On gas transport in downward slopes of sewerage mains

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ABSTRACT
Wastewater pressure mains are subject to gas pockets in declining sections. These gas pockets cause an additional head loss and an associated capacity reduction, which cannot be predicted with sufficient accuracy. The number of parameters, affecting downward gas transport in sewerage mains, is overwhelming. Therefore, the development of a numerical model is inevitable, starting from the knowledge base in the available literature. This paper includes a critical review of the literature on gas transport by flowing water in declining pipes. This review will show that the wide spread in the correlations for the clearing velocity, as reported by various investigators, is mainly caused by a subtle misinterpretation of the original data. Furthermore, new information from a few old references will be presented and integrated into a synthesis of the available literature. Finally, a new dimensionless velocity parameter is introduced, which is shown to be a more appropriate scaling parameter than the existing velocity scaling.

KEYWORDS
waste water pipelines; sewerage; gas transport; channel flow; two-phase flow; surface tension.

Nomenclature

A	pipe cross section (m^2)	θ	downward pipe angle (rad)
D	internal pipe diameter (m)	ρ	density (kg/m^3)
Eo	Eötvös number (-)	σ	surface tension (N/m)
F	Force (N)		
Fr	Froude number (-)	~	normalized quantity
g	gravitational acceleration (m/s^2)		
n	dimensionless volume as the number of filled pipe diameters (-)		
Q	discharge (m^3/s)		
S_E	Energy slope (-)		
v	velocity (m/s)		
y	water depth (m)		

Subscripts

B	buoyancy	g	gas / air
c	clearing (velocity) i.e. for gas pocket removal	i	initiation of downward gas transport
e	effective	w	water
cf	clearing velocity including friction		

INTRODUCTION

Gas pockets in pipelines originate from a number of sources. Air may entrain continuously as bubbles in case the sewer outflow is a free-falling jet into the pump pit. Air may also entrain discontinuously after pump stop if the pump inertia is sufficient to drain the pit down to the bell-mouth level. This kind of discontinuous air entrainment occurs mainly in wastewater systems with a marginal static head. If the pipeline is subject to negative pressures during normal operation or during transients, then air may leak into pipeline or may enter intentionally via air valves. Another transient phenomenon, however more unlikely, is a pump trip in a dendritic pressurised wastewater system. The induced transient may suck some wastewater from an idle pumping station, causing air entrainment in the idle pumping station. Another cause of gas pocket development consists of biochemical processes in the pipeline, mainly CO_2, N_2 and CH_4.

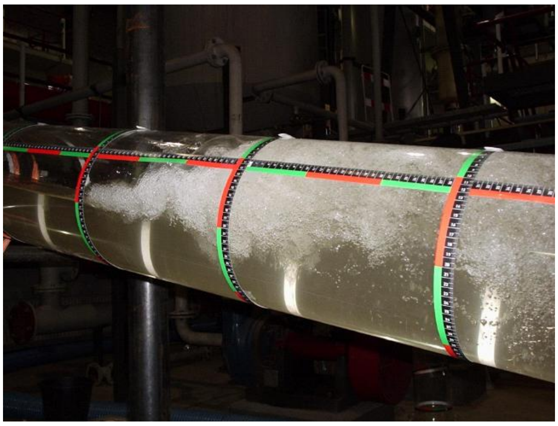

Figure 1. Gas entrainment in the hydraulic jump

Physical processes and terminology

Pressurised wastewater mains are characterized by an intermittent operation. Gas will accumulate in elevated sections of the pipeline during shut down periods and dry weather flow conditions. If an air pocket is present in the top of a declining section and a liquid flow is flowing through the conduit, then a hydraulic jump will develop at the tail of the gas volume ejecting gas bubbles from the large pocket (Figure 1). The pumping action of the hydraulic jump transports part of the ejected gas down to the bottom of the declining section, as schematized in Figure 2.

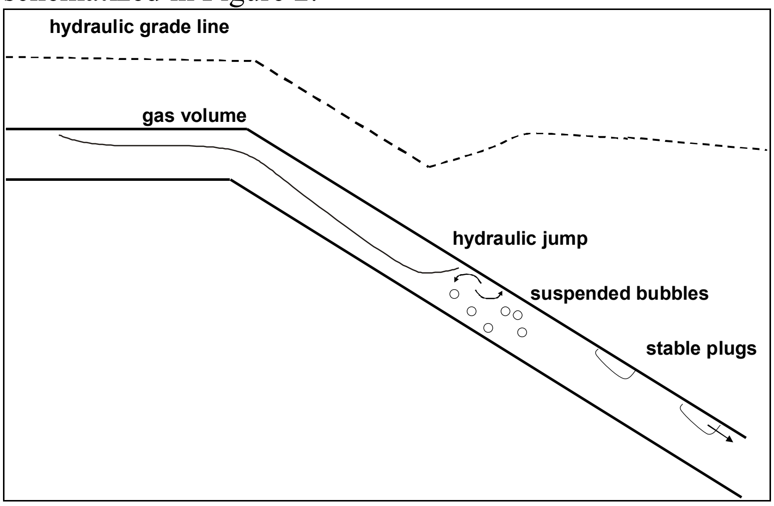

Figure 2. Schematic overview of downward gas transport by flowing water.

Set-up of paper

This paper includes a critical review of the literature on gas transport by flowing water in declining pipes. This review will show that the wide spread in the correlations for the clearing velocity, as reported by (Wisner, Mohsen et al. 1975) and (Escarameia 2006), is mainly caused by a subtle misinterpretation of the original data. Furthermore, new information from a few old references will be presented and integrated into a synthesis of the available literature.

LITERATURE ON GAS TRANSPORT IN DOWNWARD PIPES

This section provides an overview of available literature on gas transport in downward sloping pipes. The overview is presented in chronological order and the applicability of the results for pressurised wastewater pipelines is briefly discussed.

Kalinske, Bliss, Robertson

Among the oldest available research works in the field of liquid driven gas transport in downward sloping pipes are the publications by Kalinske and Bliss (1943) and Kalinkse and Robertson (1943), who worked at Iowa State University.

Kalinske and Bliss described three distinct flow regimes (Kalinske 1943):

- A blow-back flow regime at relatively small discharges, although still above the critical discharge in (1). In this flow regime, the bubbles coalesce and periodically blow back upward, which limits the net gas transport. The net gas transport is controlled by the flow characteristics below the hydraulic jump, which are described by a Froude-scaled dimensionless velocity; see eq. (2).
- A full gas transport flow regime at higher discharges, at which all entrained gas bubbles are transported to the bottom of the downward slope. The gas transport becomes almost independent of the dimensionless velocity in this flow regime. Kalinske et al. (1943) conclude that the Froude number upstream of the hydraulic jump determines the gas transport. This Froude number is defined as: $F_1 = v_1 / \sqrt{g y_e}$, where v_1 is the water velocity upstream of the hydraulic jump and y_e is the effective depth, i.e. the water area divided by the surface width.
- At the transition from the blow-back flow regime to the full gas transport flow regime, a series of 2 to 4 stationary gas pockets and hydraulic jumps were observed in the downward slope. The length of the downward slope of their test rig was 10.5 m long. Blow-back did not occur any more in this transitional flow regime.

They determined the dimensionless flow rate Q_i^2 / gD^5 at which gas bubbles are ripped off from the gas volume by the hydraulic jump at the end of the gas volume and start to move downward to the bottom of the slope. Kalinske and Bliss (1943) propose the following relation for this incipient downward gas transport, based on experiments in a 100 mm and 150 mm pipe:

$$\frac{Q_i^2}{gD^5} = \frac{\sin\theta}{0.71} \tag{1}$$

where Kalinske et al. defined the pipe slope as the sine of the angle with the horizontal plane.

This equation cannot be considered an equation for the clearing velocity, as explained by Kalinske and Bliss: "..to maintain proper air removal, the actual value of the water discharge should be appreciably larger than Q_i" (Kalinske 1943). In fact, this curve may depend on the length of the downward slope, which was 10.5 m (i.e. 105*D for the 100 mm pipe and 70*D for the 150 mm pipe). Equation (1) is equivalent with:

$$\frac{v_i}{\sqrt{gD}} = \frac{Q_i}{\left(0.25\pi D^2\right)\sqrt{gD}} = \frac{4}{\pi}\frac{Q_i}{D^2\sqrt{gD}} = \frac{4}{\pi}\sqrt{\frac{\sin\theta}{0.71}} \tag{2}$$

Kalinske et al. (1943) also determined the gas transport by measuring the gas pocket length reduction during a certain time interval. The time was started after the hydraulic jump had moved up "an appreciable distance from the end of the pipe" (Bliss 1942).

The transition to the full gas transport flow regime is highly relevant from a practical point of view, because this transition represents the clearing velocity that breaks down gas pockets (almost) completely and that minimises the head loss by the gas pockets. Bliss has reported this transition in his research report only (Bliss 1942); these results have not yet been published elsewhere to the authors' knowledge. The transition to full gas transport requires a significantly larger dimensionless velocity than the more widely reported 'start of downward gas transport' according to equation (1).

Bliss reported that the full gas flow occurred at lower water flow rates, if the gas pocket was not held in position by the roughness of a joint or a projecting point gage. The results in Figure 3 apply to the required velocities with a projecting point gage at the beginning of the downward slope, because Bliss anticipated that any prototype pipe would contain sufficient roughness elements to hold a gas pocket in position in the top of the downward slope. Finally Bliss noted that the 4″ pipe required smaller clearing velocities than the 6″ pipe.

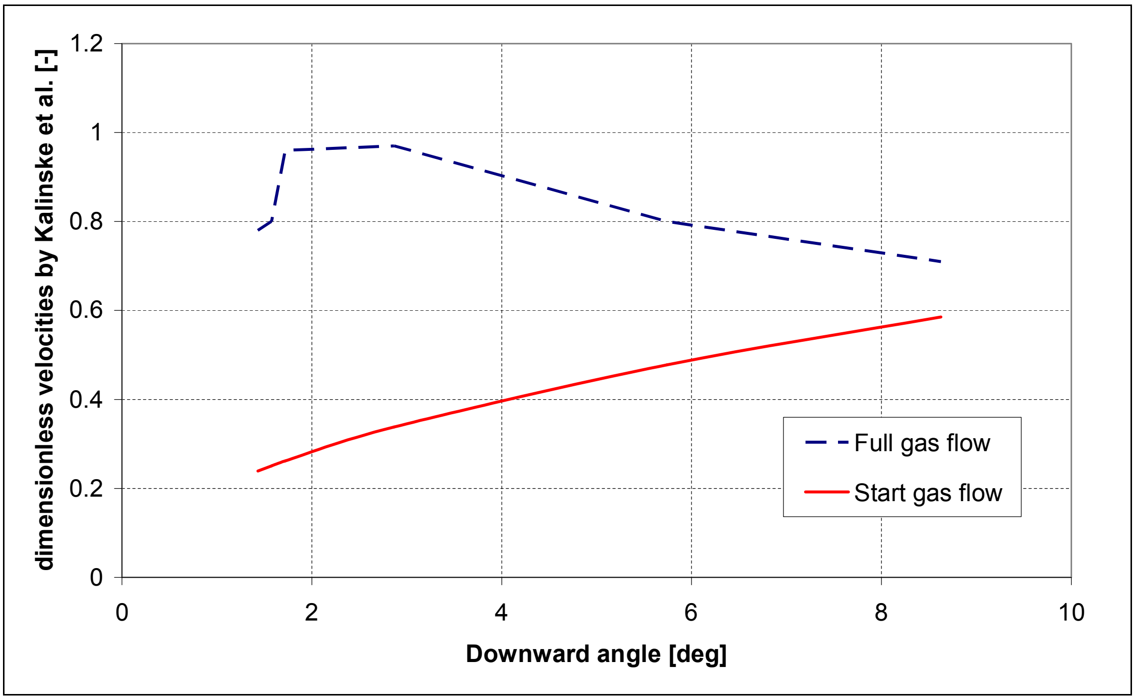

Figure 3. Required dimensionless velocities for 'start of gas transport' (Kalinske 1943) and clearing velocity (Bliss 1942).

This test setup was in reasonable agreement with the practical situation in which the gas pocket starts in the top of the downward slope. The upstream pipework consisted of an inclining pipe at 45 degrees followed by an appropriate bend towards the downward slope; the test rig did not include a horizontal section upstream of the downward slope, where the water could accelerate slowly into the downward slope. The effect of the test set-up will be discussed in more detail in the following section.

Kent

Kent (Kent 1952) has performed detailed experiments in a 33 mm pipe and a 102 mm (4″) pipe on *stationary* gas pockets in declining pipes with downward angles varying between 15° and 60°. The length of the downward slope was 5.5 m (18 ft) for the 102 mm pipe. Since the gas pockets are stationary, the flow regime is similar with Kalinske's transitional flow regime between blow-back and full gas transport. An important difference, however, is the fact that Kent injected air in the slope rather than upstream of the slope. The effect of this set-up will be discussed at the end of this section.

Kent focused on the determination of the drag coefficient, C_D, as a function of the plug length, L_b and the maximum projected plug area, A_b. Kent's gas pockets were so large that a hydraulic jump formed at the tail of the gas pocket. In order to maintain a constant gas volume, Kent continuously injected air in the stationary pocket in the downward slope. He measured the total gas volume in the downward slope by rapidly closing two valves at the beginning and end of the slope simultaneously, after which he could measure the total gas volume in the slope. This enabled Kent to determine the total buoyant force, which must balance the drag force, because the gas pocket remained stationary. Kent established the following relation from his experiments:

$$\frac{v_c}{\sqrt{gD}} = 1.23 \cdot \sqrt{\sin\theta} \qquad (3)$$

A clearly better curve fit on Kent's data, which allows for a non-zero offset is given in equation (4); see (Mosvell 1976), (Lauchlan 2005) and (Wisner, Mohsen et al. 1975), who first published the systematic deviation between Kent's data and equation (3); see Figure 4.

$$\frac{v_c}{\sqrt{gD}} = 0.55 + 0.5 \cdot \sqrt{\sin\theta} \qquad (4)$$

Equation (4) is valid for gas pockets with a dimensionless length exceeding 1.5D, which coincides with a gas pocket volume exceeding 0.55D in full pipe diameters (n > 0.55). Unfortunately, Equation (3) has been used frequently in the design of Dutch sewerage mains; also for pipe angles smaller than 15°. The significant difference between Kent's equation (3) and Mosvell's curve fit (eq. (4)) is caused by Kent's dimensional analysis that did not include an offset parameter. The difference is particularly pronounced, if Kent's equation is extrapolated to pipe angles smaller than 15°; see Figure 4.

Kent also performed measurements on relatively small gas plugs from which no bubbles were ejected by the hydraulic jump. These measurements, which have not been published before except for in Kent's thesis (Kent 1952), reveal that both the maximum stable plug length and the clearing velocity reduce at steeper slopes; see Figure 4. The length of a gas plug or gas pocket is defined as the distance from the upstream end of the gas plug to the hydraulic jump.

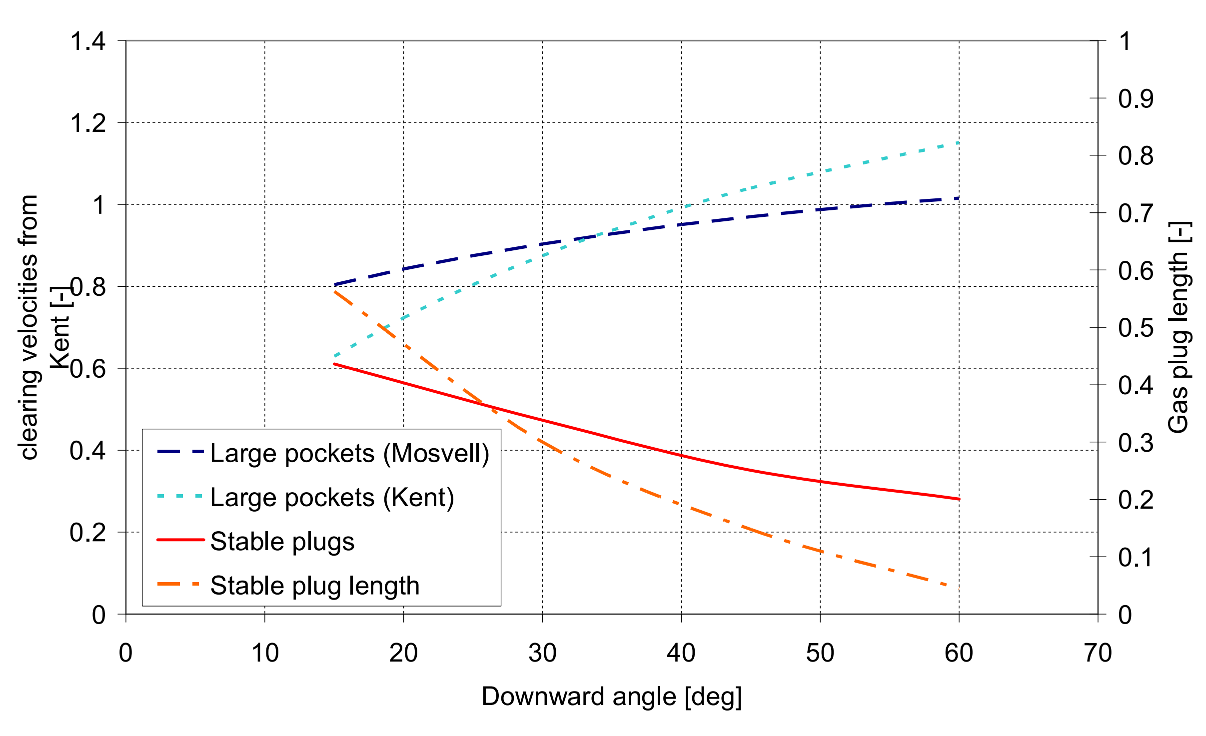

Figure 4. Required dimensionless clearing velocities for large pockets with air entraining hydraulic jumps and for stable pockets without air entrainment. The maximum stable pocket length is indicated as well.

Figure 4 shows that the clearing velocity for stable individual plugs is smaller than the clearing velocity for large pockets with hydraulic jumps and air entrainment. Figure 4 suggests that the clearing velocity for stable plugs and large pockets might become equal at a downward slope of approximately 10°, if Mosvell's line and the stable plug line are extrapolated to 10°.

It must be noted that Kent's setup is not a perfect representation of gas transport in wastewater or water pipelines, because Kent injected gas somewhere in the slope, whereas the gas pocket begins upstream of the slope in reality.

Gandenberger

Gandenberger (1957) has performed measurements on individual stationary pockets and pockets moving downward in various pipes with internal diameter between 10 mm and 100 mm at downward angles between 5° and 90°. Most of Gandenberger's results are based on measurements in a 45 mm glass pipe. Gandenberger measured a maximum clearing velocity at 40°. He investigated gas pocket volumes up to n = 1.5 and found that the gas pocket velocity becomes constant if n exceeds 0.5 at all pipe angles, which confirms Kent's results. The applicability of Gandenberger's measurements for downward gas transport in water pipelines has the same limitations as Kent's results. A further limitation of Gandenberger's measurements is the fact that Gandenberger did not inject air to maintain a constant pocket volume. Hence, the bubbly flow at the tail of the hydraulic jump could not be maintained during the experiments. Gandenberger's clearing velocities are slightly smaller than Kent's velocities, which may be attributed to the smaller pipe diameter or to the lack of air injection in the pocket.

Wisner

Wisner (Wisner, Mohsen et al. 1975) recognized the large spread in proposed critical liquid velocities for downward gas transport in the literature up to 1975 including Gandenberger (Gandenberger 1957), Kalinske et al. (Kalinske 1943) and (Kent 1952). Wisner assumed that scale effects could have caused the large spread and therefore performed experiments in a large 245 mm pipe at a fixed downward angle of 18°. Wisner focused on stable plugs rather than the clearing velocity in his experiments. Finally, Wisner et al. developed an envelope curve from the available data from Veronese (1937), Gandenberger, Kent and Kalinkse and found:

$$\frac{v_c}{\sqrt{gD}} = 0.825 + 0.25 \cdot \sqrt{\sin\theta} \tag{5}$$

It must be noted that Wisner et al. (Wisner, Mohsen et al. 1975) have misquoted Kalinske and Bliss in equation (1) by using a coefficient 0.707 instead of the correct coefficient 1/0.71, which (incorrectly) resulted in 30% smaller dimensionless clearing velocities.

Escarameia

Escarameia et al. (2006) have performed experiments in a 150 mm pipe with gas pockets up to 5 litres (n = 1.9) and pipe slopes up to 22.5°. Escarameia proposed the following formula for the dimensionless clearing velocity, which extends Kent's data, eq. (4), to angles smaller than 15°:

$$\frac{v_c}{\sqrt{gD}} = 0.61 + 0.56 \cdot \sqrt{\sin\theta} \tag{6}$$

The same limitations as mentioned in Kent's section apply to these results.

Lubbers

Lubbers (Lubbers 2007) has performed experiments in three different pipe sizes (110 mm, 220 mm and 500 mm) at various downward slopes from 5° to 30° and 90°. Lubbers injected air upstream of the downward slope in a horizontal section and determined the extra head loss due to the gas volume at different combinations of air and liquid flow rate. The clearing velocity (or critical velocity) is reached when the extra head loss due to the presence of the gas flow attains a minimum. This minimum value is close to zero. Lubbers found that the largest clearing velocity is required at downward slopes of approximately 10°. Figure 7 shows a gradual drop in clearing velocity at slopes above 10°. The dimensionless clearing velocity drops to about 0.3 for a vertical pipe with 220 mm internal diameter. An intercomparison of the clearing velocities at a downward slope of 10° and the three pipe sizes, revealed that the clearing velocity at 110 mm was smaller than at 220 mm or 500 mm (**Error! Reference source not found.**). Tukker (2007) has extended these tests to pipe diameters of 80 mm and 150 mm at the same downward slope of 10°.

SYNTHESIS OF LITERATURE ON CLEARING VELOCITIES

The literature contains intercomparable data on three different processes in downward sloping pipes, namely:

1. the transport of a stable plug (Veronese 1937), (Kent 1952) and (Wisner, Mohsen et al. 1975).
2. the transport of an individual gas pocket from which air bubbles are ripped off (Kent 1952), (Gandenberger 1957) and (Escarameia 2006) ; and

3. the breakdown and transport of a large gas volume in the top of a downward sloping pipe (Bliss 1942), (Kalinske 1943) and (Lubbers 2007);

These different processes has led to various subtle misinterpretations and the wide spread in clearing velocities. The literature on the second and third process will be compared hereafter. The third, most complex, process is most closely related to the practical situation of pressurized wastewater mains.

Individual pockets

If the results from the single-gas-pocket-investigators on their largest gas pockets are compiled into one graph, then the trends are similar; see Figure 5. The only differences between the results are probably caused by diameter differences, which induce a Reynolds number influence and possibly a surface tension influence. The Reynolds number influence is included in the friction factor. A logical extension of the dimensionless clearing velocity is the clearing velocity multiplied with $\sqrt{f}$ yielding:

$$\tilde{v}_{cf} \equiv \sqrt{\frac{f}{gD}} v_c \tag{7}$$

In fact, this definition implies that the hydraulic grade lines are identical if the dimensionless clearing velocities including friction, $\tilde{v}_{cf}$, are identical, as illustrated for pipe diameters D_1 and D_2 in equation (9):

$$\begin{aligned} S_E(D_1) = S_E(D_2) \quad &\Leftrightarrow \quad \frac{f}{D_1}\frac{v_{D_1}^2}{2g} = \frac{f}{D_2}\frac{v_{D_2}^2}{2g} \quad \Leftrightarrow \\ \Leftrightarrow \quad \tilde{v}_{cf}(D_1) = \sqrt{\frac{f}{gD_1}} v_{D_1} &= \sqrt{\frac{f}{gD_2}} v_{D_2} = \tilde{v}_{cf}(D_2) \end{aligned} \tag{8}$$

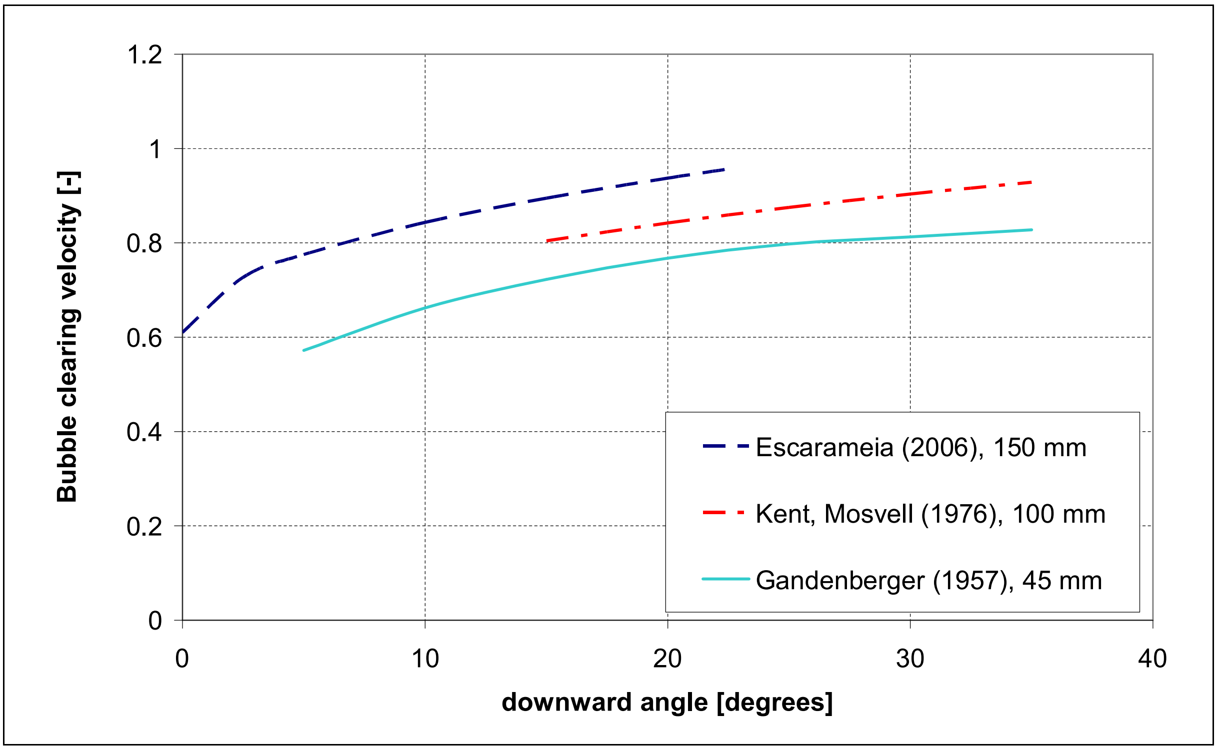

Figure 5. Clearing velocities of large individual bubbles.

Assuming a relative wall roughness of 10^{-4} for all transparent pipes, the bubble clearing velocity including friction as a function of the downward angle, shown in Figure 6, becomes independent of the pipe diameter. The remaining difference between Kent-Mosvell's curve and the other two curves could be attributed to the slightly different approach by Kent.

Apparently, the surface tension does not affect the clearing velocity of these large individual pockets with a volume n > 0.5. It is concluded that the clearing velocity of large individual pockets is driven by the hydraulic grade line, which may be represented by the parameter $\tilde{v}_{cf}$.

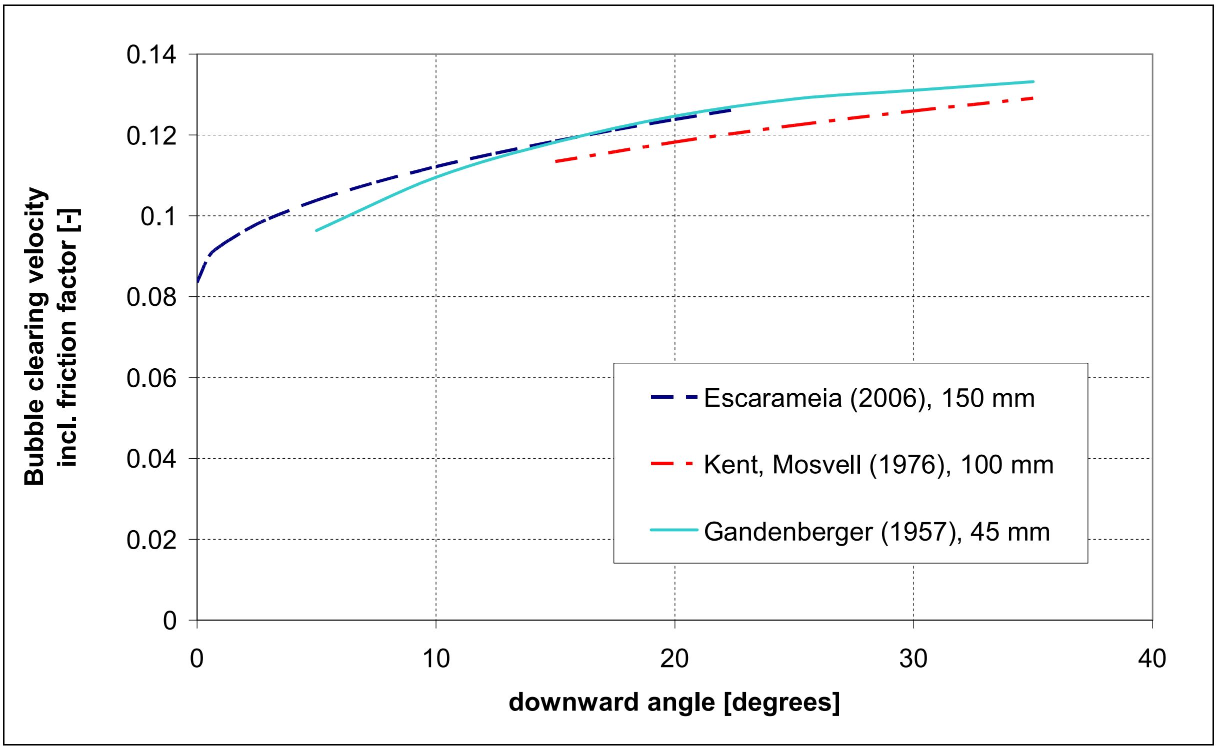

Figure 6. Clearing velocities of large individual bubbles including friction factor.

Gas volumes initiated upstream of downward slopes

The results on clearing velocities of gas volumes, Bliss (1942) and Lubbers (2007), are intercomparable as well as illustrated in Figure 7. A remarkable difference between Figure 5 and Figure 7 is the decreasing trend, measured by Lubbers (2007) at pipe angles steeper than 10°. This apparent inconsistency is explained as follows. If the liquid velocity exceeds Lubbers' clearing velocity, then the gas is transported as stable plugs downstream of the aeration zone of the hydraulic jump. These stable plugs are significantly smaller than the large injected pockets. Since the stable plug size and plug clearing velocity both reduce with the pipe angle, Lubbers' clearing velocity reduces as well. This process is not included in the experiments with individual gas pockets, injected in the slope.

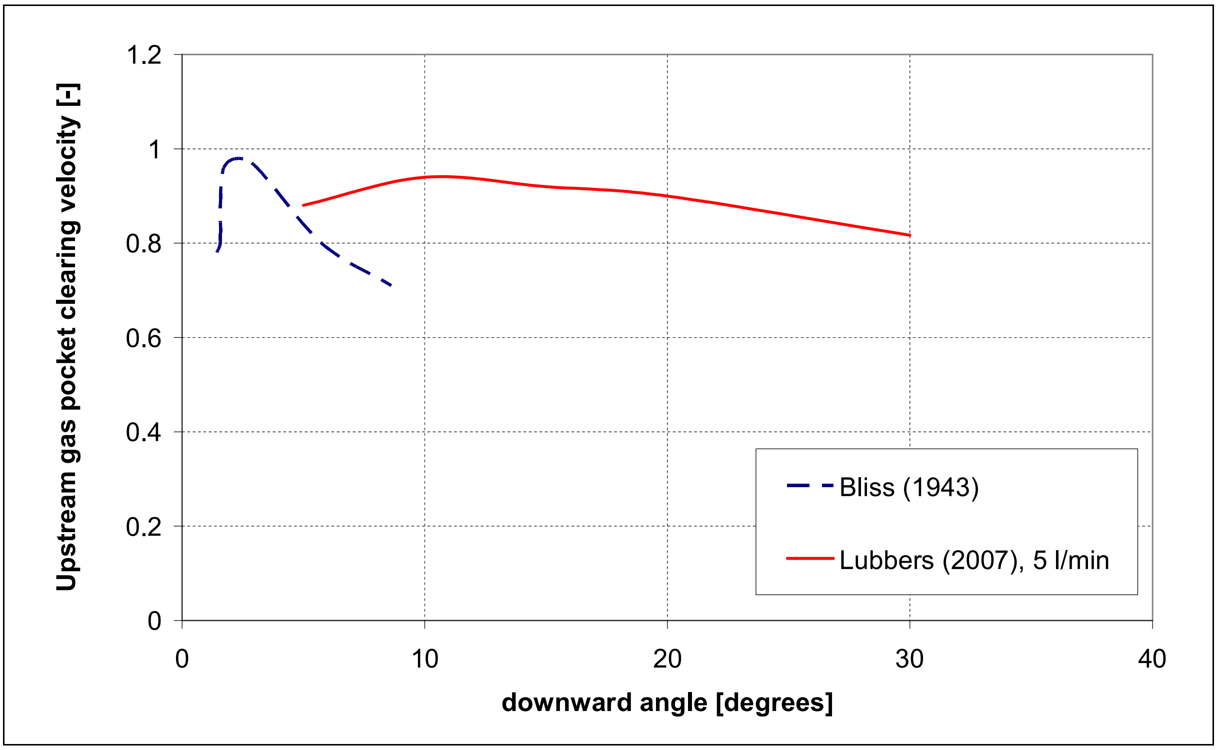

Figure 7. Clearing velocities of gas volumes, initiated upstream of a downward slope

CONCLUSIONS

A critical review of the existing literature on the clearing velocity of gas pockets in downward sloping pipes has revealed new information on the gas pocket clearing velocity (Bliss 1942) and the stable plug clearing velocity (Kent 1952).

The paper has shown that the wide spread in available correlations for the clearing velocity is caused by:

- different tested diameters in combination with a less suitable scaling parameter,
- wrongful comparison of different processes, i.e.
    - individual gas pocket transport has been compared with gas volume breakdown and
    - initiation of gas transport has been compared with complete gas clearance.

The existing literature has been analyzed and integrated to explain the opposing trends of the clearing velocity at increasing pipe angle. If the gas pockets are initiated upstream of the downward slope, then the clearing velocity reduces at pipe angles above 10°. The reason for the reduction in clearing velocity above 10°, is that the gas transport takes place by means of stable plug flow and these stable plugs become smaller at steeper downward slopes, which coincides with reduced clearing velocities.

An intercomparison of the single gas pocket clearing velocities shows a systematic increase of the clearing velocity at a pipe diameter increase from 45 mm to 150 mm. We propose to redefine the dimensionless clearing velocity as $\tilde{v}_{cf} \equiv \sqrt{\frac{f}{gD}} v_c$, which is proven to be almost independent of the pipe diameter. The clearing velocity, including friction, equals 0.11 for individual gas pockets at a downward slope of 10°.

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