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SWIRL PIPES AND THE TWO-LAYER MODEL

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This paper re-examines the case for swirl-induction of industrial slurries by reference to the geometry of a helically-lobed swirl pipe. There are two mechanisms at work in a swirl pipe. Most importantly, a *dredging* movement, rotates a dense layer away from the bottom of a pipe, while the second imparts angular momentum to fluid medium in the core flow. The Two-Layer Model ***2LM*** can be applied to the first since the optimum dredging action should occur when the lower layer of slurry in the approaching duct exactly fills one lobe of a swirl pipe. The second layer enters the upper part of the swirl pipe and most of it forms the central core of the flow. The circulatory motion of the core flow helps to keep dredged particles in suspension.

NOMENCLATURE

A, A_s	Area of upstream pipe, cross-sectional area of swirl pipe	m^2
ΔP	Pressure drop between stations on a pipe run	*Pa*
R, R_c, R_L	Radius of upstream cylindrical pipe, circular core, swirl-pipe lobe	*m*
R/D	Ratio of the radius of a toroidal bend to the pipe diameter	-
r	Variable radius from pipe centreline	*m*
S	Swirl intensity	-
u	Variable axial flow velocity	*m/s*
V	Mean flow velocity	*m/s*
w	Circumferential velocity	*m/s*
α_C, α_D	Ratio to flow area of core area, single lobe area	-
ζ	Swirl effectiveness	-
ρ	Fluid density	kg/m^3

1. INTRODUCTION

The aim of this paper is to compare the geometry of helically-formed swirl pipe with that of approaching liquid-solid mixture idealized as two segmental layers in a cylindrical pipe. The first part of this task will be to describe briefly the development of swirl pipes and the geometry of 3-lobe and 4-lobe cross-sections. The second part will be to explain and utilize the Two-Layer Model to obtain the segmental geometry of settling solids in a horizontal cylindrical pipe. Lastly the combination of the two geometries, cylindrical pipe followed by swirl pipe, will be examined with reference to a sand-water example.

Several designs of swirl-inducing pipe have been published, the earliest patented in 1899 by HM and HA Gordon (1899) (1). Continuously-ribbed swirl pipe was patented by Arthur Robinson (Robinson, 1923 (2)). Recent work has been concentrated on a four-lobed pipe broadly similar to an historic three-lobed boiler tube design by E.F.Spanner (Spanner, E.F., 1940, 1945 (3,4)), see Figure 1.

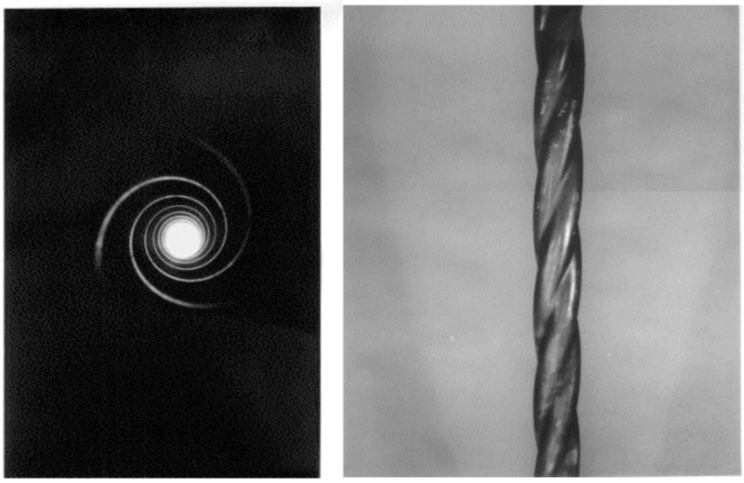


Fig. 1 Boiler tube by E.F.Spanner.
(The left-hand image taken axially down the bore shows three lobes.)

2. SWIRL-INDUCING PIPES FOR PARTICLE-BEARING LIQUIDS

Two mechanisms are at work in a swirl pipe when applied to liquids laden with solid particles. The first is a dredging action which lifts settling particles from the bottom and a second which imparts angular momentum to the particle suspension in the core. The two-layer model ***2LM*** can be applied to the upstream cylindrical pipe since the optimum dredging action should occur when its lower layer exactly fills one lobe of a swirl pipe. The upper layer suspension enters the core and the remaining lobes. The swirling core flow receives the dredged solids and the circulatory action acts to keep them in suspension.

The design of lobed pipe for industrial slurries was first tackled using Fluent Computational Fluid Dynamics software (CFD) to optimize swirl-pipe geometry for maximum circumferential velocity w at minimum pressure loss for water in a 50mm pipe (see Raylor,B., and Jones,T.F., (1998) (12), and Ganeshalingham, J. *et al* (2003) (10)). Continued refinement effort resulted in the design illustrated in Figure 2.

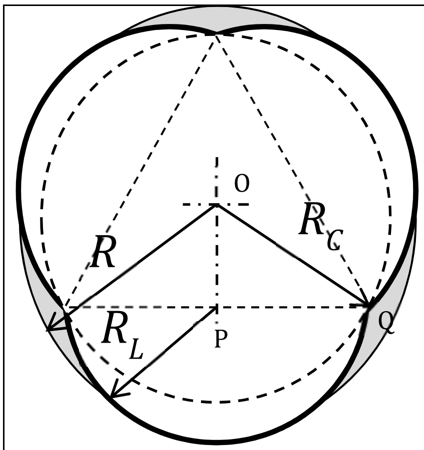
The design featured

- four lobes based on a square generator
- pitch to diameter ratio of 8:1
- entry and exit transitions of length *pitch/4* and smooth development of lobe geometry from a circular cross-section (see Jones and Ariyaratne 2007 (8)).

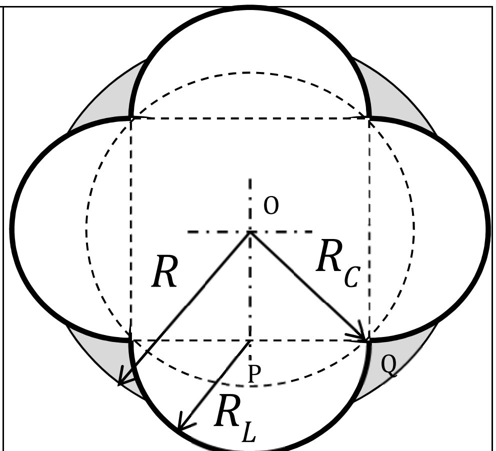
Fig. 2 Optimized swirl pipe geometry

2.1 GEOMETRY OF SWIRL PIPE LOBES

The geometry of lobed pipe is described in Figure 3.



Cross-sectional area $A_S = \left[\frac{3\pi}{2}+\sqrt{3}\right]R_L^2$
Area of upstream cylindrical pipe $A = \pi R^2$
Applying continuity equation $A_S = A$, *i.e.*
$R_L = R \times \sqrt{\frac{\pi}{\frac{3\pi}{2}+\sqrt{3}}} = 0.6982R$ [1A]
Pythagoras Theorem in triangle OPQ gives
$R_C = \frac{2}{\sqrt{3}}R_L = 0.8062R$ [2A]
Core area ratio, $\alpha_c = \frac{\pi R_C^2}{\pi R^2} = 0.64999$ [3A]
Dredging ratio,
$\alpha_D = \frac{(\pi/2)R_L^2}{\pi R^2} \times 100 = 24.37\%$ [4A]



Cross-sectional area $A_s = [2\pi + 4]R_L^2$

Area of upstream cylindrical pipe $A = \pi R^2$
Applying continuity equation $A_S = A$, *i.e*
$R_L = R \times \sqrt{\frac{\pi}{2\pi+4}} = 0.5527R$ [1B]
Pythagoras Theorem in triangle OPQ gives
$R_C = \sqrt{2}\,R_L = 0.7817R$ [2B]
Core area ratio, $\alpha_C = \frac{\pi R_C^2}{\pi R^2} = 0.61102$ [3B]
Dredging ratio,
$\alpha_D = \frac{(\pi/2)R_L^2}{\pi R^2} \times 100 = 15.28\%$ [4B]

Fig. 3 Cross-sectional geometry for 3-lobe and 4-lobe swirl pipe designs compared

The initial position of a lobe at the bottom of the pipe allows it to receive the settling contents of an upstream cylindrical pipe. The important dimensions are the radius of the feeding pipe *R*, the radius of each lobe, $R_{L,}$ and the radius of the central region or core, R_C. The lobes generate tangential velocity while in the central region (core), axial velocity predominates. Swirl pipe geometry calculations for multiple lobes are illustrated in Figure 3 to allow comparison between the designs. The core area ratio (α_c) is the ratio of the maximal central core to the whole. The area of one semi-circular lobe as a ratio of the whole is important in assessing the role of dredging in the suspending action and is termed the *dredging ratio*, α_D.

The 3-lobe design has a large lobe area and will therefore have a greater dredging ratio (24%) than the 4-lobe design (15%) for high particle concentrations. The maximal core area is also marginally larger (65%) than that for the 4-lobe design (61%), but the core envelope penetrates more deeply into the lobes. CFD contours of tangential velocity for a simple liquid or solution in these two designs in Figure 4 (from Jones and Ariyaratne, 2007 (8)) bear this out. Notice the clearer circulatory contours from hydrodynamic forces in the core flow for the 4-lobe design.

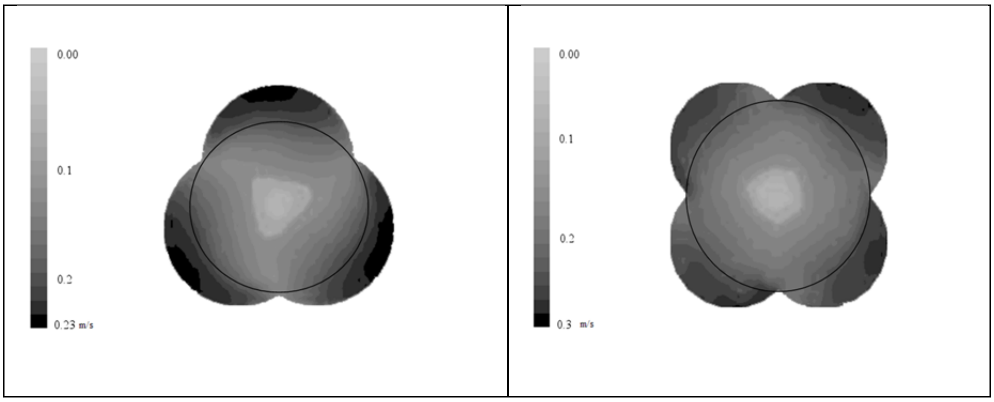


Fig. 4 Contours of tangential velocity in 3-lobe and 4-lobe swirl pipes for water

A computational study of this comparison between 4-lobe and 3-lobe ducts was carried out for water (see Jones, T.F. and Ganeshalingham, J. (2002)(9)). For this purpose a dimensionless group, *swirl effectiveness (ζ)* was used to describe the swirl produced for a given pressure drop.

$$\zeta = \frac{swirl\ intensity}{\Delta P/(\rho u^2/2)} \qquad [5]$$

where

$$swirl\ intensity, S = \frac{\int_0^R uwr^2}{R\int_0^R u^2 rdr} \qquad [6]$$

Swirl Effectiveness was calculated for a series of swirl pipe pitches and the result is shown as Figure 5. Note that swirl per pressure drop is significantly greater for a 4-lobe than for a 3-lobe pipe. This confirms qualitative judgements from the contours in Figure 4. The additional information in Figure 5 is the optimum pitch of 6 pipe diameters for a 3-lobe pipe and 8 pipe diameters for a 4-lobe pipe.

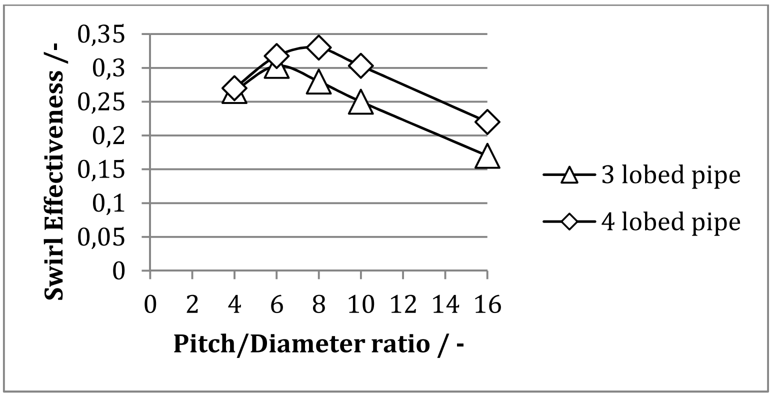


Fig. 5 Swirl effectiveness of 3- and 4-lobe swirl-inducing pipe

2.2 PRESSURE LOSSES IN A SWIRL PIPE

Pressure loss data in Figure 6 (from Tonkin, R.J.J., (2004) (19)) is presented as a <u>pressure cost.</u> A length of cylindrical pipe was inserted in the experimental pipe loop and the pressure drop was measured. The length of cylindrical pipe was interchanged with an identical length of 3-lobe swirl-inducing boiler tube and again the pressure drop was measured. Pressure cost is defined as in equation [7].

Pressure Cost = Pressure loss WITH upstream swirl–Pressure loss WITHOUT upstream swirl [7]

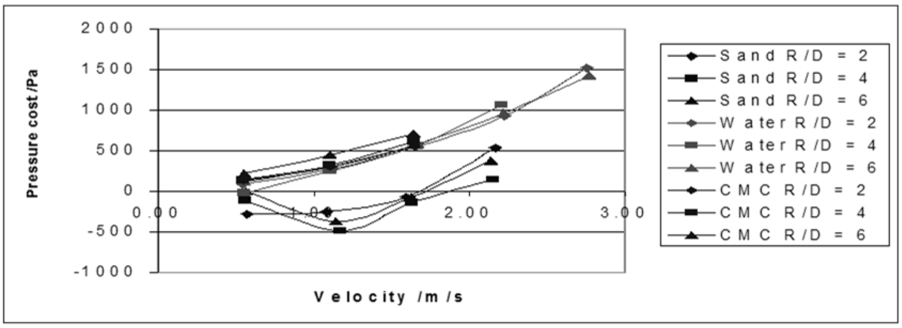


Fig. 6 Effect of a swirl pipe upstream of a toroidal bend (3-lobe pipe)
(after Tonkin, R.J.J., (2004) (19))

Note that the pressure cost is significantly improved for particle-laden liquids over water and CMC solutions when swirling flow is applied. No real advantage, in fact a disadvantage, is produced for the latter.

3 THE TWO-LAYER MODEL

This paper addresses the problem of exactly how much of the solids burden is dredged by the swirl pipe in comparison to that being swirled by hydrodynamic forces. Simplification of the flow cross-section of the approaching main into two layers provides an elegant solution to this problem.

The Two-layer model was invented by Professor K.C.Wilson (1970, 1976) (13,14). Following subsequent refinements, it is described in a more recent technical volume (Wilson *et al* (2006) (15)). Wilson applied observations by R.A. Bagnold (1956) (16) that there two fundamental ways in which particles were supported in a fluid medium – intergranular contact and suspension by the fluid. The model separates the flow of a particle-bearing liquid into distinct layers. The upper layer is flow supported solely by hydrodynamic forces while the lower is again supported by hydrodynamic forces but also by interaction with other particles and ultimately reaction from the lower pipe wall. The model was subsequently developed by C.A.Shook (Shook,C.A. and Roco, M.C., 1996 (17 and 18)) and most recently by T.F.Jones (Jones,T.F., 2011, 2013 and 2014 (5,6,7)) who produced a version (***2LM***) to give a robust direct solution without iterations.

3.1 THE TWO LAYER MODEL *2LM* APPLIED TO SAND/WATER MIXTURES

The two-layer model ***2LM*** will be used to demonstrate pipe pressure loss as a function of the pipe velocity and, crucially, the cross-sectional area of the layers, by means of an example. Figure 7 shows results from the model for a 250mm horizontal main delivering 0.5mm sand-in-water mixture at a concentration of 20% v/v. It shows the pressure losses as a summation of three components (from layer 1, layer 2 and friction of the particle bed with the pipe wall). An assumption of the model is that particle friction with the upper wall can be neglected. Salient features from Figure 7 are as follows.

1. The predicted minimum total pressure loss per metre occurs at a velocity of 1.27 m/s and dredging area ratio 0.187 for the sand/water mixture studied. For most purposes this is a relatively unimportant extremum because it lies within the stationary-bed envelope and over time the slurry would form a stationary bed.
2. The point at which layer 2 loss per metre becomes zero is at a velocity of 2.67 m/s. Zero pressure loss can only be obtained when there is a stationary lower layer. Hence this shallow minimum marks the deposition velocity. Wilson's revised nomogram (Wilson, K.C., *et al*, 2011 (19)) confirms a deposition velocity for this slurry of approximately 2.5 m/s.

3. The area ratio of the upper layer is a function increasing with velocity and gradually becoming level for completely suspended particles. Referring to the graph, the area ratio of the lower layer at the deposition velocity in the approaching cylindrical pipe is (1-0.8219) or 0.1781 (17.81%).
   a. The dredging ratio (α_D) for the 4-lobe pipe is 15.28% which indicates that 2.53% of the settling solids would be accommodated in the core of the swirl pipe at the deposition velocity.
   b. The dredging ratio (α_D) for the 3-lobe pipe is 24.37% which indicates that all the settling solids at deposition velocity will fit into one lobe but, detrimentally, 6.56% of the suspended layer will be included as well.

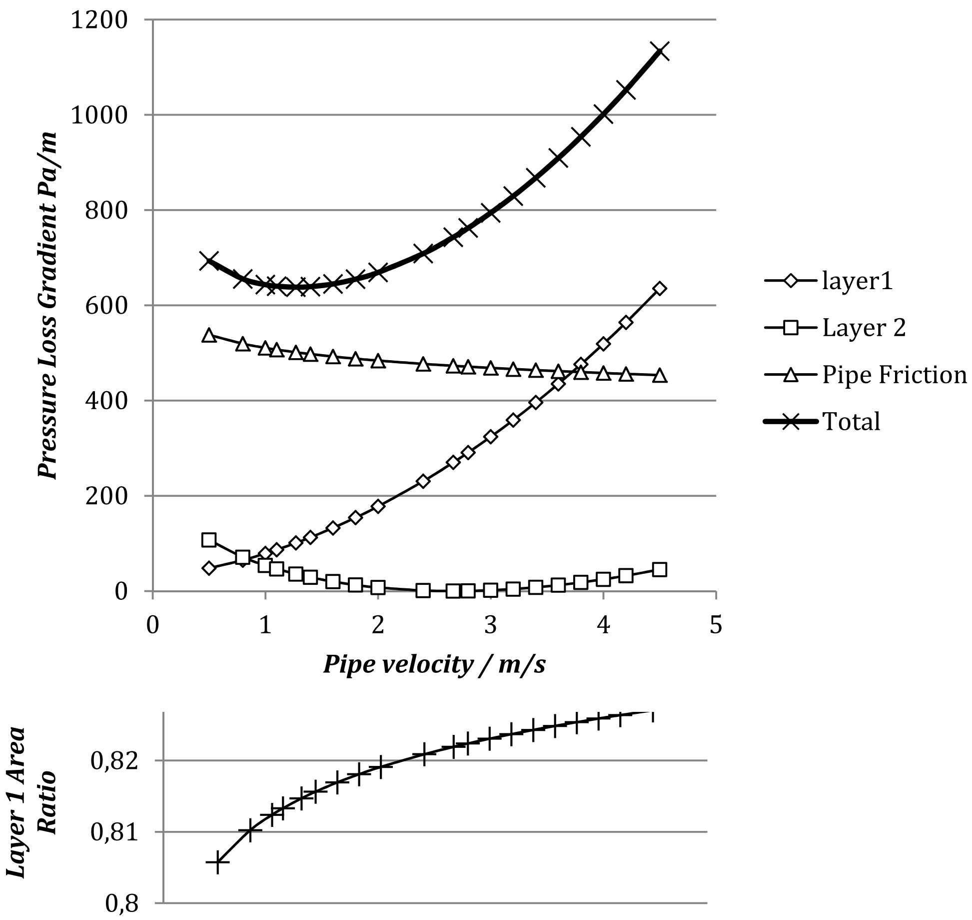
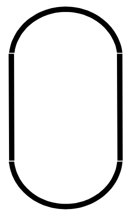


Fig. 7 *2LM* pressure-loss predictions for a 250mm horizontal main transporting 0.5mm sand/water at a delivered concentration of 20% v/v

4 DISCUSSION AND RECOMMENDATIONS

4.1 DESIGN

The design of swirl pipes has many challenges and the two designs described earlier are by no means the only possible. The two-lobe pipe is a notable omission. The cross section of a two-lobe pipe can be created by distorting a circular tube and the swirling action can be created by twisting it at the desired spatial frequency. This is a pressure-efficient design and the ease of manufacture (hot- or cold-forming) also commends it. However, tangential velocity and swirl intensity in a 4-lobe pipe are significantly greater for marginally greater (+3%) pressure cost.



Discussion of swirl creation would not be complete without mention of the technique of forming circular pipe into a helical coil. The fascinating medical prospect that small amplitude helical pipes might be used as bypass grafts to prevent occlusion by thrombosis has been the subject of scholarly study (see A.N. Cookson (2009) (21)). A recent work (Caro, C.G. (2013) (22)), demonstrates the implications of coiled stents in blood flow. In an industrial context, manufacturing would be relatively easy, but the dredging action would be less effective and space would have to be found to fit the coiled pipe.

4.2 COMPUTATIONAL STUDIES

The 3-lobe pipe has a large capacity for dredging settled solids or debris from a pipeline. In the example analysed (sand/water at 20% v/v in a 250mm main) there was a surplus of dredging capacity disrupting the core flow for this design. At the deposition velocity, about 6½% of the upper layer would also be present in the lobe. For this example it is clearly an engineering decision to opt for the 4-lobe design, which does not dredge 2½% of the settling layer, but which provides the other benefits elaborated above.

5 CONCLUSIONS

- Swirl induction was shown to be effective in transportation of particle-bearing liquids, but of little apparent use for simple liquids or solutions. Computational modelling of the swirl pipe, using Computational Fluid Dynamics (CFD) for example, can be augmented with the Two-Layer Model applied upstream.
- The 4-lobe pipe was the better of the designs tested for many applications but matching of the settling layer to the lobe area is an important pre-requisite to an informed choice. For a simple liquid or solution, it provided the most swirl as a proportion of the pumping pressure provided. There is still a case for the 3-lobe pipe when very dense slurries are being transported because the lobe capacity is 24% of cross-section compared to 15% for the 4-lobe pipe.

- Short lengths of swirl pipe are to be preferred because they can be used strategically. Figure 6 shows an example when a swirl pipe has been used before a bend. Where there are no positions of strategic importance, simply spacing swirl elements should allow low pumping velocities to be achieved. In itself this provides a reduction in pumping power requirement and a reduction in risks of blockage.
- The Two-Layer Model provided useful information when investigating swirl pipe applicability. The matching of settling layer to available dredging capacity was useful in comparing 3- and 4-lobe swirl pipe designs for an example sand/water mixture at deposition velocity. Potential wear investigations will also be aided by information as to the burden being supported by the wall.

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