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SUPPRESSION OF TERRAIN SLUGGING WITH AUTOMATIC AND MANUAL RISER CHOKING

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ABSTRACT

Experiments on suppression of terrain slugging by means of a remotely controlled choke valve, installed in the riser top, are presented for naphtha/nitrogen flow at system pressures 20 and 45 bar.

For riser choke in manual mode (constant valve closure) significant valve closure was necessary to reduce the terrain slugging. Going from 60 % to 80 % in valve closure, terrain slugging was observed to disappear completely at 20 bar nominal pressure level. By this change in valve closure the pressure drop over the valve increased from some 1 bar to 7 bar.

Terrain slugging was successfully alleviated whenever the riser choke was put in automatic mode. The corresponding pressure drop was typically 1-2.5 bar.

An analytical expression for the upper pressure limit for terrain slugging was derived. The expression explains the different performances on suppression of terrain slugging when operating the choke valve in manual and automatic modes.

NOTATION

A	–	riser pipe cross section	[m^2]
B	–	flow coefficient	[-]
H	–	liquid hold-up in slug	[-]
H'	–	liquid hold-up at riser entrance	[-]
L	–	terrain slugging parameter	[-]
N	–	terrain slugging parameter	[-]
p	–	pressure	[N/m^2]
Δp	–	pressure drop	[N/m^2]
R	–	modification term	[-]
t	–	time	[s]
TS	–	terrain slugging	
U	–	velocity	[m/s]
U^s	–	superficial velocity	[m/s]
UGS	–	superficial gas velocity	[m/s]
ULS	–	superficial liquid velocity	[m/s]
V	–	volume	[m^3]
β	–	pipe angle	[°]
μ	–	dynamic viscosity	[Ns/m^2]
ρ	–	density	[kg/m^3]
σ	–	surface tension	[N/m]

Subscripts

0	–	at zero mixture velocity
D	–	downstream
G	–	gas
gr	–	gravity
L	–	liquid
R	–	riser base
U	–	upstream
V	–	valve

INTRODUCTION

Simultaneous flow of gas and liquid in pipes can be divided into two main flow classes; steady state flow and transient flow. The latter class comprises flow phenomena resulting from operation procedures like start-up and shut-in, rapid changes in flowrates and pressure and, finally, slugging caused by a special pipeline profile or topography. This slugging type, denoted severe slugging or terrain slugging, can occur whenever there exist a low-point in the pipeline. The low-point is often realized by a downsloping pipe terminating a riser.

The occurence of terrain slugging is highly system dependent. Accordingly, different mechanisms have been reported for low-pressure, small scale systems and high-pressure, large scale systems, compare the experimental findings in [1], [2] and [3] to the large scale data reported in [4], [5] and [6]. Nevertheless, for all systems reported above the highly periodical flow at the riser outlet may roughly be described by the sequence; no flow - liquid flow - gas flow. During a terrain slugging period the gas- and liquid production varies considerably. Such a flow situation will eventually cause great operational problems unless special precautions are taken.

The large slugs associated with terrain slugging can be satisfyingly handled if sufficient large slug catcher are installed. However, construction and installation of such facilities can be very expensive, especially if it is located on an offshore platform.

In order to prevent fatal operational difficulties, the pre-design of the multiphase flow transportation system is of primary importance. By proper choice of pipe diameter, pipeline topography and operation procedures, occurence of terrain slugging can be eliminated. The reliability of such a design study strongly depends on the simulator tool applied. Due to the system dependent nature of terrain slugging a dynamic simulator should be applied.

For some cases it is impossible to avoid terrain slugging without using "artificial" installations like a gas injection system or a choke valve. The latter installation requires a modest investment and should therefore be of considerable interest to designers and operators. Clearly, this justifies a study on suppression of terrain slugging by using a choke valve.

Accordingly, this paper deals with experiments on choke valve performance at a pipeline topograhy allowing for terrain slugging. A choke valve was located in the riser top at the large scale facility at The SINTEF Multiphase Flow Laboratory and operated in both manual and automatic mode. The terrain slugging mechanism as it was observed for this specific system will be shortly presented. The choke valve performance in manual mode will be shown by flow maps, whereas the performance in automatic mode will be presented qualitatively by means of time series, only. Finally, a criterion for the upper pressure limit for terrain slugging which applies with the presence of a choke in the riser top, will be presented. This criterion is a modification of a criterion published in [5].

PIPE CONFIGURATION AND PARAMETER RANGE

The experiments were run with a closed-loop system at the SINTEF Multiphase Flow Laboratory, described in some detail in [7] and [4]. A principal sketch is shown schematically in Fig. 1. and the relevant gas volumes are listed in Table 1.

Table 1: *Volume data for the SINTEF Multiphase Flow Laboratory*

Section	Length [m]	Volume [m³]
High pressure gas volume (upstream mix. point)	–	3.0
Flowline upstream low point[a]	950	13.3
Riser[a]	54	0.8
Downstream facilities	–	51.6

[a]Calculated for hold-up 0.5

The two-phase pipeline topography is illustrated in Fig. 2 with the gamma densitometer locations indicated. The lengths of the subsequent pipe sections, inner pipe diameter 0.19 m, are as follows:

- 30 m 5° downward inclined line
- 334 m 1° downward inclined line
- 218 m horizontal curved line
- 303 m horizontal line
- 65 m 2° downward inclined line
- 54 m riser

The liquid- and gas phases were naphtha and nitrogen, respectively. Fluid properties of nitrogen saturated naphtha are listed in Table 2 for the relevant experimental conditions; temperature 30°C and system pressures 20 and 45 bar.

Table 2: *Fluid properties of naphtha/nitrogen at 30° celsius*

P [bar]	ρ_l [kg/m^3]	$\mu_l \cdot 10^3$ [Ns/m^2]	$\sigma \cdot 10^3$ [N/m]	ρ_g [kg/m^3]
20	680.0	0.28	15.8	23.6
45	677.3	0.29	14.0	52.3

VALVE OPERATION

The valve used for choking was installed in the riser top at absolute location 1002 m. The valve, denoted V250 by the manufacturer Fisher Control Int., yielded a modified equal percentage characteristic. Flow coefficients as supplied by the manufacturer are listed in Table 3. The valve was operated remotely from the control room by means of a PC-based I/O-system. The valve position is given in terms of closure (%), where 0 % indicates open valve and 100 % represents closed valve. Intermediate closures are determined linearly from the actuator signal related to the reference points 0 and 100 % closures.

Table 3: *Flow coefficients vs. valve rotation as supplied by the manufacturer.*

Coefficient	Valve rotation [°]				
	10	30	50	70	90
C_v (liquid)	1.48	91.8	308	720	2190
K_m	0.81	0.81	0.73	0.46	0.20
$C_g \cdot 10^3$ (gas)	0.035	3.31	9.79	19.9	32.5
C_l	24	38	32	28	15

For automatic valve mode operation a PI-algorithm (proportional- and integral action) was applied. Thus change in valve closure was determined from the difference between a process signal and its set point, proportional action, and an accumulated value of this difference, integral action. Integral action causes the valve action to be smooth and counteracts long period oscillations which are typical for terrain slugging. As process signal the pressure drop over the riser was chosen.

EXPERIMENTAL PROCEDURES

For a fixed combination of superficial gas- and liquid velocity experiments on different choke settings were run. The experimental sequence in terms of valve closure was generally 0-20-40-60-80 %. The sequences were run with flow controllers both in automatic and manual mode. As the pressure drop over the choke was significant for the highest valve closures, this led to somewhat reduced feed rates for the corresponding experiments. However this is compensated for in the flow maps.

RESULTS

The experiments were run in the two operational modes; riser choke valve in manual- and in automatic mode operation. Superficial gas- and liquid velocities used to identify the individual experiments refer to the conditions at the turbine- and vortex meter, respectively. The nominal pressure level refers to the pressure at the riser outlet.

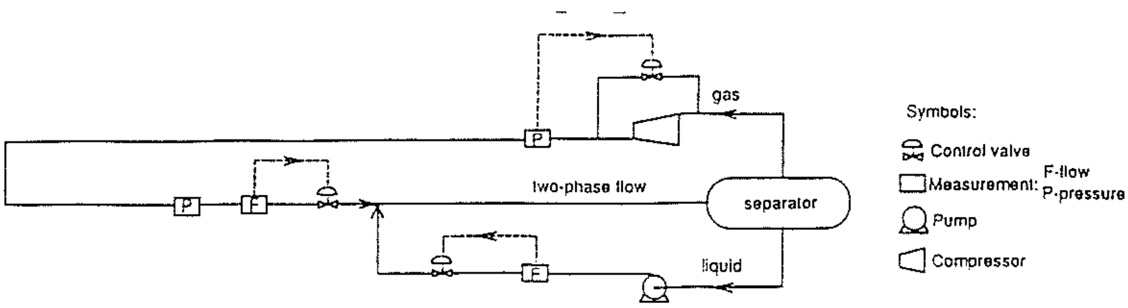

Fig.1 Schematic sketch of the SINTEF Two Phase Flow Loop

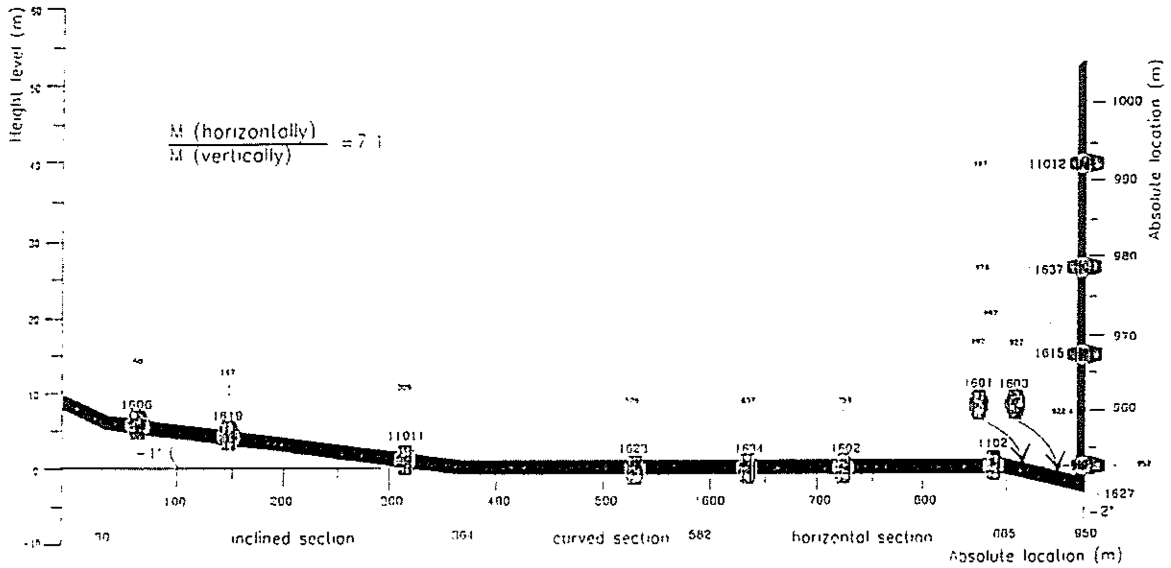

Fig. 2 Two-phase flowline topography

In terms of flow behaviour the experiments were classified in the three main regimes:

- no terrain slugging (continuous flow)
- transitional flow (terrain slugging occurs occasionally)
- terrain slugging

Furthermore the terrain slugging regime is divided into the sub-regimes:

Terrain slugging I: The blockage at the line-riser connection consists of pure liquid.

IA the slug grows to the top of the riser before slug release.

IB the slug does not grow to the top of the riser.

Terrain slugging II: The liquid in the blockage at the line-riser connection is aerated.

The separation between the three main flow regimes is done by means of extended power spectral analysis applied to the pressure difference over the riser. The experiments classified as transitional flow are checked manually. The procedure may therefore be characterized as semi-automatical.

The terrain slugging mechanism

As the flowline upstream the low-point is significantly longer than for any of the topographies reported earlier, see [4] and [6], the terrain slugging mechanism as observed for the actual geometry is of special concern. Experiment no. 6869, identified by superficial gas velocity 0.97 m/s, superficial liquid velocity 0.92 m/s and absolute pressure 26.6 bar at the inlet, is chosen to illustrate the terrain slugging mechanism for the actual topography. The experiment was run with open riser choke valve. Time series for selected gamma densitometers are shown in Fig. 3.
The sequence of these liquid hold-up recordings is arranged according to increasing instrument distance from the gas/liquid mixing point. The individual locations are indicated in Fig. 2. The moments of riser slug release and line-riser blockage, indicated by r's and b's, respectively, are determined from the liquid hold-up recordings in the riser bottom, represented by instr. no. 1627. When the gas pocket enters the riser, the riser slug release is initiated, and consequently the liquid hold-up in the riser bottom drops abruptly. Moreover, as the fall-forward slug makes up the line- riser blockage, a distinct increase in liquid hold-up is recorded by instr. no. 1627.

The liquid hold-up recordings in the downward inclined pipe, pipe angle -1°, instr. no. 1619, reflect smooth stratified flow with very modest oscillations in liquid hold-up, the hold-up oscillations being approximately 0.015. The average liquid hold-up is 0.40 which is below the no-slip value 0.49. Thus the liquid phase velocity exceeds

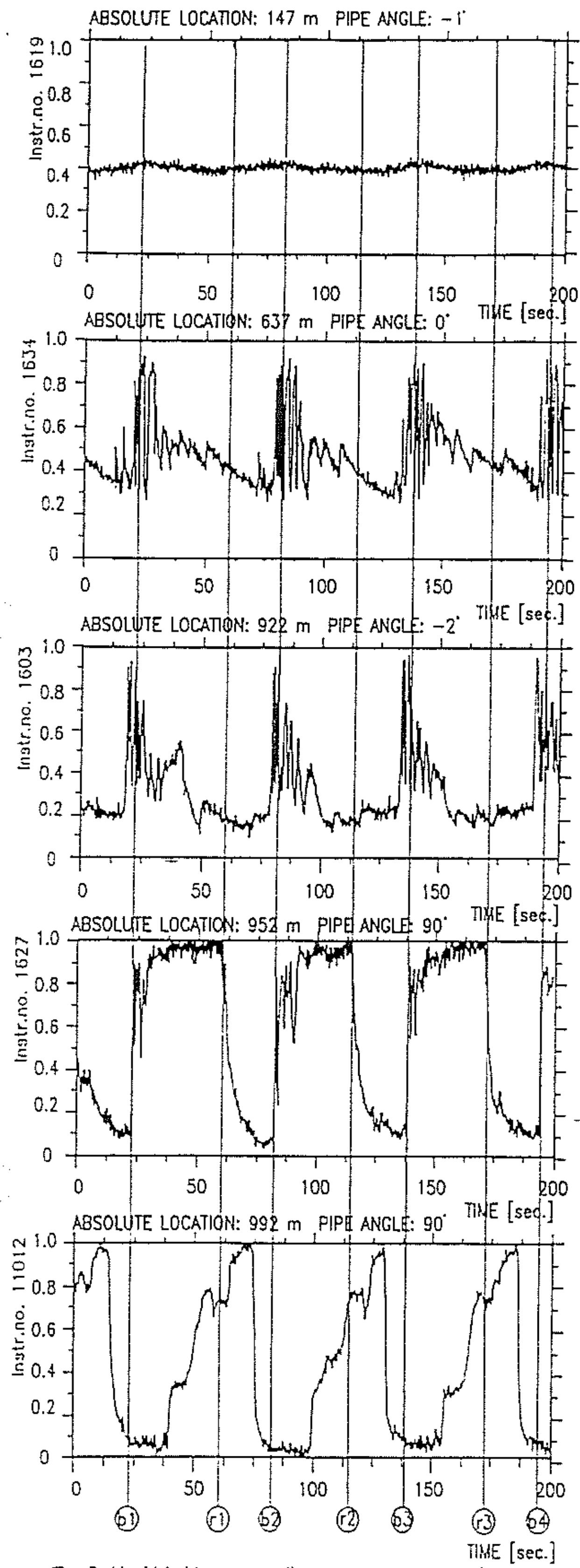

Fig. 3. Liquid hold-up recordings from gamma densitometers.

that of the gas, and the gas-liquid interfacial shear stress is likely to be negligible compared to the wall shear stress for the liquid. The pressure fluctuations typical for terrain slugging will therefore practically not influence the flow in the downward inclined pipe.

In the horizontal sections the terrain slugging induced pressure oscillations/gas accelerations are observed to cause highly intermittent liquid transport in the upstream line. Transient liquid waves/slug train units are generated in the horizontal line during the riser slug release period. These waves/units do not collapse during the riser slug build-up period, but propagate, although retarded, towards the low-point. This is readily seen from instr. no. 1634, where the slug front passes during the build-up period. The front passing instr.no. 1634 at 78 sec. is recognized in the downward inclined line by instr. no. 1603 at 189 sec.. Eventually the slug blocks the line-riser connection at 194 sec., see instr.no. 1627. At the moment of blockage the liquid is decelerated, and liquid fall-back in the riser modifies the slug front somewhat as it moves up the riser, see instr. no. 11012.

Detailed inspection of the liquid hold-up recordings at all positions available indicates that 4 transient liquid waves/slug units exist in the upstream line during the riser slug release period, whereas the number was 2 for the shorter topography reported in [4]. The basic terrain slugging mechanism does not differ for the two geometries, but the length of the horizontal line seems to be decisive for the number of transient units existing in the flowline. For the actual topography the flow situation at the moment of blockage is illustrated schematically in Fig. 4.

Riser choke operation in manual mode

The riser choke influence on the terrain slugging occurence is shown in terms of flow maps for different valve closures. At each pressure level a terrain slugging flow map for open valve was established to serve as a reference map.

The results for pressure level 20 bar are shown in Fig. 5 for the valve closures 0 %, 60 % and 80 %, arranged in increasing order of valve closures. Experiments were also run at valve closures 20 % and 40 %, but no reduction in terrain slugging compared to the open valve experiments was noticed.

At valve closure 60 % the terrain slugging heaviness is somewhat reduced at the highest superficial liquid velocity tested; ULS = 1 m/s, but no reduction was observed at ULS = 0.5 m/s. Increasing the valve closure further to 80 % terrain slugging vanished. At this closure the highest superficial liquid velocity obtainable was 0.5 m/s. Going from 60 % to 80 % in valve closure the average pressure drop over the choke valve increased from about 1 bar to 7 bar for the highest superficial liquid velocities.

Terrain slugging flow maps for the pressure level 45 bar are shown in Fig. 6. A small region with terrain slugging II, only, was observed for open valve, whereas for valve closure 40 % terrain slugging was suppressed. Here the pressure drop over the valve was typically 0.2 bar for the experiments presented.

Riser choke operation in automatic mode

Terrain slugging was successfully alleviated for all experiments where the choke was automatically operated. This applied to all the proportional- and integral action settings tested.

The valve performance in automatic mode will be illustrated by exp. no. 6866, see Fig. 7. This experiment was initially run with

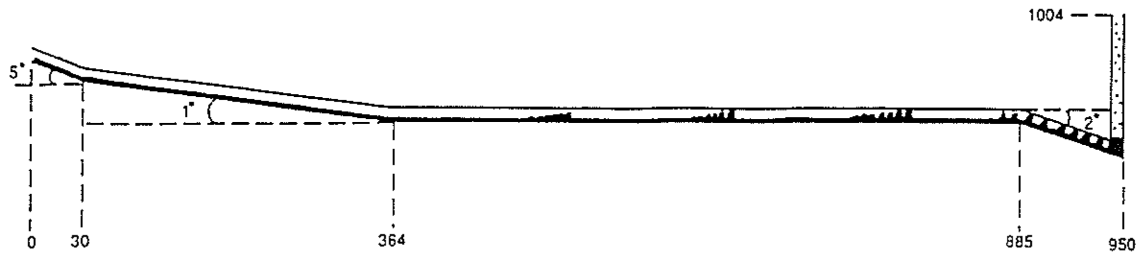

Fig.4 Flow situation at the moment of blockage.
Numbers indicate distance from the mix.point.

open valve, revealing typical terrain slugging. At 370 sec.'s operation of the valve was changed to automatic mode. The moment of operational change is indicated by A in Fig. 7. The valve closure in automatic mode reflects rather high frequent oscillations in valve closure, see instr. no. 501. From instr. no. 14835, it is readily observed that the pressure drops considerably over the valve, typically 2 bar, when running in automatic mode. The process signal used for valve operation in automatic mode, instr.no.14081; pressure drop over the riser recalculated to equivalent liquid height, illustrates the stabilization of the liquid imposed by automatic mode operation. Riser filled with stagnant liquid is equivalent to a liquid height of 50.5 m as measured by instr.no. 14081. The riser slug build-up and release sequences are therefore easily recognized from this instrument. Onset of automatic choking immediately transfers the flow to a more continuous and stable flow mode. The same flow transition, from typical terrain slugging IA to continuous flow, is recorded by the gamma densitometer in the riser bottom.

DISCUSSION

Previous experimental work

In [8] Schmidt et. al. reported experiments on alleviation of terrain slugging. The experimental facility consisted basically of a 30 m long pipeline downwardly inclined into a 15 m long vertical riser. The inner pipe diameter was 0.05 m, and at the top of the riser a choke was installed. Careful choking was reported to eliminate severe slugging efficiently.

The choke influence on terrain slugging was explained by analysis of the total pressure drop in the riser, only. Actually the flow dynamics upstream the riser was neglected. This is reasonable as long as the blockage is generated by liquid fall-back in the riser as is the case for the small-scale and low pressure loop described in [8].

In the SINTEF large-scale loop the blockage at the low-point is made up by slugs generated in the line upstream the line-riser low point. These slugs, denoted "fall- forward slugs", are observed as slug trains or compact slug units, depending on the upstream pipeline topography. It is therefore reason to believe that the stability considerations presented in [8] cannot be applied for the present large scale experiments.

Choke influence on the upstream flow dynamics.

The terrain slugging cycle is typically observed as relatively long riser slug build-up periods and short riser slug release periods. During the release periods the gas accelerates quickly and immediately generates a fall-forward slug. The relative velocity difference between the gas- and liquid phases plays an important role in the slug generation mechanism. By introducing a restriction in the riser top in terms of a choke, a significant part of the pressure drop occurs over the choke. Accordingly the available pressure drop used to accelerate the gas phase in the line during the release period will be lower. The gas phase acceleration will be reduced together with the ability to generate fall- forward slugs or liquid waves in the upstream line. The experiments readily show that a significant restriction in the riser is necessary to reduce terrain slugging. Thus for the valve in manual mode a valve closure at 60 % at 20 bar and 40 % at 45 bar had to be used before any noticeable reduction in the terrain slugging mode was observed. At these continuous flow conditions the resulting pressure drop over the valve was in the same order as or beyond the pressure drop in the riser below the valve.

The upper pressure limit for terrain slugging.

In [5] Fuchs derived a criterion on the form

$$L = \frac{\frac{P_U A}{V_{GU}} + \frac{P_D A}{V_{GD}}}{g sin\beta(\rho_L - \rho_G)} < N \qquad (1)$$

N is a non-dimensional parameter expressed in terms of flow variables. It is stressed that its numerical value can be determined experimentally, only. The nominal values of the flow variables shall be taken as maximum values occuring during the slug release.

The criterion is based on the requirement for riser slug release,

$$\frac{d}{dt}(P_U - P_D) > \frac{d}{dt}\Delta P_{gr} \qquad (2)$$

With the presence of a choke valve in the riser top a terrain slugging criterion can be derived analytically similarly as in [5] if the requirement in Eq. (2) is modified to

$$\frac{d}{dt}(P_U - (P_D + \Delta P_V)) > \frac{d}{dt}\Delta P_{gr} \qquad (3)$$

The pressure drop over the valve, ΔP_V, is defined positive for flow out of the riser.

The resulting criterion for the pressure limit can be written as

$$L < N(1 - R) \qquad (4)$$

The parameter R represents the modification term given by

$$R = \frac{\frac{d}{dt}\Delta P_V}{g sin\beta(\rho_L - \rho_G)} \frac{1 - H'}{H - H'} \frac{1}{u_{GR}^2} \qquad (5)$$

Similar to the parameter N the numerical value of R must be determined during the release phase where the fluids accelerate throughout the riser. Accordingly R will be positive. Assuming that N is given from the fluid properties, the pipeline topography and gas volumes, the introduction of a valve in the top of the riser reduces the maximum value of the parameter P and hence also the

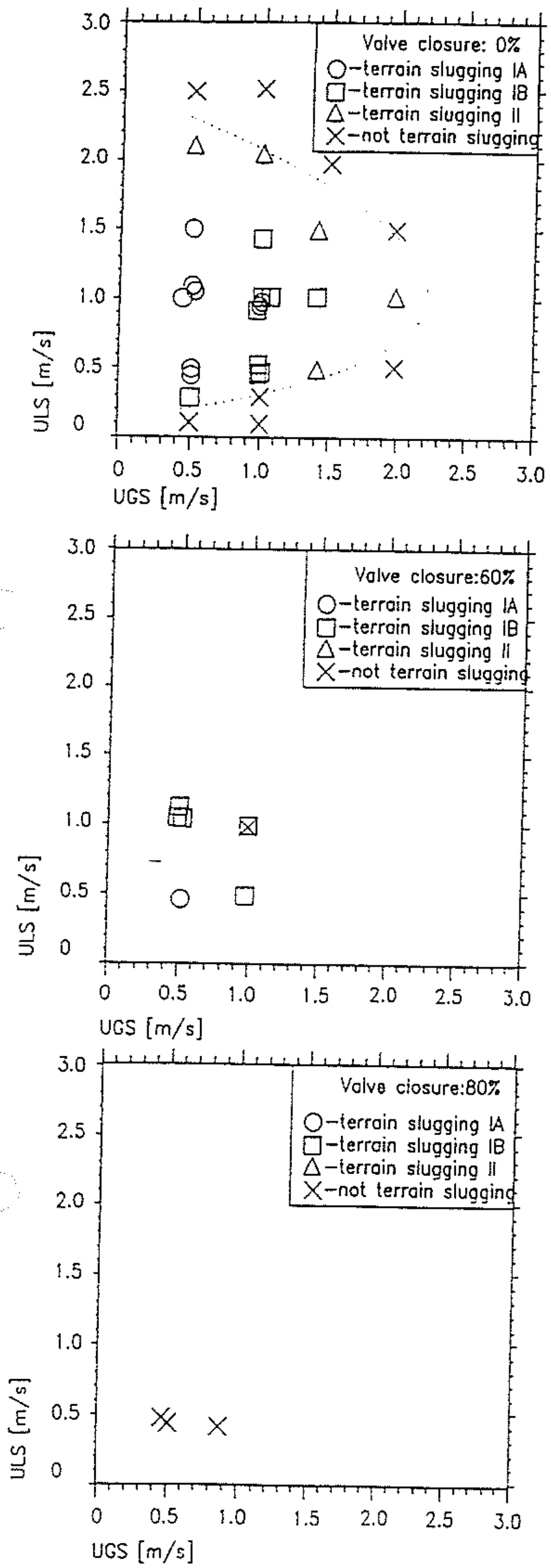

Fig. 5 Flow maps, terrain slugging
Pressure level: 20 bar

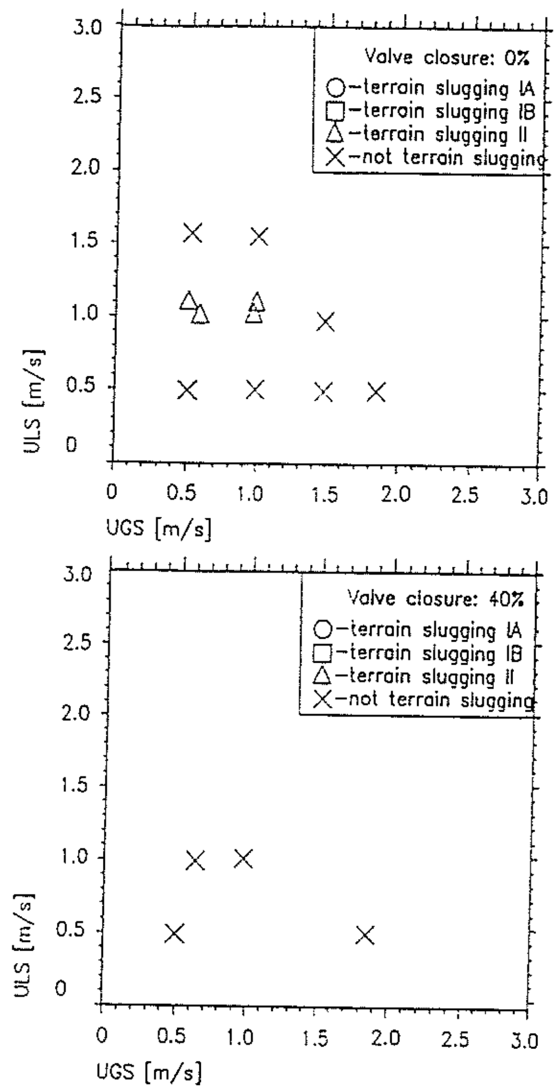

Fig. 6 Flow maps, terrain slugging
Pressure level: 45 bar

upper pressure limit for terrain slugging. Clearly, the pressure drop over the choke, ΔP_V, or rather the time derivative of this pressure drop serves to increase the stiffness of the system.

During riser slug release for terrain slugging I (pure liquid slugs, H=1) we can express the pressure drop over the choke as

$$\Delta P_V = B \rho_L u_{LV}^{s2} \tag{6}$$

Here B is a function of valve closure, and u_{LV}^s is the local superficial liquid velocity at the valve. The expression relevant to Eq. (6) will then be

$$\frac{d}{dt}\Delta P_V = 2B\rho_L u_{LV}^s \frac{d}{dt}u_{LV}^s + \rho_L u_{LV}^{s2}\frac{d}{dt}B \tag{7}$$

For riser choke operation in manual mode the last term on RHS is zero. In automatic mode the valve closure increases in the riser slug release phase, yielding a positive value for the last term on RHS. This gives a higher positive value for the modification term

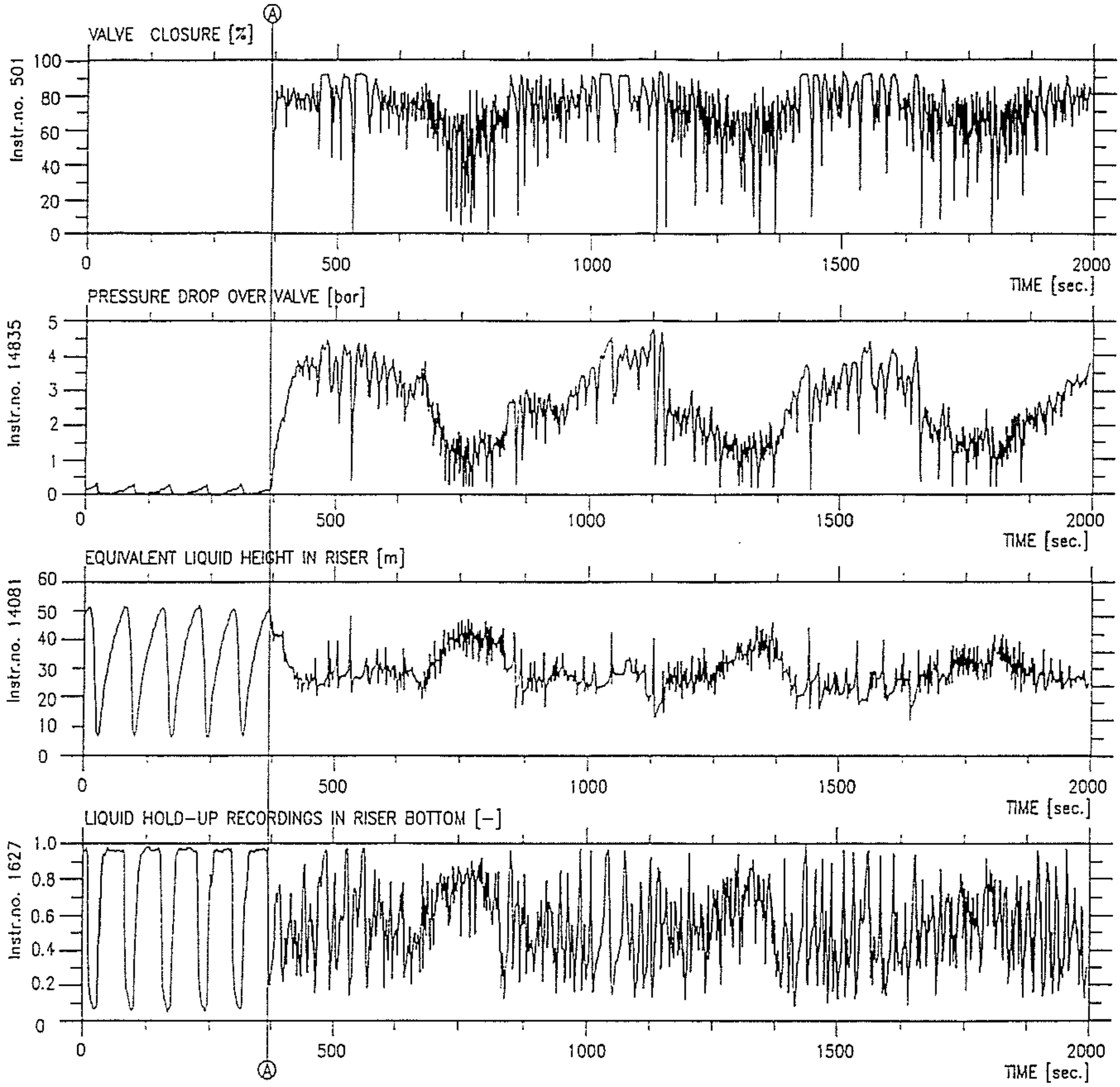

Fig. 7.. Selected time series for Exp.no. 6866, illustrating onset of automatic choking.

R compared to manual mode and explains the automatic modes superior performance on suppression of terrain slugging.

Special case: Terrain slugging I, riser choke in manual mode By combining Eqs. (5)-(7) and using the approximation

$$u_{LV}^s = (1 - H')u_{GR}^s \tag{8}$$

we obtain for the modification term R, assuming constant H':

$$R = \frac{2B\rho_L(1 - H')^2 \frac{d}{dt} u_{GR}^s}{g \sin\beta(\rho_L - \rho_G)} \tag{9}$$

Similarly to [5] the numerical value of the RHS of Eq. (4) should be obtained from a terrain slugging experiment with known valve closure. The upper pressure limit calculated from Eq. (4) will then apply for the actual valve closure.

Due to the instrumentation reliable estimates on the acceleration term in Eq. (9) could not be obtained. Consequently no numerical values for the RHS in Eq. (4) have been calculated.

Analogously to Fuchs [5], Taitel [9] derived a criterion for terrain slugging in which the effect of a riser choke was included. As discussed in [5] the criterion suffers from simplifications which make its applicability questionable for a high pressure system.

CONCLUSION

For riser choke operation in manual mode (constant valve closure) significant valve closure was necessary to reduce the terrain slugging. Going from 60 % to 80 % in valve closure terrain slugging was observed to disappear completely at 20 bar system pressure. By this change in valve closure the pressure drop over the valve increased from some 1 bar to 7 bar. At pressure level 45 bar terrain slugging II only was observed for the reference experiments with open valve. Experiments with valve closure 40 %, pressure drop over the valve typically 0.2 bar, revealed no terrain slugging.

Terrain slugging was successfully alleviated whenever the riser choke was put in automatic mode. The corresponding pressure drop over the valve was typically 1 to 2.5 bar at system pressure 20 bar.

An analytical expression for the upper pressure limit for terrain slugging was derived. The expression is a modification of a criterion published by Fuchs in [5] and applies with the presence of a choke valve in the riser top. The expression explains the different performance on suppression of terrain slugging when operating the choke valve in manual and automatic mode.

Although the experiments represent much longer upstream flowline compared to previous terrain slugging experiments published [4], the basic mechanism is similar with liquid waves/slug trains generated in the upstream line. In the first main section of the flowline, pipe angle -1°,stratified smooth flow was observed. Transient liquid waves/slug trains were generated in the first part of the horizontal line. A total of 4 transient units were observed in the horizontal line during the riser slug release. The experiments indicated that the number of transient units existing in the line is approximately proportional to the length of the horizontal line.

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Sigurd,
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Målet med prosjektet var i første rekke å verifisere at det var mulig å strupe vekk terreng slugging både med manuell og automatisk choking samt å se på graden av nødvendig økt baktrykk i de respektive modusene. Gjennomføringen bestod i design og innkjøp av ventil, innstallering denne på toppen av tårnet på Tiller, skriving av et spesialprogram for lesing av utvalgte måleverdier og styring av ventilen samt kjøringen av selve eksperimentalprogrammet. Alt dette ble gjort i løpet av noen få travle måneder og tiden som jeg hadde til rådighet til å foredle selve regulatoren var minimal. I utgangspunktet benyttet jeg en standard PID regulator hvor pådraget til ventilen ble styrt av væskehøyde i riser beregnet fra målt differensialtrykk. Settpunktet ble bestemt dynamisk ut i fra en "læreperiode" hvor svigningene for den aktuelle strømningssituasjonen ble analysert. Prinsippet fungerte greit, men det er nok en del å gå på i forhold til stabilisering av selve reguleringen.

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Hallo Pål,

Takk for fint innlegg på møtet.

Kan du sende meg en kopi av den publikasjonen du nevnte der du har brukt regulering til stabilsering.

-Hilsen Sigurd

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