Gas flow through a porous mantle
the example of fluidisation

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Introduction to fluidisation

Granular matter in a fluidised state behaves as a fluid, since its weight is supported by the drag of a gas or liquid flowing upward through it. It is hypothesised that such a state could occur in a cometary mantle under certain conditions, which will be explored here.

The process of fluidisation is most easily described by a fluidisation curve, in which the gas velocity through a packed bed is steadily increased and the pressure drop across the bed recorded. To begin, imagine a packed bed with particles having intimate contact. Gas is flowed vertically upwards through this bed, whilst gravity acts in the opposite sense. At zero gas velocity there is no pressure drop across the bed, and the bed has a fixed depth. As the flow velocity through the bed is increased, a pressure drop develops, increasing linearly with gas velocity.

At a critical gas velocity, the frictional forces (i.e. the gas drag) acting upwards equal the gravitational forces (i.e. the bed weight) acting downwards. This is the onset of fluidisation. From this point, increasing the gas velocity does not result in a further increase in the pressure drop, but instead results in the expansion of the bed. The particles are no longer in intimate contact, but are separated and move freely throughout the bed, changing the dominant heat transfer mechanism, for example.

Figure 1 shows a fluidisation curve calculated using a two-fluid model for the terrestrial case by way of example.

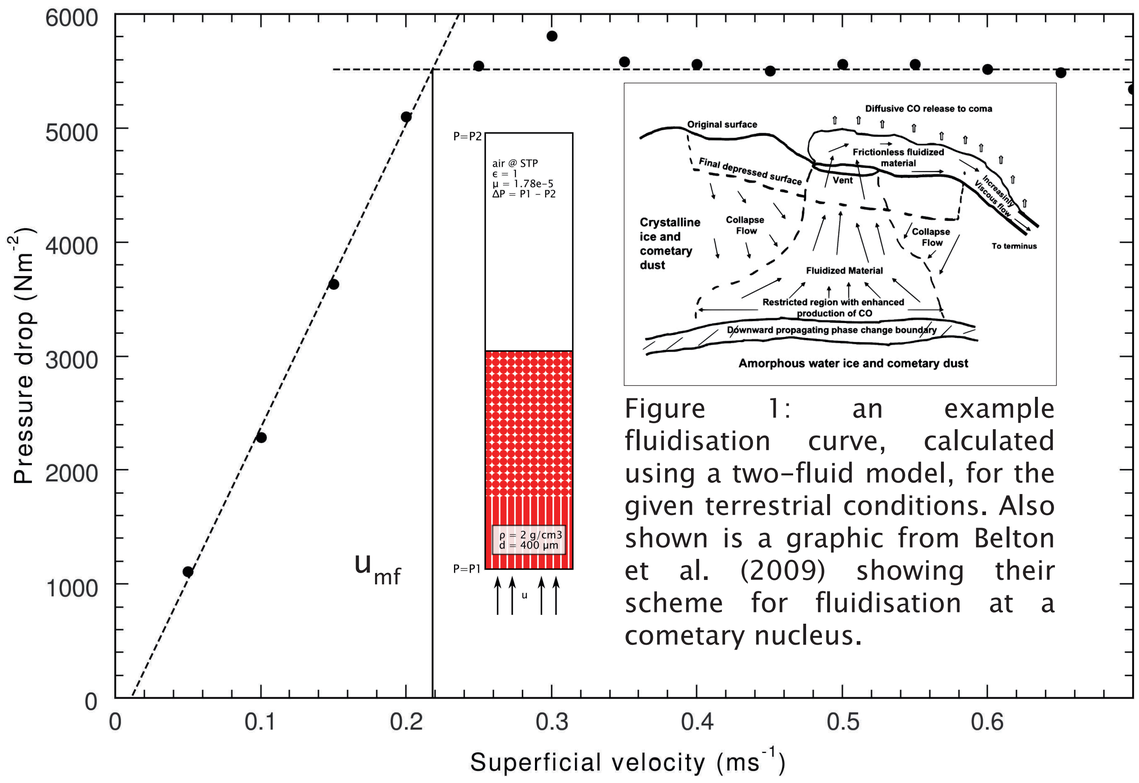
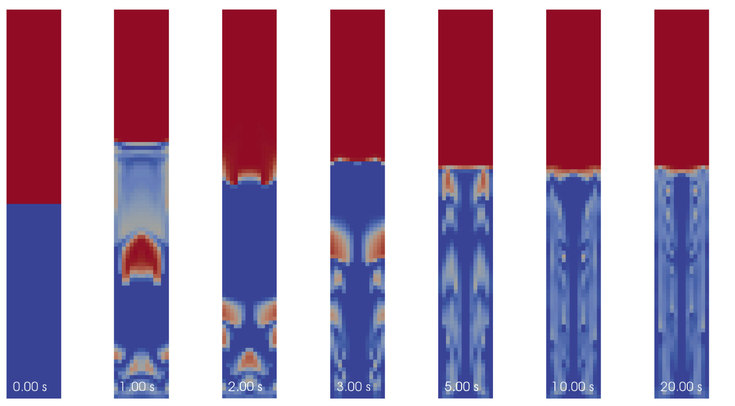
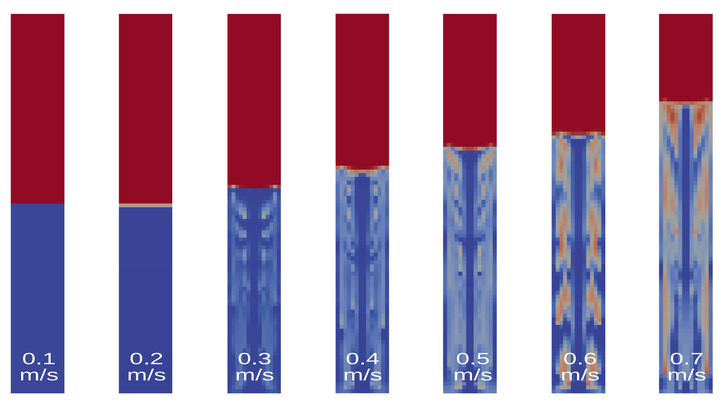


Figure 1: an example fluidisation curve, calculated using a two-fluid model, for the given terrestrial conditions. Also shown is a graphic from Belton et al. (2009) showing their scheme for fluidisation at a cometary nucleus.

Visualising a fluidised state

Snapshots of terrestrial fluidisation for a fixed inlet velocity of 0.4 m s^{-1} over time. The colour scale shows the void fraction, where 1 is free space and 0.4 is typical for a packed particle bed. The bubble seen rising through the solid is a typical characteristic of fluidisation and can result in effective mixing of the solid and gas.

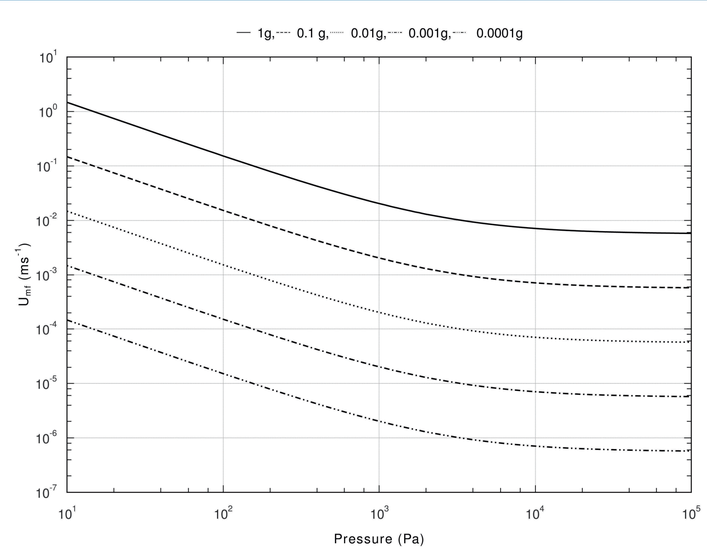




Snapshots of steady state fluidisation for increasing gas velocities. u_{mf} ~0.22 m s^{-1} as in Figure 1.

As can be seen for velocities beyond u_{mf} the averaged bed height expands. This has been suggested as a method for forming smooth deposits, via expanded particle beds (Belton et al., 2009).

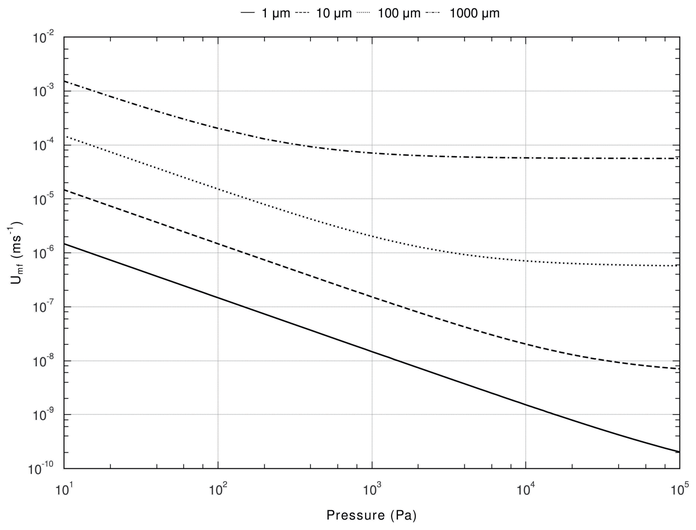
The influence of gravity and pressure on fluidisation



The minimum fluidisation velocity (u_{mf}) as a function of pressure for different gravities. 100 μm particles of 2000 km m^{-3} have been modelled, fluidised by water vapour at 200 K. As expected, the velocity depends linearly on gravity; as the bed weight is reduced, so the drag force needed to compensate reduces in turn.

The minimum fluidisation velocity u_{mf} as a function of pressure for different particle sizes at 10^{-4} g.

At higher pressures the velocity is relatively constant, but as the pressure is reduced into the slip flow regime, it increases relatively quickly. This effect is more pronounced for smaller particles/void sizes.



A key parameter in describing fluidisation is the minimum fluidisation velocity u_{mf} which is shown in Figure 1 as the intersection of the linear packed bed curve and the constant pressure line once fluidised. This occurs when the bed weight is equal to the buoyancy and drag forces, and can be expressed as $\Delta PA = hA(1-\epsilon)(\rho_{solid}-\rho_{gas})g$.

Llop (1996) derived an expression for the pressure drop across a bed taking into account flow in the molecular, slip and viscous regimes:

$$\frac{dP}{dl} = \frac{u}{\frac{16}{45}\cos^2\psi\,\frac{\epsilon^2\phi\,d}{1-\epsilon}\sqrt{\frac{2}{\pi\rho P}} + \frac{\cos^2\psi}{72}\,\frac{\epsilon^3\phi^2 d^2}{\mu(1-\epsilon)^2}} + 1.75\,\frac{(1-\epsilon)}{\epsilon^3\phi\,d}\,\rho u^2$$

where ϕ and ψ describe the particle shape, μ is the gas viscosity, A the cross-sectional area of the bed and other parameters are as above.

This expression, along with supplementary expressions for the gas viscosity and other parameters, allows the calculation of the Reynolds number at minimum fluidisation, which in turn gives u_{mf}. This can be used to estimate the minimum fluidisation velocity (and hence gas flux) for a low gravity, low pressure scenario.

The results shown (left) demonstrate that the gas velocity required to fluidise a particle bed increases as pressure decreases, that decreasing gravity linearly decreases u_{mf} as the bed weight changes and shows the effect of particle size.

Fluidisation is only possible in slip and viscous flow, so when the Knudsen number (K_n=gas mean free path/pore space) is less than ~1. Thus a 1000 μm particle can be fluidised by water vapour at 200 K down to a pressure of ~10 Pa and a 100 μm particle to ~100 Pa. For these particles u_{mf} is 1.5 mm s^{-1} and 0.15 mm s^{-1}, respectively.

Implications for Rosetta

The Rosetta target, 67P/Churyumov-Gerasimenko has an effective diameter of 3.44 km, a bulk density of 370 kg m^{-3} and a mass of ~8×10^{12} kg (Lamy et al. 2007). From these values a surface gravity of 1.8×10^{-4} g and an escape velocity of ~0.8 m s^{-1} are found.

Given that the fluidisation velocities predicted above are in the order of mm s^{-1}, there is a large theoretical range of gas fluxes that could support fluidisation. These values will later be compared to those from insolation driven dust/ice mantle models.

One aspect of fluidisation that has not yet been discussed is the fundamental transition of a granular medium to a fluid-like state. In such a state, dense objects can readily be submerged into a fluidised bed; this is in fact the behaviour of so-called “quicksand”, which occurs during liquid-solid fluidisation. Thus, scientific interest notwithstanding, the stability of the lander could be compromised if the mantle under it were to fluidise.

Conclusions and outlook

- Fluidisation is possible under low gravity and low pressure
- But only when K_n <~1 (it is not possible in true free molecular flow)
- Reducing pressure increases u_{mf} whilst reducing gravity decreases u_{mf}
- u_{mf} is in the order of mm/s for "typical" cometary conditions
- This calculation ignores interparticle forces, which are important in low g
- And it assumes constant pressure - in reality we have P & u gradients
- A "two-fluid" model is under development to understand flow dynamics

References

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Lamy, P., Toth, I., Davidsson, B. et al.(2007). Space Science Reviews 128, 23-66.
Llop, M. F., F. Madrid, J. Arnaldos, and J. Casal (1996). Chemical Engineering Science 51 (23), 5149-5157.

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