



ESDU TECHNICAL MEMORANDUM

Operations on surfaces covered with slush

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THE PREPARATION OF THIS TECHNICAL MEMORANDUM

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OPERATIONS ON SURFACES COVERED WITH SLUSH

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OPERATIONS ON SURFACES COVERED WITH SLUSH

1. NOTATION AND UNITS

		Units
k	function of P/p_0 (see Equations (5.9) and (5.10))	–
P	dynamic pressure	lbf/in ²
P_t	tyre pressure	lbf/in ²
p	static pressure	lbf/in ²
r	ratio of volume of water+ice to air at undisturbed conditions (see Equation (5.8))	–
V	speed	ft/s
V_p	critical speed	ft/s
V_0	ground speed	ft/s
v	volume	ft ³
γ	= 1.0 for isothermal process, 1.4 for adiabatic	–
ρ	density	slugs/ft ³
σ	specific gravity (ratio of density to that of water)	–

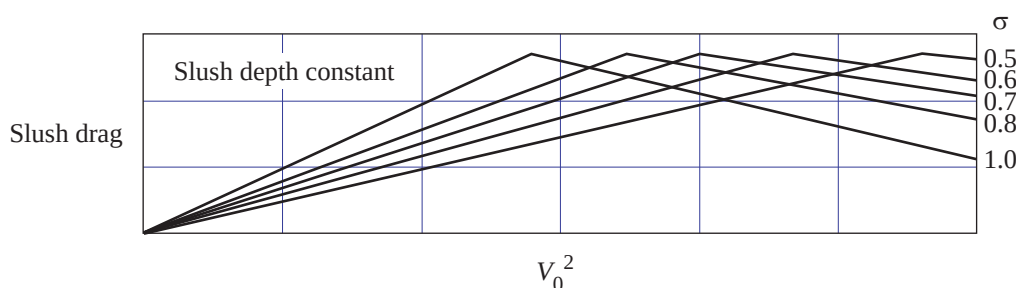
Subscripts

a	air
s	slush
w	water
wi	water/ice mixture
0	undisturbed conditions, well ahead of wheel

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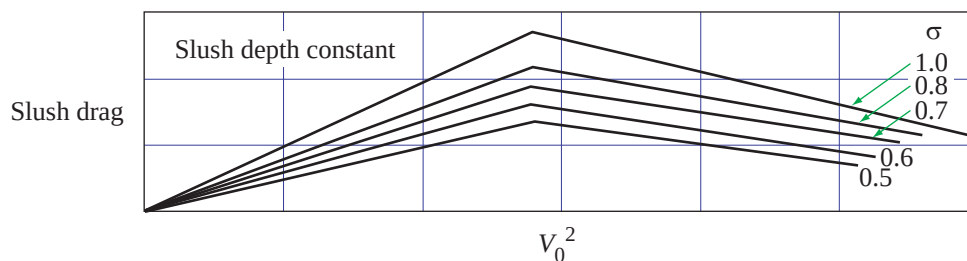
2. INTRODUCTION

In addition to operation on surfaces covered with water, aircraft and other wheeled vehicles have occasionally to contend with surfaces contaminated by other precipitation-caused substances, in particular slush. For many years the drag of single tyres operating in slush has been estimated on the assumption that the specific gravity of the undisturbed slush, $(\sigma_s)_0$, is used both in the estimation of critical speed ($V_p = 9\sqrt{P_t/(\sigma_s)_0}$, in which P_t has units lbf/in² and V_p is in knots) and in the estimation of drag. This leads to drag variation with speed (at constant slush depth) of the form shown in Sketch 2.1 (Reference 1).



Sketch 2.1 One possible form of variation of slush drag with speed

An alternative view, which has gained some acceptance, is to assume that critical speed varies as though $(\sigma_s)_0 = 1.0$, i.e. $V_p = 9\sqrt{P_t}$, while drag is dependent on slush density. This leads to drag variation with speed of the form shown in Sketch 2.2 (again for constant slush depth.)



Sketch 2.2 Another possible form of variation of slush drag with speed

Fluid dynamic considerations indicate that the specific gravity of the slush is increased during the passage of the wheel. Cooke (Reference 2) derived a “slush equivalent density” that he used to predict aquaplaning speed for an aircraft operating from a slush-covered runway.

The present report examines the origins of slush (Section 3), reports briefly on various theoretical models of the flow around a wheel operating in slush (Section 4), considers the physics of operating in slush (Section 5) and reviews the fluid dynamic compressibility characteristics of the flow (Section 5.2). Finally, some suggestions are made in Section 7 for future research work.

3. PHYSICAL CHARACTERISTICS OF SNOW AND SLUSH

3.1 Snow

Snow takes several forms, depending upon the ambient temperature at the time of precipitation (Reference 3).

- At very low temperatures, snow falls as single ice crystals (which may be complex in form).
- At higher temperatures, the ice crystals may aggregate into blobs or into the intricate geometrical forms called snowflakes.
- Close to freezing point, snow turns to sleet as it begins to thaw. Snow is usually only formed at temperatures below -4°C (above that temperature precipitation normally takes the form of rain) but dry snow can occur at any temperature up to 0°C .

Fresh snow, or “new snow”, is freshly deposited snow and is a loose, low-strength material that has not been subjected to compaction or metamorphism (Reference 4). **Note** that the depth of fresh snow is defined as referring to snow fallen in the last 24 hours and that, consequently, “fresh” snow could already be partially compacted if there is strong wind during snowfall. In fresh snow, the original shape of crystals is still recognisable. After deposition, metamorphism sets in and, with passage of time, the individual snowflakes become increasingly rounded in shape, eventually breaking up into smaller grains that are fairly uniform in size. Simultaneously, both the strength and density of the snow pack increase to form what may be referred to as “old snow”. Even in the absence of temperature gradients in the snow pack, overburden pressure, or melting, the strength and density of old snow continue to increase with time (Reference 5).

The initial properties of snow deposited at the ground depend not only upon the size, shape and temperature of the snow crystals but also on the packing arrangement (which is determined by the manner in which they are laid down). In calm weather, crystals settle gently to the surface, where they lie in loose contact to form a mass of low density. Large and intricate crystals (most common when air temperature and humidity are relatively high) form fluffy masses with very low specific gravity (0.004 to 0.03, see References 6 and 7), whereas small crystals of simple shape achieve closer packing, giving specific gravities up to 0.2 (Reference 6).

Snow cannot be treated as a fluid; in particular, its behaviour in response to wheeled traffic is more plastic than fluid, *i.e.* it does not return to its former shape and size after deformation (snow behaves elastically only under loadings of short duration, with strains small enough to be accommodated without disruption of the grain structure). It is highly compressible and subject to compaction.

Snow will be compacted if energy is added to the system in the form of work done upon it by external forces or in the form of heat exchange with the environment. If the temperature is below freezing point, then the energy absorbed in the compaction process will raise the temperature. Compacted snow can have a specific gravity of up to 0.6 (Reference 8) or even 0.8 (Reference 6). If the snow is compacted further, the pores of the snow seal off to form closed air bubbles and render the material impermeable to air flow. By convention, this event is taken as the transition from “snow” (permeable) to “ice” (impermeable). As ice the specific gravity can rise to 0.92.

Snow may be subdivided into various degrees of wetness, as follows (Reference 9).

- **Dry snow** - can be blown if loose or, if compacted by hand, will fall apart again upon release. Liquid water content is 0% and specific gravity is $\sigma < 0.35$.
- **Moist snow** - when lightly crushed, has a distinct tendency to stick together. Liquid water content is $< 3\%$.
- **Wet snow** - if compacted by hand will stick together to form a snowball. The water can be recognised at $10 \times$ magnification by its meniscus between adjacent snow grains but water cannot be pressed out by moderately squeezing by hand. Liquid water content is 3 to 8 % and specific gravity is in the range $0.35 \leq \sigma < 0.5$.
- **Very Wet Snow** - water can be pressed out by moderately squeezing by hand, but there is an appreciable amount of air confined between the pores. Liquid water content is 8 to 15%.

The diagram in Figure 1a presents the whole range of combinations of the three components of snow and slush (ice, air and water) within a triangular axis system. The three components form a homogeneous system, *i.e.* air + water + ice = 1. Lines of constant values of slush density, $(\sigma_s)_0$, are shown as solid lines, based on a specific gravity for ice of 0.92. Dry snow and compacted snow appear along the water = zero boundary at the upper right hand of the diagram with the various classifications of wet snow lying just within the triangle. Note that some regions within the triangle may represent conditions which are not physically realistic (see Section 3.2).

3.2 Slush

When the temperature is near freezing point, energy absorbed (either from the environment or from the mechanical effects of, say, a rolling wheel) in the compaction process will melt some of the snow, producing a snow/air/water mixture, *i.e.* slush. In the early stages of this process the mixture will be nearer to snow than to water and will behave in a plastic rather than a fluid manner. Its temperature will stay approximately constant, whilst its density will increase.

As the proportion of water increases, at some stage (as yet undefined) the slush mixture will begin to behave as a fluid. Again, temperature will stay approximately constant, whilst density will increase. Eventually, the snow content is all broken down (warmed by the compaction process) to water. Density will then be that of water.

Reference 16 describes slush as “water-saturated snow which with a heel-and-toe slapdown motion against the ground will be displaced with a splatter”. It defines slush as having a liquid water content greater than 15% and a specific gravity in the range

$$0.5 \leq \sigma_s < 0.8.$$

However, it will be seen below that 0.5 is an unrealistic value and that the range should be defined as

$$0.5 < \sigma_s < 0.8.$$

Knowledge of the slush density and water content is sufficient to determine the proportions of water, ice, and air in slush. The triangle in Figure 1b, identical in form to that of Figure 1a, contains the whole range of combinations of the three components. The baseline represents a simple mixture of water and ice, the upper right hand boundary describes snow, and the upper left hand boundary describes air/water foams.

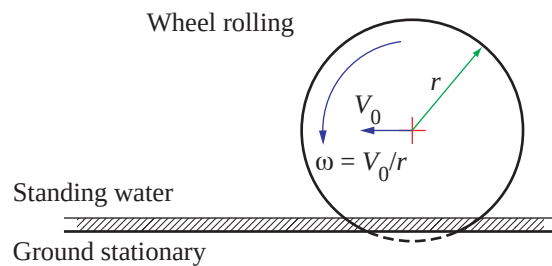
“Slush” as defined for the present purpose, is restricted to the clear region in the diagram, for the following reasons.

- The (shaded) top right hand half of the triangle corresponds to an air content equal to or greater than the water content, a condition that is unlikely to be representative of real slush. It will be seen that excluding that region eliminates values of slush density up to (and including) 0.5.
- Slush specific gravity is restricted to values below 0.8, *i.e.* excluding the shaded area at the bottom of the triangle. The combined effect of this and the above restriction limits the water content to values greater than 0.15.

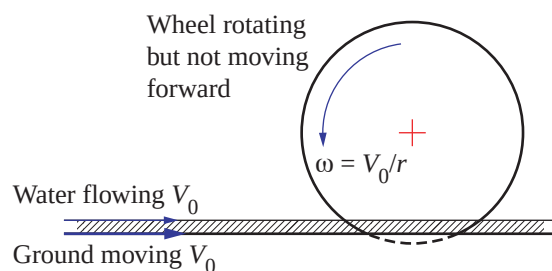
4. MODELLING OF FLUID FLOW ABOUT A TYRE

When considering the aerodynamics of an aircraft it is convenient to transform from the air-based axis system, *i.e.* an aircraft moving through air, to an aircraft-based axis system, *i.e.* air moving past the aircraft.

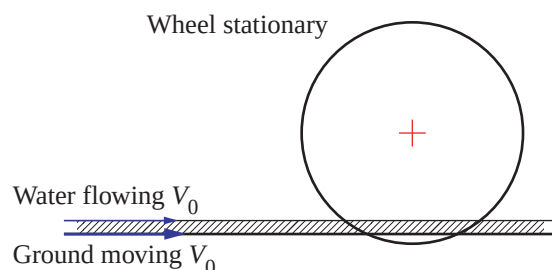
Similarly, when considering the fluid dynamics of a wheel in water (or slush) it is convenient to transform from the ground based system (Sketch 4.1), in which the wheel rolls (or planes) through the fluid, to one in which the fluid and the runway surface move past the wheel. Ideally, the rotation of the wheel will be maintained (Sketch 4.2) but the problem can be simplified further by ignoring the rotation (Sketch 4.3).



Sketch 4.1 Actual situation (ground-based axes)



Sketch 4.2 Mathematical model (wheel-based axes)



Sketch 4.3 Simplified mathematical model

The only difference between the flows in Sketches 4.2 and 4.3 is the circumferential velocity at the surface of the wheel in Sketch 4.2. This would only affect the flow through boundary layer effects in an essentially viscous fluid. Martin (Reference 10) suggests that, since the translational speed, V_0 , is usually large and the viscosity of water is quite low, the Reynolds number will be large (of the order of 15×10^6 /ft at 100 knots). Hence, the effect of viscosity can probably be neglected. An exception might be where the thickness of the boundary layer on the wheel is of the same order as the tyre/ground gap - which might be dealt with as a lubricated bearing.

Several attempts have been made to investigate the flow theoretically, *e.g.* References 10, 11, and 12, approximating the problem variously to

(a) two-dimensions, *i.e.* an infinite thickness,

(b) a low aspect ratio planing surface

and (c) a viscous region beneath a tyre with a rectangular cross-section.

None have been entirely satisfactory for the wheel in water problem and, consequently, can be of little use in determining the characteristics of the flow in slush.

Numerical methods exist which could, in principle, be extended to the three-dimensional problem of a tyre running in water (see, for instance Reference 13).

5. THE BEHAVIOUR OF SLUSH

Although, above some level of water content slush acts like a fluid, its air content is compressible and the slush cannot be treated as an ideal incompressible fluid. It is necessary to understand how the air behaves in order to be able to predict the behaviour of the slush as a wheel passes through it. Three physical processes are involved, as follows:

- some of the air will be simply released to atmosphere,
- some will be absorbed by the water and
- some will remain as a distinct component in the slush.

The proportion of the air released from the slush to atmosphere is not known but simple considerations suggest that

- the larger the proportion of air in the slush the more likely some will be released and, conversely,
- the more the air is dispersed throughout the slush the less likely that it will be released.

In any case, it is certain that this process is irreversible, *i.e.* once released it will not be returned to the slush. Consequently, the density of the slush will steadily increase towards that of the water/ice mixture.

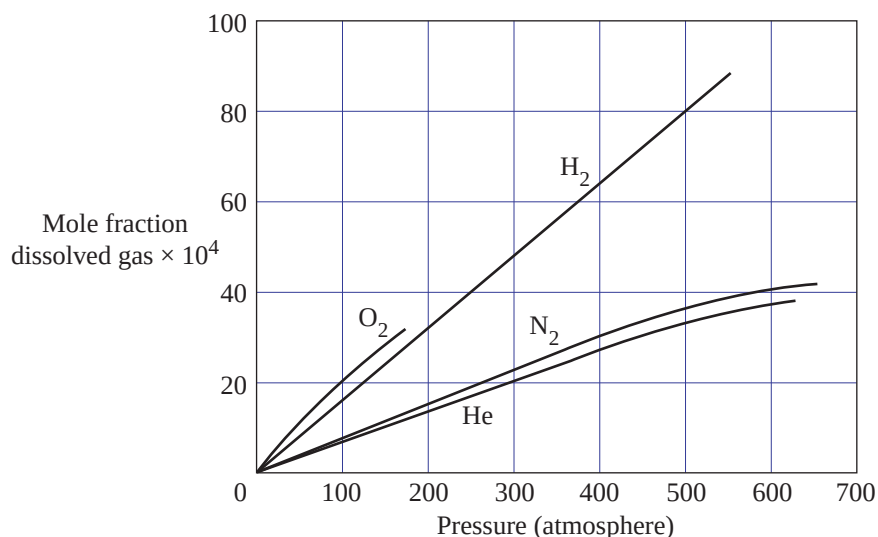
The other two possibilities will be discussed separately in Sections 5.1 and 5.2 and the combined effect will be discussed in Section 5.3.

5.1 Absorption of Air by Water

At atmospheric pressure and at 0°C, a litre of water in equilibrium with air contains 19 ml of nitrogen and 10 ml of oxygen, a total of about 3% by volume.

The solubility of gases in water varies with (a) temperature and (b) pressure, as follows.

- The solubility decreases with rise in temperature; however, this is of no concern here since, with a water/ice mixture, the temperature will remain near 0°C.
- According to *Henry's Law* the mass of gas dissolved by a given volume of a liquid is proportional to the gas pressure. In fact, the variation is not quite proportional to pressure, see Sketch 5.1 (from Reference 14, figures not available for 0°C), but the approximation will be sufficient for the present purposes.



Sketch 5.1 Solubility of gases in water at 25°C as a function of pressure