Substrate Characteristics & their Effects on Air Entrainment in Dip and Curtain Coating

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Introduction

Air entrainment, in all its forms, afflicts most industrial coating operations. It will always occur under certain critical conditions, usually low speeds particularly when the coating fluid is viscous. To overcome this limitation, industry retorts to experimenting with various substrates, playing on roughness, surface energies and other properties to improve productivity.

Most academic studies on air entrainment have been made in dip coating, where the geometry is simple and the experiments easy to perform. Such coating operation is however “not hydrodynamically assisted”, the substrate merely plunges into the liquid and this minimises wetting and results with low coating speeds (<1m/s). At the other extreme, curtain coating where the liquid impinges on the substrates shows remarkably large entrainment speeds (>1m/s). This set-up has been studied almost exclusively by the photographic industry which recently has come-up with interesting ideas on the effect of roughness. The results are that one can overcome the limiting effect of increasing viscosity on air entrainment speed.

The present study follows broadly on this perspective and present data on the performance of various substrates in both dip and curtain coating. This study however differs from previous work in that it attempts to predict the performance of substrates in curtain coating using data obtained in dip coating. It also examines the effect of properties other than roughness on air entrainment. Also, apart from the earlier work by Gutoff and Kendrick (1987) in slide coating, no experiments have been carried out to measure the effect of vacuum pressure on air entrainment speed and mechanism. Such experiments, particularly at the lowest vacuum attainable, are fundamental in that air cease to have a viscosity and this effect is removed.

There are essentially three theories of dynamic wetting. The first, the molecular-kinetic theory of dynamic wetting initiated by Blake and Haynes (1969) and further developed by Blake (1993) predicts a finite maximum speed of wetting even if the displaced phase is inviscid. In other words, the viscosity of air plays no effect in its entrainment by the liquid. The second, the hydrodynamic theory of Cox (1986), on the contrary, predicts a maximum speed of wetting, which tends to infinity when the viscosity of the displaced phase tends to zero. In other words air and its viscosity affect its entrainment by the liquid and the air entrainment speed increase exponentially with decreasing air viscosity. Put differently, if air had no viscosity, it would not be entrained according to Cox. The most recent and third theory, attributed to Shikhmurzaev (1993, 1997) proposes a hydrodynamic model with flow-induced surface tension gradients along the liquid / solid interface. This model always predicts a maximum speed of wetting when the displaced phase is viscous. However, when the displaced phase is an inviscid gas, a finite maximum speed of wetting is predicted only if the interfacial tension σ_{SG} of the gas-solid interface is negative. The effect of this σ_{SG} parameter is however difficult to assess experimentally.

It must be said that these theories are all a-priori valid and have been supported by experimental data. In particular, a corollary of Blake's theory has been verified by the angled coating experiments of Cohu and Benkreira (1998). Nevertheless, the key experiments, which will help to resolve the disagreement between these theories, are those with a phase of variable viscosity down to zero. This is precisely one of the subjects of this paper, which draws from experiments carried out with a dip coater under various vacuum levels.

Experimental Method

This study uses the same dip coating equipment and methods for assessing the onset of air entrainment as those reported earlier (Benkreira & Cohu (1998) and Cohu & Benkreira (1998). For experiments under vacuum conditions, a steel chamber (800 x 400 x 400 mm) with walls of 10 mm thickness and three viewing windows was constructed and the dip coating rig placed inside it. The substrate winder roller was driven from the outside by a geared motor via a labyrinth type vacuum seal. The substrate speed was measured by a remote sensor placed inside the vacuum chamber. Glycerine-water solutions with viscosities ranging from 40 to 733 mPa.s (surface tension 65 mN/m) and silicone oils with viscosities ranging from 8.9 to 145 mPa.s (surface tension 19 mN/m) were used for in the dip coating studies.

The experimental curtain coater consists of a slot die (0.200m x 0.001m) with edge guides and was manufactured by Troller & Co AG, Switezland. The coating liquid is fed to the die by a variable drive gear pump. The substrate (width of 0.110m) is looped around a series of sixteen small diameter idler rollers with two large idler rollers, 0.30m apart, holding the substrate flat underneath the suspended die at a control height. The run of the substrate is kept straight by an automatic web guiding system and control of the tension along it. Static charges are removed by mounting copper wires on the belt and earthing them on the metal structure. The dynamic wetting line flow area is illuminated and observed using a CCD camera with magnification up to 33 times and/or a long distance microscope (Infinity Series). The images collected are displayed on a monitor and recorded on a VCR.

Newtonian and Non-Newtonian shear thinning fluids (lubricating oils, glycerine-water, glycerine-water-CMC) have been tested together with a number of plastic and paper substrates supplied by Ilford Imaging Switzerland. The fluids were characterised rheologically in a Brabender Rheotron and a Bohlin CVO viscometer. The topography of the substrates was characterized using the MicroXam surface-mapping microscope at AG Electro-Optics (Tarporley, Cheshire, UK).

Results

Results with both glycerine-water solutions and silicone oils show that there exists a critical viscosity beyond which the behaviour switches from V_{AE} being larger with smooth surfaces than rough surfaces to V_{AE} being larger with rough surfaces than smooth surfaces. This result, obtained from this simple but fundamental experiment, confirms the observations made by Clarke (2002) in curtain coating and brings out the importance of hydrodynamic effect on air entrainment. It also provides a full explanation of the effect of roughness. Only above a critical viscosity is a rough surface more dynamically wetting than a smooth surface. This is very useful in practice as it implies that higher solid content formulations (higher viscosity) can be coated faster by increasing the roughness of the substrate. The critical viscosity increases as roughness increases. Roughness of order R_Z only of 3 microns can cause this behaviour. Also, the V_{AE} at the “switch” position has been found to be a function of the surface tension of the fluid i.e. the V_{AE} at the “switch” point decreases with increasing surface tension.

The initial results from the dip coating under vacuum conditions favour the hydrodynamic theory. They show that the air entrainment speed V_{AE} does not vary much when the pressure is reduced from 1 bar down to 500 mbar but further reduction down to 50 mbar and below show significant increase in V_{AE}. Examples are shown in Figures 1 to 4 where the air entrainment velocity is plotted as a function of the chamber pressure for two of the substrates (908 and 929) studied. The two sides of the substrates are labeled “Front” and “Back”, with the front sides being rougher than the back.

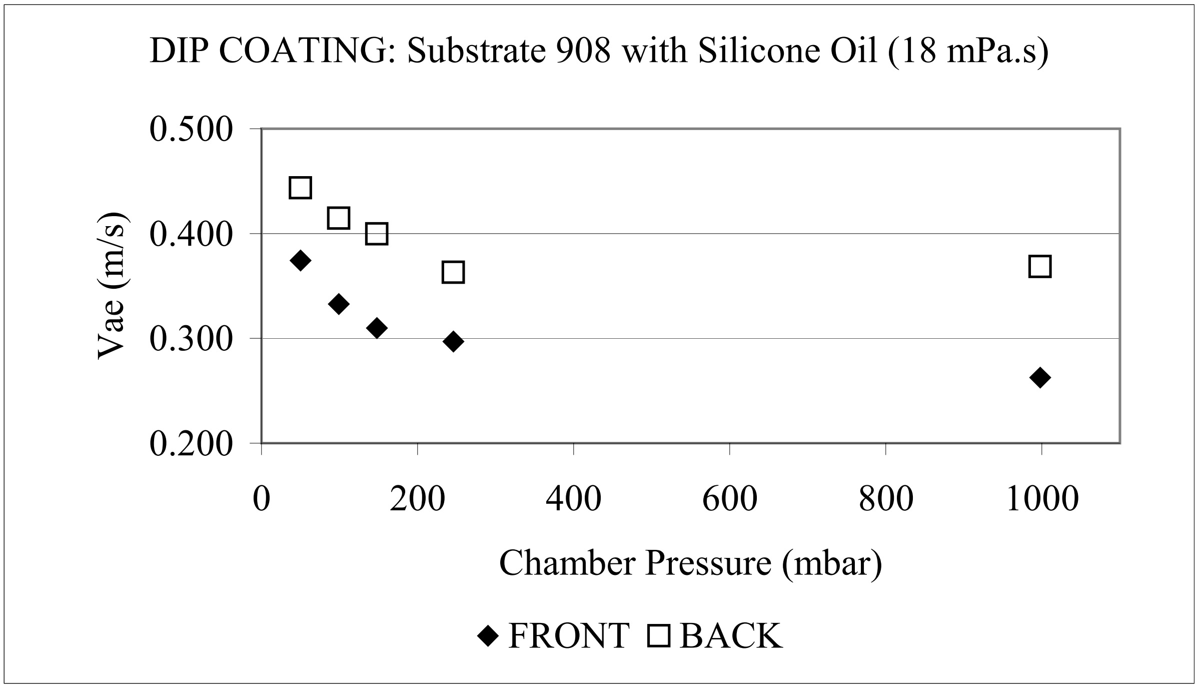

Figure 1

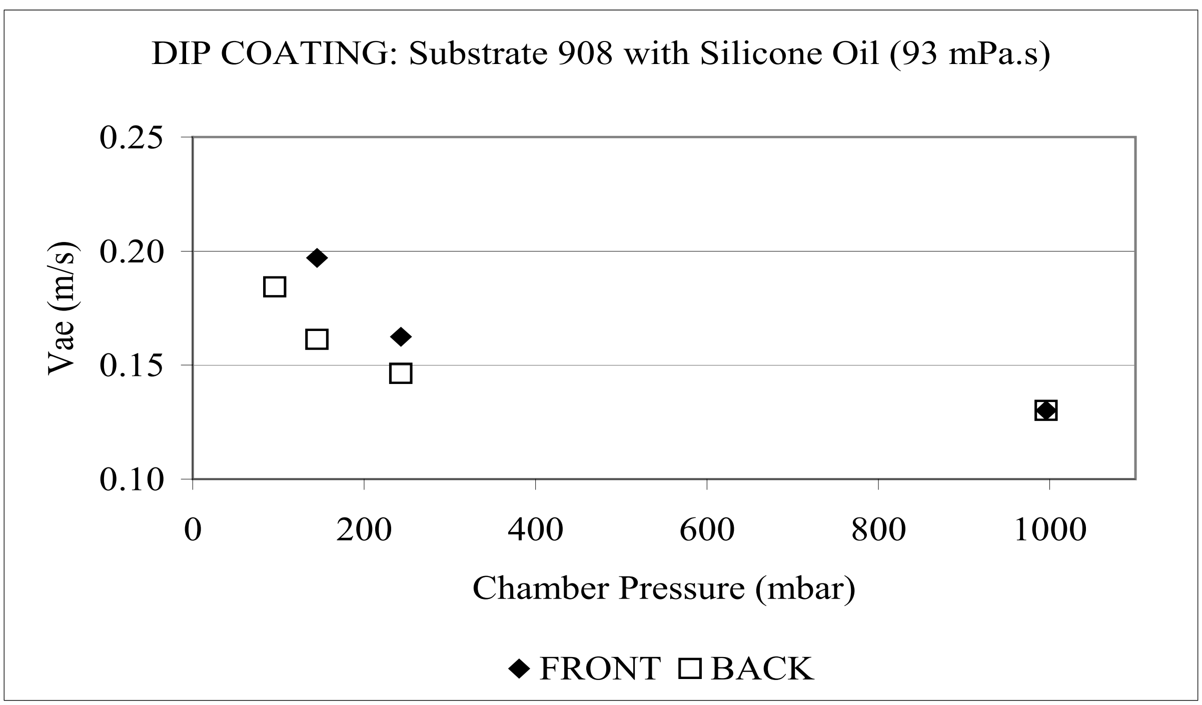

Figure 2

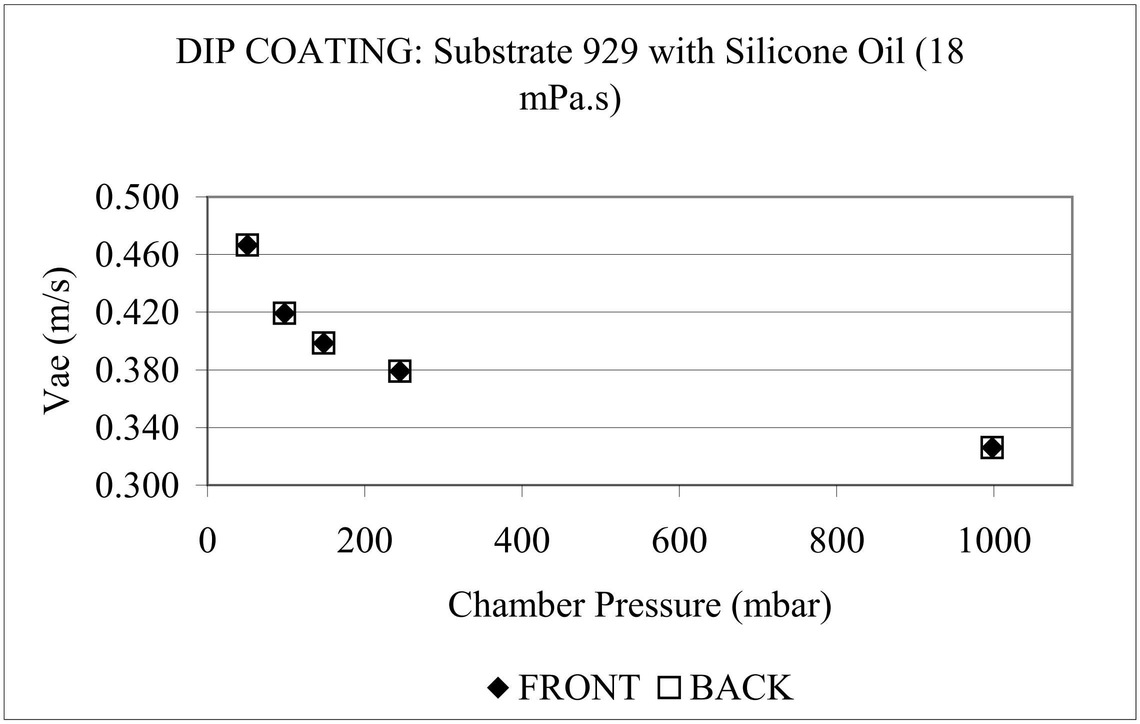

Figure 3

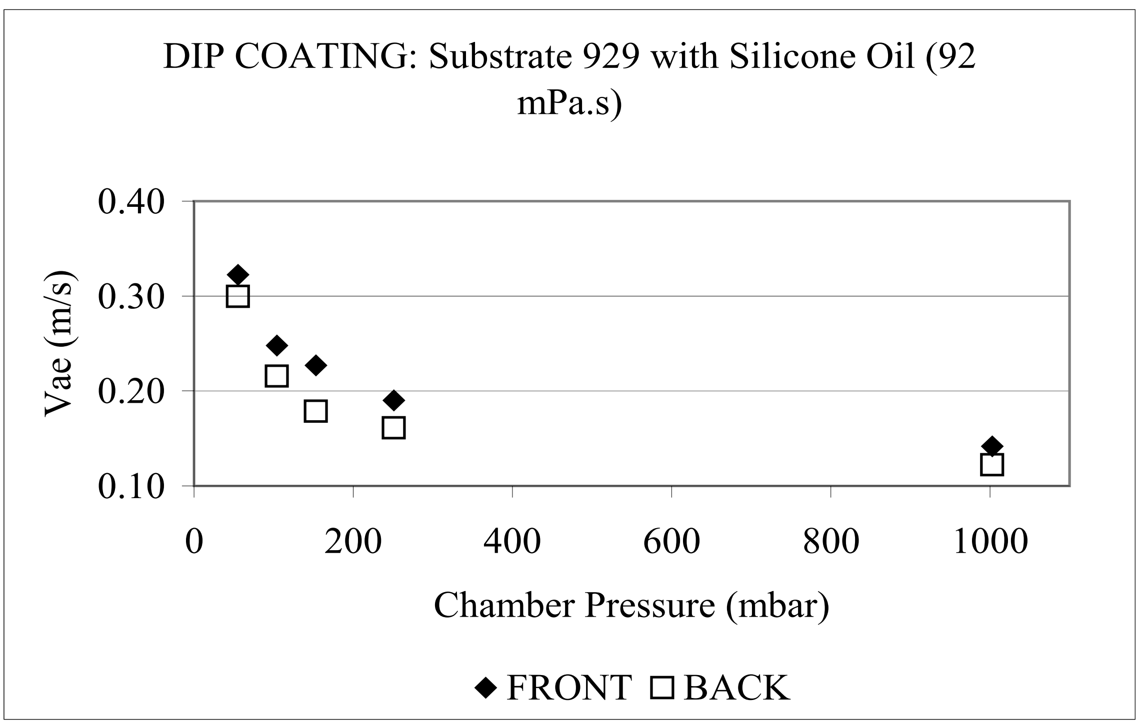

Figure 4

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