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FRICTION DRAG REDUCTION (AN SPECULATIVE ESSAY)

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14. Abstract/Notes

The application of gas dynamics concepts can clarify and explain many aspects of aerodynamic phenomena. In the case of friction drag, this approach suggests some new possibilities for its reduction, such as the use of "ultrasmooth" surfaces having specific phusical and chemical characteristics or used in conjunction with a noble gas lubricating layer. Such possibilities are discussed in the text which, due to the multidisciplinary knowledge involved, is kept at a conceptual and heuristic level.

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ABSTRACT

The application of gas dynamics concepts can clarify and explain many aspects of aerodynamic phenomena. In the case of friction drag, this approach suggests some new possibilities for its reduction, such as the use of "ultrasmooth" surfaces having specific physical and chemical characteristics or used in conjunction with a noble gas lubricating layer. Such possibilities are discussed in the text which, due to the multidisciplinary knowledge involved, is kept at a conceptual and heuristic level.

INTRODUCTION

The study of gas motion phenomena has evolved in two distinct sciences: aerodynamics and gas dynamics. In the first, the simplification resulting from the continuum assumption adopted has permitted an enormous evolution, with technological applications going from buildings to vehicles, these ranging from ultralights to supersonic jets.

In gas dynamics the complexity of the discrete gas modelling seems to have hampered an equivalent techonological success. Anyway, the explanation of the reasons and "whys" of any aerodynamic phenomenom seems not to be found without considering the discrete approach, since the real air is far from being a "continuum".

Let us look, for instance, at the characteristics of nitrogen, one of main air constituents, for which we have at S.L. pressure and 15°C [1]:

Molecular dimeter	~ 4 Å
Mean distance betwenn molecules	~ 30 Å
Mean quadratic modelcular speed $\sqrt{\bar{c}^2}$	~ 500 m/s
Mean collision free distance: (λ)	~ 600 Å

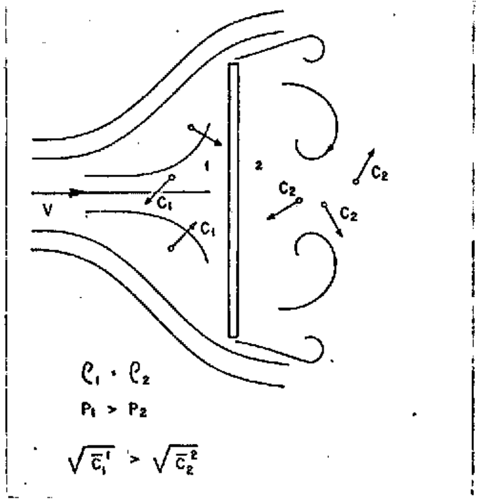
Although oxygem and carbon dioxide molecules present larger diameters, to consider this "empty space" a continuum seems, at a first glance, an oversimplification. However this is fully justified if we consider the time between molecular collisions, $\lambda/\bar{c} \sim 10^{-10}$ s. and the time scale of the aerodynamic phenomena, most of them stationary.

So, the discrete approach with its cumbersome statistical formulation is reserved to cases where the continuum hypothesis fails, such as in rarefied flows, for simplified cases such as couette flows, etc., or simplified computations of continuum "bulk" properties.

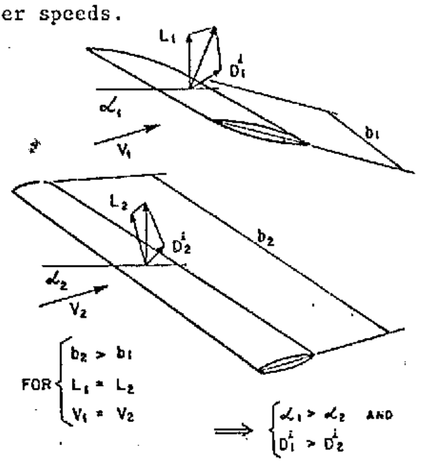
However, the continuum hypothesis assumed for the real corpuscular gas constitution must be present in every aerodynamic study, and one of the main physical realities not to be forgotten is that:

> All aerodynamic forces acting on a body moving in a fluid must result from a momentum exchange between fluid and solid molecules colliding *at body surface*.

This is applicable to lift, pressure drag, etc. including the induced, drag of which many aerodynamic text books give a false physical idea of being created at distance by trailing vortices, like gravity, magnetic or other field forces! In Figure 1 we attempt to show a discrete approach of pressure and induced grad.



In incompressible flow the number of molecules in front of and behind the plate are the same. Molecular speed being function only of pression and temperature, collisions in front of plate occur with higher speeds.



At same speed, the number of air molecules colliding with the shorter span wing is lower (wing area role is negligible). To result in the same lift they must be deflected with a greater angle and drag component is greater.

Fig. 1 - Drag as molecular collision effects.

Concerning friction drag forces, we intend to examine it a little further, in an effort to find new possibilities for its reduction, but when trying to do so, we will be confronted with subjects dealing with solid state and quantum physics, surface science, etc, all outside the aerodynamic and fluid mechanical engineer's as well as the author's experience,

As a consequence, this note was kept only at a conceptual level and was written with the main objective of bringing the attention of the specialists of these fields to points of common interest with aerodynamics.

THE FRICTION DRAG AND THE "NO SLIP CONDITION"

In aerodynamics, the flow generated forces tangential to body surface are called friction forces and their resultant in the flow direction is called friction or surface drag.

For streamlined bodies such as airplanes and gliders, nearly all friction forces act as drag and can represent the major part of the total drag for a cruising airplane or a high speed flying glider, which is not the case for blunt bodies or satellites,

Using continuum fluid mechanics, the friction forces can be computed for various flow regimes and types using the highly developed "Boundary Layer Theory" [2] and the basic relation:

$$\tau = \mu . dV/dy \ ,$$

where τ is the tangential force shear stress and dV/dy is the continuum fluid velocity gradient at the surface normal direction, both computed at the body surface, μ is a fluid property, the viscosity, which leads to an alternative name to the friction drag, that is, viscous drag, and to the corollary assumption that viscosity is the only responsible to this drag!

In reality, when doing so, we take for granted one of the basic hypothesis of the boundary layer theory: the "no slip condition" which states that the continuum tangential flow velocity vanishes at the solid surface, that is, $V \to 0$ when $Y \to 0$,

This no slip condition has been extensively confirmed by tests, holding not only in flows where the "Knudsen number", which relates a flow characteristic lenght to the molecular collision free path, approachs the unit ($\lambda/L \to 1$),

Typical examples are rarefied gas flows and conditions at the very beginning of the boundary layer,

Although fluid dynamics text books quote this no slip condition "en passant" without further explanations, we must recognise its important role to the friction drag onset and that the fluid viscosity role is only to determine how this zero velocity propagates into the boundary layer,

As already said, the momentum exchange which resulted in the friction drag has already acurred at surface in fluid to solid molecular collisions!

All this may be more evident when we consider, for instance the events in a bondary layer of a surface starting from rest.

Since, for usual flows, pressure and, less frequently, temperature are constant across the boundary layer, the surface colliding molecules and the outside boundary layer "free flow" molecules have nearly the same speed, it is intriguing to know why the continuum tangential velocities always vanish even for very smooth surfaces.

Prandtl, who estabilished the boundary layer theory basis, considering experimental effects of roughness on drag, used to ponder that solid surface contained more voids than matter and that fluid molecules, after penetrating these voids, returned to surface having lost all tangential momentum.

Today we know that, although fluid diffusion into solid may occur, solid molecular distances are not so great to allow a generalised penetration, except in pores of macromolecular dimensions.

What seems to happen is that even for a perfectly smooth surface such as that of a single crystal, fluid molecular tangential velocities are broght to zero value by molecular attraction forces kmow as "Van der Waals" forces,

These forces govern the physical adsorption phenomena and in conjunction with the chemisorption forces are fundamental in technological processes such as catalysis, bonding, thin film formation, etc.

Although they are considered "weak" forces when compared to other atomic or molecular forces (see table 1), they result from dipole attractions present in polar fluid molecules or induced in nonpolar ones and have sufficient strenght to bring slip (tangential) fluid molecular velocities to zero.

TABLE 1 - Order of Magnitude of Atomic and molecular forces

ATOMIC FORCES	
NUCLEAR	2000 KeV
NUCLEUS/INTERNAL ELECTRON	20 KeV
NUCLEUS(EXTERNAL ELECTRON	10 KeV
MOLECULAR FORCES	
ION OR "METALIC" BOND	4 eV
VAN DER WAALS BOND	1-7 eV
HYDROGEN	0,5 eV

obs.: 1 eV = 23 Kcal/mol,

The complete model of fluid and solid substrate molecular collision processes is still to be fully developed for liquids or gases, and according to Ref. [3] quantum mechanic models are a must to account for the molecular electron clouds interactions accuring in the collision process.

In most cases adsorption and sometimes chemical reactions may be present so that for practical flows a theoretical complete picture of the no slip condition and any action to modify it seem to be far out of reach of teoretical treatment (See Figure 2).

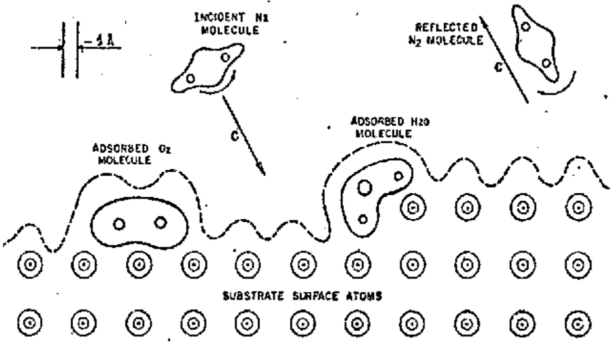


Fig. 2 - Schematic view of single crystal surface and air molecules iteractions.

COULD WE SLIP THE "NO SLIP"?

In our present era of "chips" and semiconductors, the solid state physics, surface and thin film technology have received a tremendous push, which also may help to give an affirmative answer to above headline question.

To study surface characteristics, a highly used tool has been the measurements of surface reflected molecules of a gas beam in vacuum, known as beam scattering tests.

In most cases these experiments show reflected distributions that closely follow the theorical "Maxwellian" or sinus law distributions with zero tangential mean speed.

Other, as in the case of helium over a single crystal halide surface [4], results in lobular distributions which are oriented in the specular direction of the incident beam, that is, they result from *nearly perfect elastic collisions* with the substratum (See Figure 3).

I understand that these results indicate the possibility of obtaining friction drag reductions, with slip flows for atmospheric flight vehicles and low tangential accomodation coefficient flows for satellites.

To better evaluate these possibilities in terms of possible practical applications, two important questions must be posed:

- How to obtain large porous free and at molecular level smooth surfaces?
- How to reduce molecular attraction forces between such surfaces and the air gases molecules?

For the first question, it seems that metal deposition with epitaxial growth film fabrication processes can provide at least a partially satisfactory answer.

Low porosity polymer films such as polyester films which are characterized by a very low gas permeability may offer a good starting substratum.

It is interesting to remark the increased aeronautical use of polyester as films in ultralights and as gel coats and paints for gliders and airplanes.

For the second question, the answer is quite complex due to the already discussed difficulties of modelling the attraction forces and to the presence of air constituents such as water vapour and oxygen.

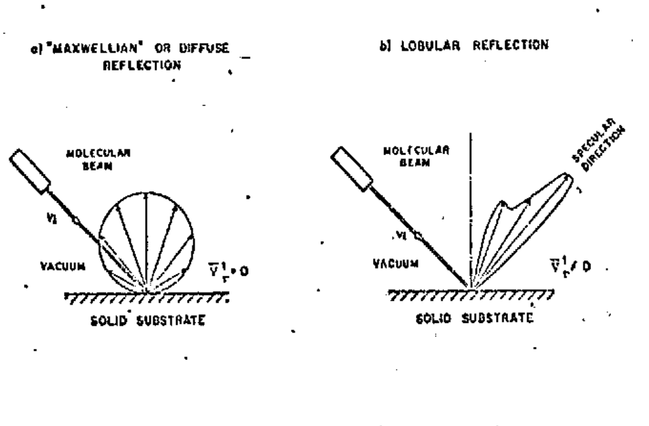


Fig. 3 - Beam scattering experiments,

Also, most of the researches in this area are directed to apposed objectives of increasing attractive force as necessary for catalysis, film growth, etc.

Tests to measure the influence of factors such as surface energy, electrostatic charge, etc. on gas to solid attractive forces, as well as beam scattering tests using air beams, are necessary.

In Table 2 the surface energy of some elements inlcuding some metals are shown. But we know that alloy properties may exceed those of their constituents.

TABLE 2 - Surface Energy of Some Elements

Element	Boiling and melting points		Volume energy		Surface energy	
	T_b (°C)	T_m (°C)	$\log \nu_v$ (monolayers s^{-1})	H (eV)	γ (erg cm^{-2})	η (eV)
Potassium	760	63	13.7	0.93	90	0.05
Sodium	880	98	14.0	1.12	210	0.12
Cadmium	767	321	13.8	1.14	550	0.25
Zinc	907	419	14.0	1.32	830	0.33
Lead	1740	327	13.3	1.99	440	0.25
Bismuth	1560	271	14.5	2.04	350	0.22
Indium	1450	155	14.0	2.46	340	0.18
Silver	2250	960	13.9	2.83	1120	0.43
Tin	2270	232	13.9	3.11	650	0.39
Aluminium	1800	660	14.7	3.28	1050	0.47
Copper	2325	1083	14.0	3.38	1720	0.58
Gold	2960	1063	13.9	3.54	1370	0.60
Chromium	2200	1560	14.1	3.65	2300	0.80
Iron	2590	1536	14.0	3.85	2010	0.70
Nickel	2840	1452	14.7	4.15	1810	0.61
Silicon	2600	1410	13.4	4.41	—	—
Titanium	3000	1800	14.3	4.51	1690	0.74
Platinum	4300	1773	14.2	5.63	2280	0.91
Molybdenum	5560	2620	14.2	6.28	1960	0.80
Carbon	—	—	16.1	7.32	—	—
Niobium	3700	2478	15.2	7.54	2260	1.0
Tantalum	4100	2996	15.0	8.20	2500	1.1
Tungsten	5900	3410	15.9	9.07	1650	1.1

For instance, what about film properties of the chemically inert corrosion resistant; or alloys of beryllium (one of the smallest metal atoms) etc. ...?

In the case of plastic materials, some can be molecularly oriented, blended in copolymers and even made electrical conductors.

Fluorinated plastics widely known by their remarkable low solid sliding friction coefficient present an interesting combination of low surface energy and chemical inertia, and in the case of the CTFE (trifluorochlorethylene) it has a low gas permeability not found in the TFE (tetrafluoroethylene) or teflon.

There is no guarantee that those above mentioned properties will result in the elastic collisions and slip flows we are searching for.

They are only heuristic guesses and the only highly probable successful one will be the combination of them with a lubricating layer of a noble gas. (Figura 4).

In that case neon, having density and viscosity (here not affecting drag!) values closer to that of air, could result in a better interface with it and a more stable lubricating layer.

Such a solution, being far from simple to apply, could at least be considered for intermittent use in brief periods of operations in military airplanes.

In any case, to "slip the no slip" (if ever possible) will result in a great challenge to material scientists, but it will be largely paid in terms of benefits in commercial airplane fuel economies, increased glider performances and satellite increased low orbit lifetimes.

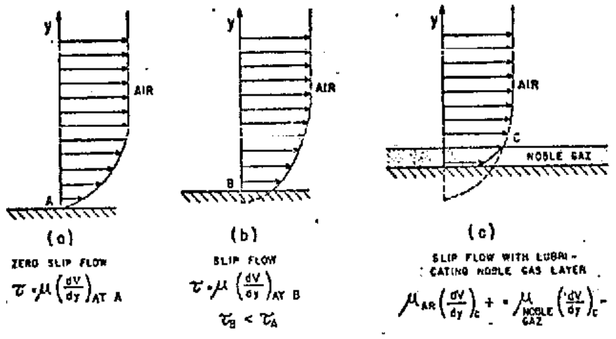


Fig. 4 - Boundary Layer Profiles for Three Flow Types.

In addition, such surfaces will not need the protection means needed for other drag reducing devices such as boundary layer suction, being presently considered.

After all, neither insects nor dust will adhere where the air itsefl will refuse to do so.

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