

FRICTION DRAG REDUCTION (AND SPECULATIVE ESSAY)

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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 "ultra-smooth" surfaces having specific physical and chemical characteristics used in conjunction with a noble gas lubricating layer. Such possibilities are discussed in the text which, owing to the multidisciplinary knowledge involved, is kept at a conceptual and heuristic level.

1. Introduction

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

In gas dynamics the complexity of the discrete gas modelling seems to have hampered an equivalent technological success. Anyway, the explanation of the research and "whys" of any aerodynamic phenomenon seems not to be found without considering the discrete approach, since the real aim 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 diameter	~	4 Å
Mean distance between molecules	~	30 Å
Mean quadratic molecular speed: $\sqrt{C_2}$	~	500 m/s
Mean collision free distance: $(\bar{\lambda})$	~	600 Å

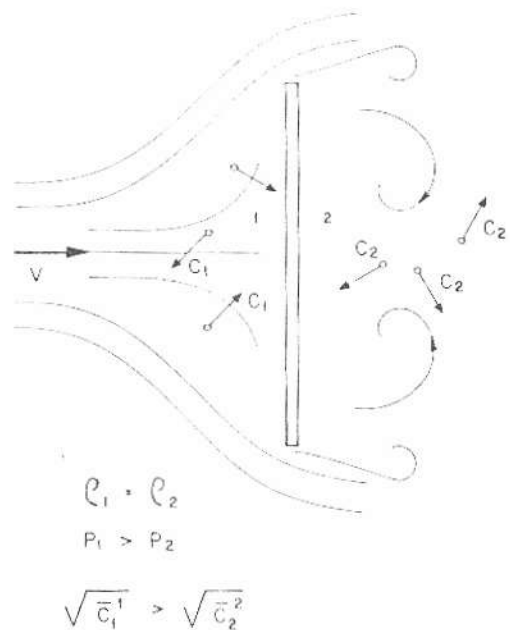
Although oxygen and carbon dioxide molecules present larger diameters, to consider this "empty space" a continuum seems, at a first glance, an oversimplification. However, this is fully justified if we consider the time between molecular collisions, $\lambda/c \sim 10^{-10}$ s, and the time scale of the aerodynamic phenomena, most of them stationary. Hence, the discrete approach with its cumbersome statistical formulation is reserved for 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:

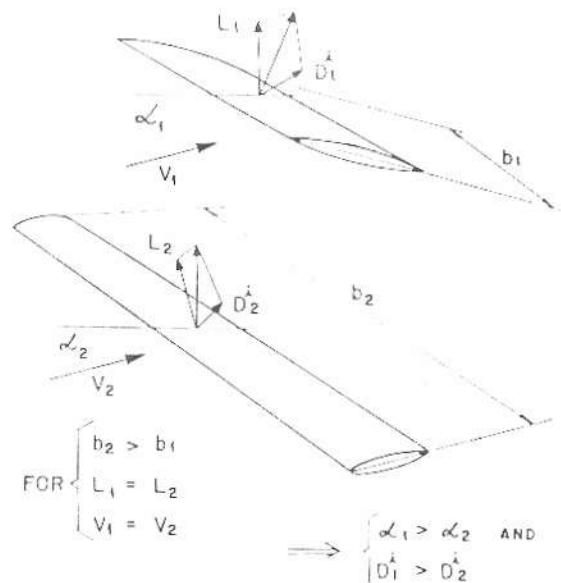
All aerodynamic forces acting on a body moving in a fluid must result from a momentum exchange between fluid and solid molecules colliding at the body surface.

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 explanation of pressure and induced drag.

Concerning friction drag forces, we intend to examine it a little further, in an effort to find new possibilities for its



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



At the 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 the drag component is greater.

FIGURE 1. Pressure and induced drag as molecular collision effects.

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 has been kept at a conceptual level and written with the main objective of bringing the attention of the specialists of these fields to points of common interest in aerodynamics.

3. The Friction Drag and the "No-Slip Condition"

In aerodynamics, the flow-generated forces tangential to the 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:

$$\tau = \mu \cdot dV/dy$$

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. The latter leads to an alternative name to the friction drag, that is, viscous drag, and to the corollary assumption that viscosity is solely responsible for this drag.

In the above, we take for granted one of the basic hypotheses of the boundary layer theory: the "no-slip condition" which states that the continuum tangential flow velocity

vanishes at the solid surface, that is, $V \rightarrow 0$ when $Y \rightarrow 0$. This no-slip condition has been extensively confirmed by tests, holding not only in flows where the "Knudsen number," which relates a flow characteristic length to the molecular collision free path, approaches the unit ($\lambda/L \rightarrow 1$). Typical examples are rarefied gas flows and conditions at the very beginning of the boundary layer.

Although fluid dynamics textbooks quote this no-slip condition "en passant" without further explanations, we must recognize 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 occurred at the surface in fluid to solid molecular collisions.

All this may be more evident when we consider, for instance, the events in a boundary 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 established the boundary layer theory basis, considering experimental effects of roughness on drag, suggested that solid surfaces contained more voids than matter and that fluid molecules, after penetrating these voids, returned to the surface having lost all tangential momentum. Today we know that, although fluid diffusion into a solid surface may occur, solid molecular distances are not so great to allow a generalized penetration, except in pores of

TABLE 1
ORDER OF MAGNITUDE OF ATOMIC AND MOLECULAR FORCES

ATOMIC FORCES	
NUCLEAR.....	2000 KeV
NUCLEUS/INTERNAL ELECTRON.....	70 KeV
NUCLEUS/EXTERNAL ELECTRON.....	10 KeV
MOLECULAR FORCES	
ION OR 'METALLIC' BOND.....	4eV
VAN DER WAALS BOND.....	1-7 eV
HYDROGEN (OR CO-VALENT).....	0,5 eV

NOTE: 1 eV=23 Kcal/mol.

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 brought to zero by molecular attraction forces known 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, painting, 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 strength to bring slip (tangential) fluid molecular velocities to zero.

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 occurring 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 out of reach of theoretical treatment (See Figure 2).

4. Could We Slip the "No-Slip"??

In our present era of "chips" and semiconductors, the solid state physics, surface science and thin film technology have received a tremendous push, which also may help to give an affirmative answer to the above headline question. To study surface characteristics, a much used tool has been the measurements of surface reflected molecules of a gas beam in vacuum, known as beam scattering experiments (see Figure 3). In most cases, these experiments show reflected distributions that closely follow the theoretical "Maxwellian" or sinus law distributions with zero tangential mean speed. In others, as in the case of helium over a single crystal halide surface [4], there are 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.

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

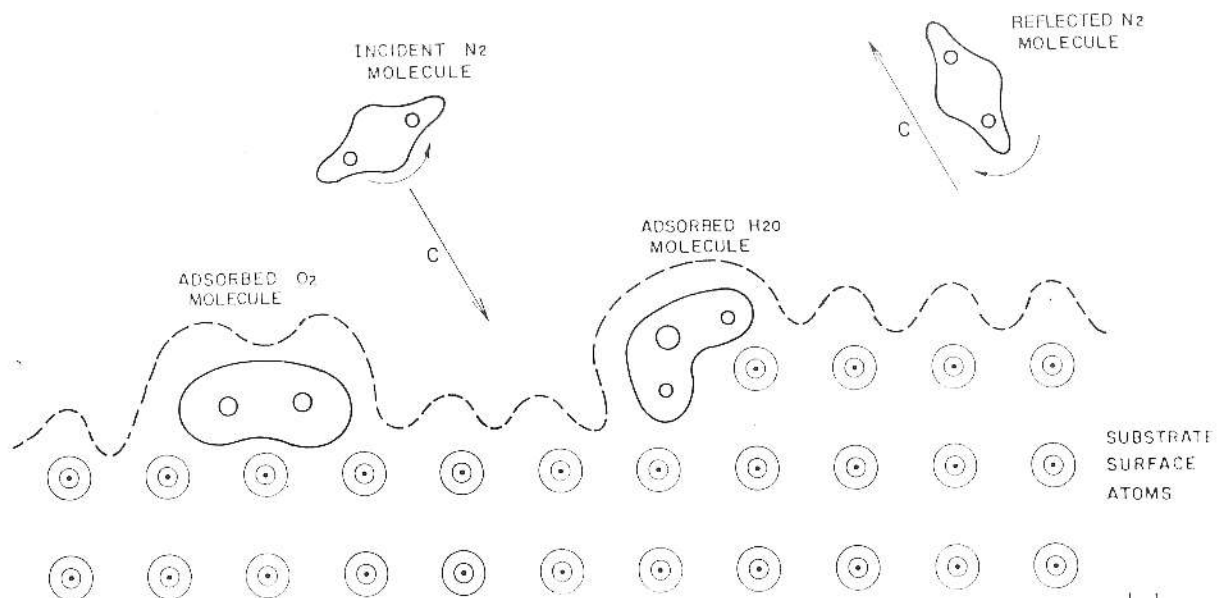
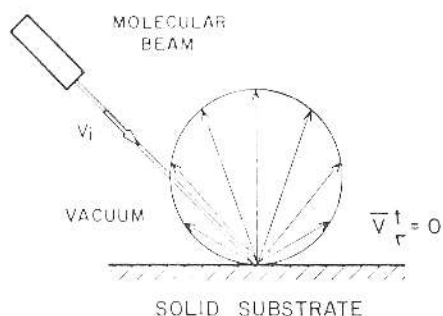


FIGURE 2. Schematic view of single crystal surface and air molecules interactions.

a) "MAXWELLIAN" OR DIFFUSE REFLECTION



b) LOBULAR REFLECTION

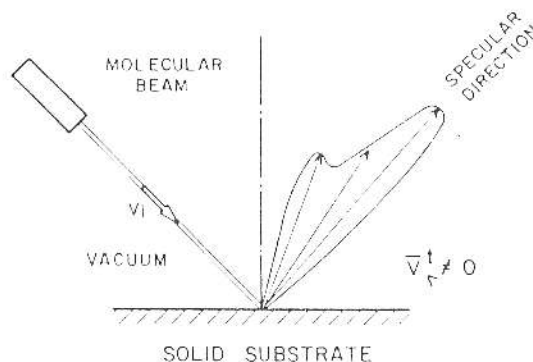


FIGURE 3. Beam scattering experiments.

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. Also, most of the research in this area are directed to opposed 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 including some metals are shown. But, we know that alloy properties may exceed those of their constituents. For instance, what about

film surface properties of the chemically inert corrosion resistant alloys of beryllium (one of the smallest metal atoms) alloys, 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 remarkably low solid sliding friction coefficient present an interesting combination of low surface energy and chemical inertia, and in the case of CTFE (trifluorochlorethylene), it has a low gas permeability not found in TFE (tetrafluoroethylene) or teflon.

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

TABLE 2
SURFACE ENERGY OF SOME ELEMENTS

TABLE 2. Boiling point T_b , melting point T_m , volume energy parameters v_m and H derived from thermodynamic and vapour pressure data (Still and Stone, 1956), and surface energy parameters γ and H derived from surface tension (Smithells, 1955) or creep (Stern, 1971) measurements, just below the melting point, in order of sublimation energy ($s = 0^1$ is the area per atom)

Element	Boiling and melting points		Volume energy		Surface energy		Rates	
	T_b (°C)	T_m (°C)	$\log v_m$ (monolayers s^{-1})	H (eV)	γ (erg cm^{-2})	γ (eV)	H γ	$\frac{s}{H}$
Potassium	760	63	13.7	0.93	90	0.08	11.5	0.09
Sodium	880	98	14.0	1.12	210	0.12	9.3	0.11
Caesium	767	321	13.8	1.14	550	0.25	4.6	0.21
Zinc	907	419	14.0	1.32	830	0.31	4.0	0.25
Lead	1740	327	13.2	1.24	440	0.25	8.0	0.12
Bismuth	1560	271	14.5	1.24	380	0.22	9.3	0.11
Iridium	1450	155	14.0	2.46	340	0.15	13.7	0.07
Silver	2200	960	13.9	2.83	1170	0.48	5.9	0.17
Tin	2270	232	13.9	3.11	680	0.39	8.0	0.17
Aluminium	1800	660	14.2	3.28	1080	0.47	7.0	0.14
Copper	2325	1083	14.0	3.38	1320	0.58	5.5	0.17
Gold	2960	1063	13.9	3.54	1390	0.60	5.9	0.17
Chromium	2200	1860	14.1	3.65	2300	0.80	4.6	0.21
Iron	2890	1536	14.0	3.85	2000	0.70	5.5	0.18
Nickel	2810	1452	14.7	4.15	1810	0.61	5.8	0.15
Silicon	2600	1410	15.4	4.44	—	—	—	—
Titanium	3000	1800	14.3	4.51	1690	0.74	6.1	0.15
Platinum	4300	1773	14.2	5.63	2250	0.91	6.2	0.16
Molybdenum	5560	2620	14.2	6.73	1960	0.80	7.8	0.13
Carbon	—	—	16.1	7.52	—	—	—	—
Niobium	3700	2478	15.2	7.54	2260	1.0	7.5	0.13
Tantalum	4100	2996	15.0	8.20	2500	1.1	7.5	0.13
Tungsten	5900	3410	15.9	9.07	1650	1.1	8.2	0.12

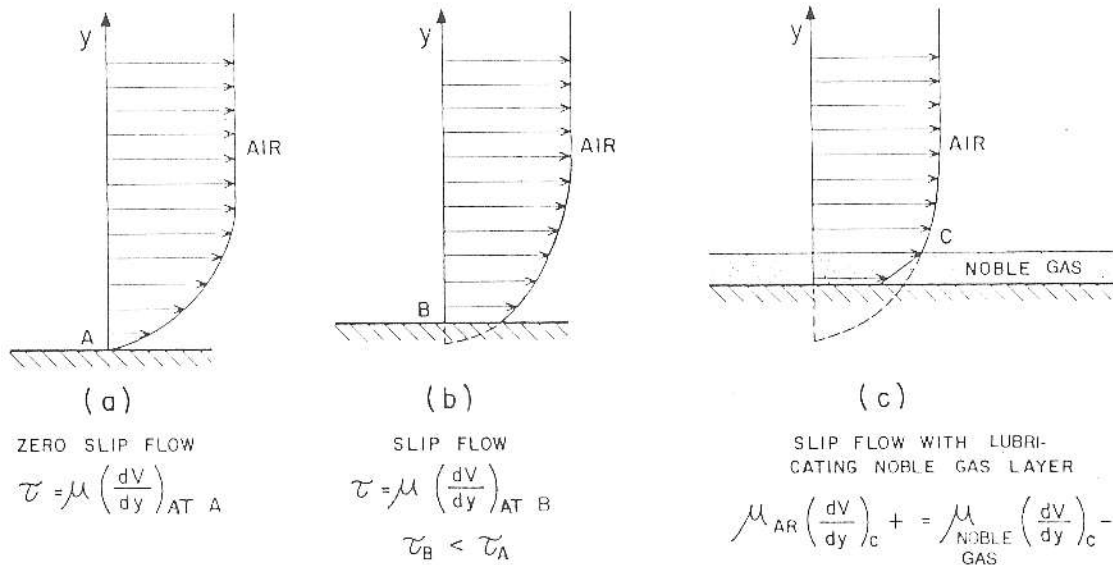


FIGURE 4. Boundary layer profiles for three flow types.

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 (see Figure 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.

5. References

- [1] VICENTI, W.G. and KRUGER, JR., C.H. "Introduction to physical gas dynamics" Robert E. Krieger Publishing Co., 1965.
- [2] SCHLICHTING, H. Boundary Layer Theory — MacGraw Hill Int. Book Co.
- [3] LEWIS, B. and ANDERSON, J.C. "Nucleation and Grow of Thin Films" Academic Press, 1978.
- [4] GOODMAN, F.O. and WACHMAN, H.Y. "Dynamics of gas surface scattering" Academic Press, 1976.
- [5] PATTERSON, G.N. "Molecular nature of aerodynamics" Utias Publication 1981.

In any case, to "slip and 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. 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 itself will refuse to do so.