2LM: Pipeline transportation of particle-laden liquids

Particle-laden liquids are found in many places. The food industry, water supply and process industries all depend on the safe pumping of liquids of this type in pipes. In fact there are very few instances of liquids in which particles are not present in one form or another.

If you are piping particulate liquids, your primary concern is to make sure that all of the particles arrive at the destination and do not block the pipe. You can always pump the liquids at high velocity to ensure that particles stay in suspension but this is an expensive way to deal with the problem: the power consumed by the pump is approximately proportional to the fluid velocity to the power of three. In other words, if you could reduce the velocity by half you would require only one eighth, 12.5 %, of the original power into your pump. So it is important to know how well the particles are being transported, and of course the minimum velocity required to keep them in suspension.

The *Two-Layer Model* (***2LM)*** provides answers to these questions. It is a simplification of particle-laden flow in a pipe and has proved remarkably effective. The model builds on observations of blown sand in the Egyptian desert[1] and has been applied to the transportation of suspended solids by Canadian research workers[2 3] and subsequently in the UK[4]. It proposes two layers in a pipe: the lower layer relying on particle-to-particle interaction and the upper layer relying only on the force of the flowing liquid. Between the layers is an interface from which some particles can be pulled away and others can settle down in a kind of dynamic equilibrium.

The spreadsheet version of ***2LM*** requires you to input the properties of your pipe and slurry as follows. A set of up to 5 cases can be entered at the same time. This is useful when you want to see the effect of changes to pre-set variables (an example of pipe velocity progression follows).

1.	Estimate of pipe roughness	*m*	ε	This is used to calculate fluid friction. For commercial steel pipe $\varepsilon \approx 4.5E{-}05\ m$, cast iron $\varepsilon \approx 2.6E{-}04\ m$, concrete $\varepsilon \approx 3.0E{-}03\ m$ - $3.0E{-}04\ m$ and drawn tubing $\varepsilon \approx 1.5E{-}06\ m$
2.	Coefficient of friction for the pipe wall	-	η_s	This is used to calculate the friction of the settling particles in the lower layer with the pipe wall. Start with $\eta_s \approx 0.5$
3.	Viscosity of liquid	Ns/m^2	μ	At 293°K, water $\mu=0.001$, glycerol $\mu=0.0015$, olive oil $\mu=0.08$, paraffin oil $\mu=1.0$
4.	Density of solid particles	Kg/m^3	ρ_s	
5.	Density of liquid	Kg/m^3	ρ_L	
6	Limiting concentration of lower layer	-	C_{lim}	This is the loosely packed limiting concentration of particles in the lower layer. Start with $C_{lim} \approx 0.6$. *NB* if a wide distribution of particle sizes is present, particle-packing effects might require this value to be increased.
7.	Angle of inclination of pipe	°	θ	
8.	Pipe bore diameter	*m*	*D*	
9.	Particle diameter	*m*	*d*	Use 50th percentile d_{50} in the first instance.
10.	Pipe velocity	*m/s*	v	
11.	Concentration of solids by volume	-	*Cv*	This is the overall or delivered concentration by volume of the particles. The *in situ* value will be different because of *holdup* in the system.

[1] Bagnold,R.A. (1954), *The Physics of Blown Sand and Desert dunes*, Dover Publications Inc.
[2] Wilson, K.C. (1970), *Slip point of beds in solid-liquid pipeline flow,* Proceedings American Society of Chemical Engineers, J. Hyd., Div., 96, 1-12
[3] Shook,C.A. and Roco, M.C. (1996), *Slurry Flow Principles and Practice,* Butterworth Heinemann, Chapter 6
[4] Jones,T.F. (2011), *A spreadsheet version of the Two-Layer Model for solid-liquid pipeflow,* 15th International Conference on Transport and Sedimentation of Solid Particles, Wroclaw, Poland , pp101-114

Holdup

The delivered concentration (c_v) in a pipe is always less than the *in situ* concentration (c_r) at a given position along the pipe because of *holdup (λ)*, the lag between the velocity of the solids (v_s) and the mean pipe velocity (v). So

$$\lambda = \frac{v - v_s}{v}$$

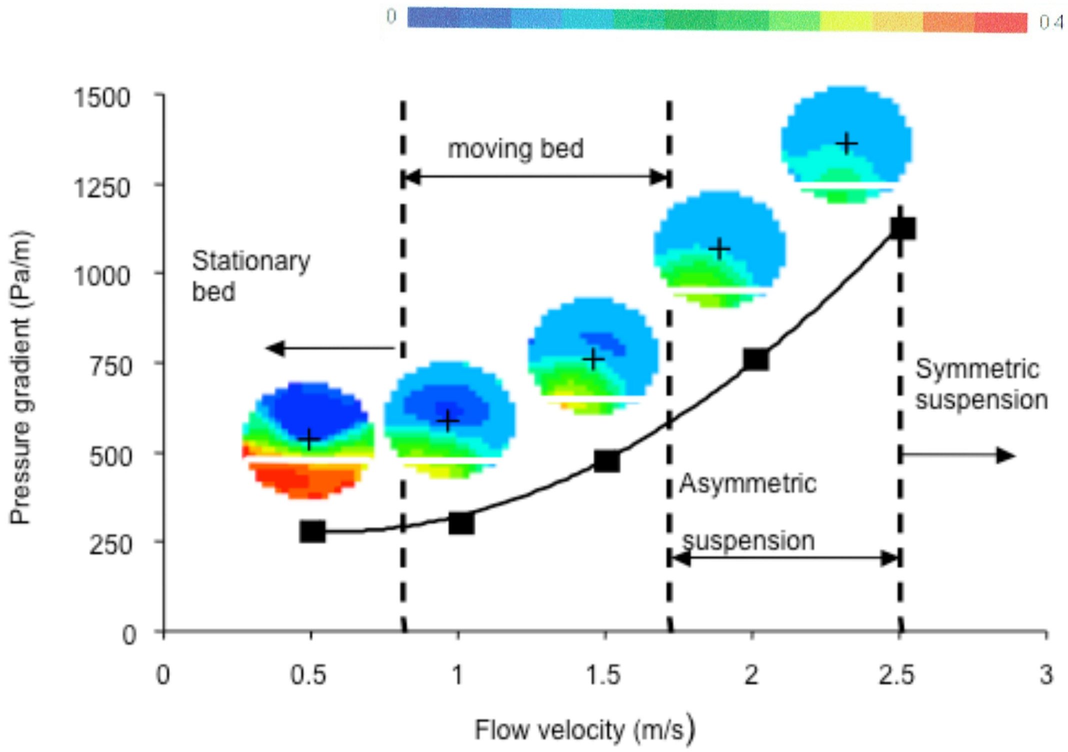
It follows that

$$\lambda = 1 - \frac{c_v}{c_r}$$

Holdup (λ), a number between 0 and 1, is the most influential parameter in the flow of any particulate liquid. If $\lambda=0$ there is no holdup: the solids are travelling at the same velocity as the liquid. If $\lambda=1$ all the solids are stationary and blockage is imminent. In reality λ will lie between these two extremes. ***2LM*** uses an iterative procedure to calculate holdup for us.

Example:

The example is of a 50mm bore pipe carrying coarse plastic beads of density 1450 kg/m^3 and size 1.75mm in water. The overall (delivered) solids concentration is 8% v/v. Electrical Resistance Tomography (ERT) has been used to measure the distribution of particle concentrations. The graph shows the comparison between the predictions of interface position by ***2LM*** at five increasing mean pipe velocities and the tomographic images. Notice the good fit of ***2LM*** (the white lines) at stationary and near stationary bed conditions and the more diffuse interface as flow velocity increases towards a symmetric suspension. In this case, ***2LM*** calculates that the lower layer becomes stationary at a velocity of 0.362 m/s.



Getting *2LM*

2LM is a Microsoft Excel application, so you will need a license for Microsoft Office for Windows or Macintosh. ***2LM*** can be obtained from TFJ Consulting Ltd on payment of a nominal fee of £49.99