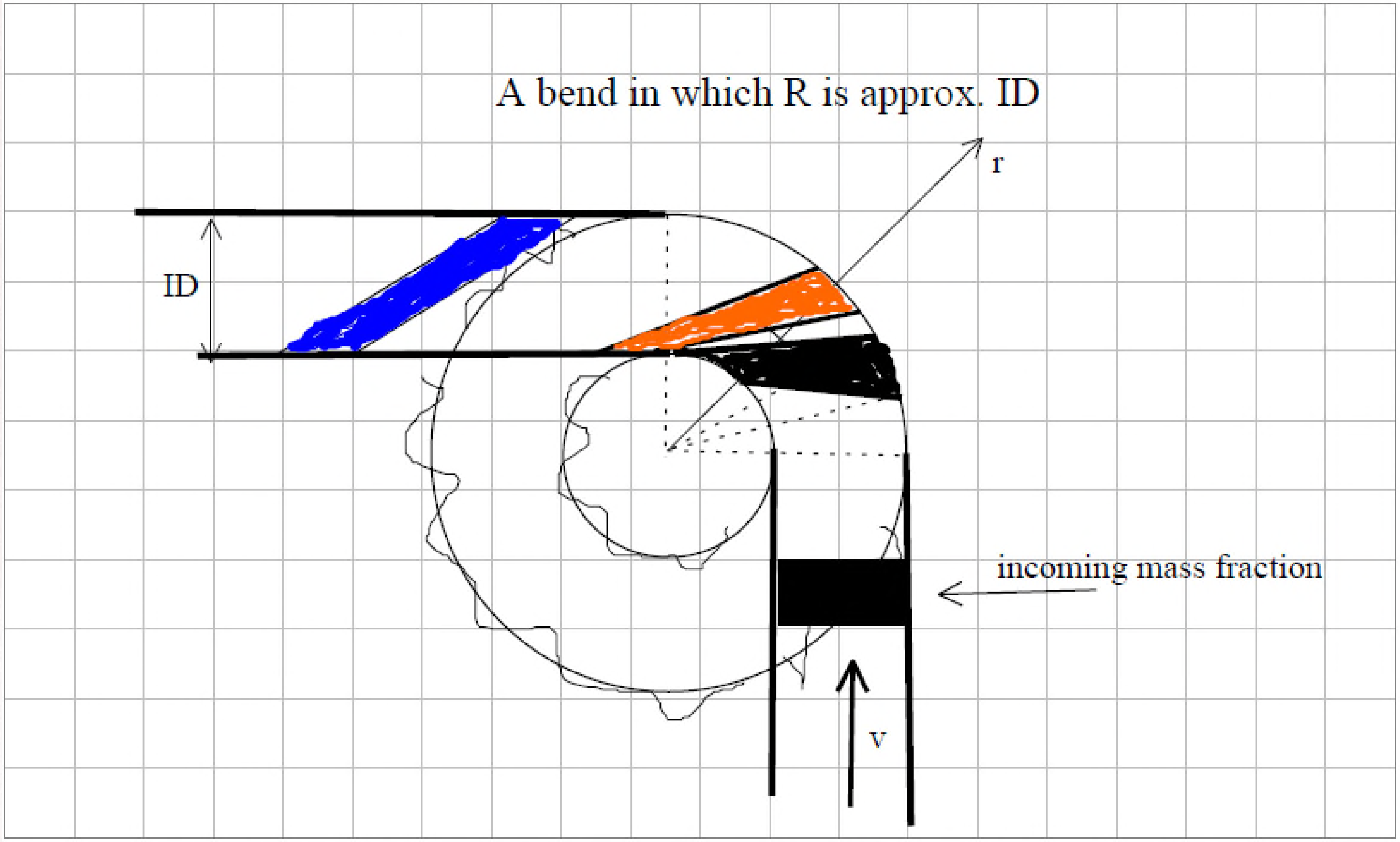
Slug Load in Pipe Bends

Unresolved Challenges

It can be shown that the inner part will be approximately 1.6·ID in front of the outer part, regardless of the radius of the bend.

What happens with a slug when it hits a bend?

When a slug hits a bend, it will "turn around the corner" in a rather special way, because the velocity is the same all over a cross section.



On the figure above you see a mass fraction entering a bend with a velocity *v*. What will happen to this fraction on passing the bend? We will assume laminar flow, although this for the most is unrealistic. The velocity is the same for the inner part and the outer part.

Unresolved Challenges, Cont'd

When the material turns around the corner, the circular motion creates a fictive gravitational field (R= 1.80 m. v= 20 m/s, ID= 0.6 m) of magnitude (v^2/R) :

Outer part: 190 m/s^2 approx. 19 G
Inner part : 267 m/s^2 approx. 27 G

This field creates a bouyancy that (my guess) will separate denser phases in the outer part of the bend, and lighter phases in the inner part.
The shift in position in the bend might speed up the inner part and slow down the outer part (again a guess) created by conservation of angular momentum.
The high pressure of the field might also result in (rapid?) phase transitions.

Conclusion

In a realistic case, where mass flux and velocity of the phases are changing rapidly, one cannot use the instantaneous values at a given point (e.g. the entrance of the bend) to calculate the resultant force on the bend, because the bend is filled with material from several cells with different phases, mass flux and velocity.

If neighboring cells differ significantly from each other, it can cause unrealistic high (or low) forces to be calculated.

Conclusion, cont'd

In order to calculate a realistic force on a bend, one has to know:

1) The geometry of the bend
2) What is in the bend, and
3) How it is moving.

In lack of a better solution for the time being, we will suggest to calculate, from the data delivered from OLGA, the mass that will be in the bend at any time, and calculate an average velocity from conservation of the linear momentum it had before entering the bend.

A big THANK YOU:

… for your attention !

… to Statoil and Aker Solutions for the opportunity to give this presentation !

Slug Load in Pipe Bends