Aerodynamics at the Particle Level

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Preface

The purpose of this work is to examine the causes of fluid behavior. While the standard approach to fluid dynamics, which is founded on the "fluid approximation," is effective in providing a means of calculating various behavior and properties, it begs the question of causality. This is because it cannot account for the interaction of the fluid either with itself, other fluids, or with solid bodies. The old Logical Positivist approach to the behavior of fluids precluded models that included elements not directly observable. Ludwig Boltzmann was castigated for pursuing Statistical Mechanics, a theory based on invisible particles. (String Theory would certainly have been dismissed by the Vienna Circle, a stronghold of the Logical Positivist school of thought.)

It is not clear that Boltzmann believed in the literal existence of the invisible particles but, "acting as if" they existed, he, Paul Ehrenfest, and others developed a theory which, despite calculational difficulties, provides a way of understanding Thermodynamics in the light of the relatively simple behavior of particles. Those early workers may not have taken the particle model seriously, as evidenced by the problems they encountered when they tried to consider the trajectories of the particles. They apparently assumed point particles and hence, as also was the case later with point-particle quantum mechanics, ran into mathematical difficulties. The trajectories of such colliding particles would not be differentiable and the probability of any collision at all would be zero. As we know now the particles *are* real and so have finite dimensions and even internal structure. Similarly, for fluid mechanics, a particle model is crucial for a basic causal understanding.

Introduction

The behavior of real fluids, i.e. compressible and viscous, is to this day baffling in many ways. Part of the reason seems to be that explanations of fluid behavior are based on the old belief that a fluid is a fundamental entity, not made of anything else. The trouble with this approach is that it provides no way of understanding how the fluid interacts with itself or with solid bodies other than just to list results of experiments. However since the work of Boltzmann and Einstein, i.e. theory based on the postulate that fluids are composed of tiny particles, deeper insight is possible by considering the interactions of these particles with each other, those of other fluids, and those of solid bodies in the flow. In fact it may be helpful to remember that the only interactions a fluid can have, according to this model, are through momentum transfer or van der Waals forces between its particles[1]. The molecules of a gas at standard pressure are only within van der Waals distance 1/100th of the time they are apart so these forces only play a part in particle-particle scattering. The notion that a streamline in a gas flow is "attracted" by a surface is not correct. If a stream of gas, as in Coanda flow, seems attracted to a solid object it is due to its self-interaction, interaction with gas outside the flow, and the forces its particles exert on the surface as they strike it. In contrast to the work of Bernoulli, there is no "Coanda equation." Coanda observed effects that are widely incorporated into modern aerodynamic design but physicists have not developed a tractable mathematics to describe the behavior of such a large number, $\sim 10^{23}$, of simple interactions.

Although Bernoulli's equation employs densities as factors in the potential and kinetic energy terms, the equation is only valid when the fluid can be assumed incompressible and non-viscous because compression heating and viscous interactions create heat energy. To account for this energy, thermodynamics would have to enter the equation and a thermodynamic process be identified. This process, in general, would vary in unpredictable ways.

In addition, no fluid must enter or leave a Bernoulli stream tube through its sides. In the tube there is no shear of the fluid. And finally, since the flow must be laminar, the tubes themselves must have a smooth, gently varying shape. These assumptions preclude turbulence or eddy formation or, indeed, any interaction at all. They allow for the calculation of some general behavior of simple flows but because of these assumptions the theory is not able to explain *how* aerodynamics works. This is because these assumptions amount to denying any interaction of the

[1] We do not consider plasmas, which are affected by long-range electromagnetic forces.

fluid either with a solid object or with itself. It is these very interactions, however, which are the causes of aerodynamic effects.

Aerodynamic forces affecting a rigid surface are always net forces produced by pressure differentials between different parts of the surface. The pressure on a surface area element is the density of the *normal components* of the forces acting on the surface there.

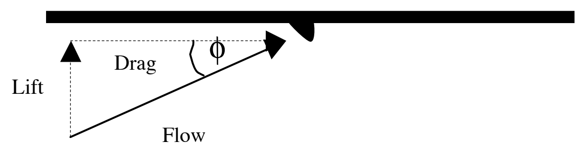

Figure 1

Aerodynamic forces on a body are caused *only* by collisions of fluid particles with the body's surface[2]. At the molecular level, the flow particles encounter any surface as a molecular structure which is rough, with protuberances whose size is of the order of magnitude of the flow particles themselves (see Figure 1 above). As particles collide with the surface, their momentum components normal to the surface there cause lift, positive or negative, and stagnation pressure and the parallel components cause viscous drag (and give rise to a "boundary layer" which is carried along by the surface). It is clear, then, that the microscopic structure of the surface and the properties of the fluid will affect drag and lift, even for $\phi = 0$. A perfectly smooth surface would have no viscous drag, and, it would appear, a wing made of this material would have lift only if the air flow momentum density had components normal to the bottom surface of the wing, i.e. due to the angle ϕ.

Even though these momentum transfers occur only in the boundary layer that appears to be "dragged along" by the surface, they are responsible for the whole of lift and drag. Actually, fluid particles can leave and enter the boundary layer by moving normal to the surface. Dust on a surface in a flow is not disturbed laterally because the distribution of the components of the boundary layer particles' momenta parallel to the surface has zero mean, i.e. in any small patch of the boundary layer the sum of the particles' velocity components parallel to the surface is zero. As we will see, the boundary layer is kept in place by the interaction of the main flow particles with particles bouncing off the surface. For the time being, we

[2] The Coanda effect in liquid-surface flow, however, may be caused in large part by van der Waals' forces, which are attractive.

assume that all collisions, particle-particle and particle-surface, are perfectly elastic and that the particles are spheres.

Let us consider the unphysical situation in which a surface has no boundary layer, i.e. the particles in the flow that impact the surface do so specularly and perfectly elastically. The surface is perfectly smooth. The pressure on the surface, of course, is due only to the normal components of the momenta of the impacting particles. Flow tangent to such a surface will not exert or affect surface pressure[3]. Pressure on the surface, as on a real surface, is due to collisions of particles with the surface if the flow momentum density has a component normal to the surface[4]. Where the flow has no normal component, the pressure is due only to the thermal motion of the particles in the boundary layer, i.e. the static atmospheric pressure. Hence this pressure will be a function only of the mass of a particle, the particle density, and Kelvin temperature at the surface.

In reality, the fluid particles in a layer around a surface boundary seem to be carried along with the surface, i.e. the distribution of the components of their velocities parallel to the surface is circularly symmetric about the velocity of the surface relative to the free-stream velocity[5]. However, particles continually leave the boundary layer and enter it transversely from the flow due to heat energy[6] and the kinetic energy of the flow towards the surface. Beyond a mean free path[7] or so but still in the boundary layer, the distribution of the normal components of particles' velocities moving toward or away from the surface will depend on the temperature and density of the particles as well as on the variation of the velocities of particles far from the surface. The latter effects are retarded in time and propagate into the boundary layer with the speed of sound (a thermodynamic property) in the fluid. Even though it is regularly driven at high speed, a car will accumulate dust on its body. An air stream directed toward the surface, however, will blow off some of that dust. As we will see, it is the mutual interaction of flow particles and these "stagnant" boundary layer particles that is responsible for a part of the lift on an airfoil at subsonic speeds.

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[3] Place a sheet of paper flat on your hands. Blow over the top surface of the paper. This experiment refutes the notion that the pressure in a free flow is less than the ambient static pressure. Bernoulli flow is confined to a tube and not free.

[4] There may be a small pressure effect on the surface when the particles of the tangential flow strike protuberances and are projected away.

[5] This property of fluid flow was utilized by Nicola Tesla in his unique design of a rotary pump.

[6] It can be seen, then, that dust particles on a surface in an air flow are not disturbed not because the fluid particles are necessarily entrained but that they come and go normal to the surface. Hence they do not impart lateral forces to the dust particles.

[7] $\sim 9 \times 10^{-8}$ meters for N_2 at standard pressure and temperature.

An increase in the free-stream velocity means that the components of the velocities of the flow particles increase in the direction of the free-stream velocity and parallel to the surface. The reason that the boundary layer remains quiescent, or stagnant, is that the components of the colliding particles' velocities parallel to the surface reverse as they collide with microscopic irregularities. This causes aerodynamic drag and accounts for the fluid's viscosity[8]. If the collisions are not perfectly elastic, the rebound speed is less than the incident speed and the surface absorbs some of the particle's energy, i.e. it heats up.

Bernoulli at the particle level

Bernoulli's equation does not apply over a free surface because particles can move lateral to the flow, violating a Bernoulli assumption. Think of a pressure vessel of a non-viscous gas feeding a Bernoulli tube (a real one, glass). Before flow starts, the energy in the vessel is equally distributed between the 3 degrees of freedom. When the fluid is vented into a tube, the pressure in the high-velocity section is less than that in the vessel. Entropy decreases and the temperature drops in the exit tube as the flow becomes more orderly, i.e. thermal energy changes to the kinetic energy of the orderly translating particles.

The reason that the pressure in the exit tube is less than in the vessel at that level is that the only particles that exit into the tube are those with velocity components in the exit direction. Of course these particles exert a pressure lower than that of the vessel since they are selected for their momentum components being outward into the tube. Because energy is conserved, these particles' initial energy density is now apportioned between pressure on the walls of the tube (manometer pressure) and the kinetic energy density of their velocity in the tube, $\frac{1}{2}\rho v^2$. This means that there will be a lower manometer reading in the exit pipe than in the vessel. The pressure difference between the vessel and the end of the exit pipe allows the flow of the exiting particles. Bernoulli's equation, where the exit tube is in the x-direction, is

$$P_{vessel} = \frac{1}{2}\rho(v_x^2 + v_y^2 + v_z^2) = P_{tube} + \frac{1}{2}\rho v_x^2,$$

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[8] Though viscosity is supposed to be a property of the fluid, it is measured by the terminal velocity of a ball in the fluid or the force it takes to slide two plates with the fluid between them. Viscosity, then, has to do with the interaction of the fluid with itself as well as with solid bodies.

where $P_{tube} = \frac{1}{2}\rho(v_y^2 + v_z^2)$ is the pressure at the tube walls, holds, at least approximately.

At the exit orifice, it is just those particles that are moving toward the hole that actually exit. The hole is a sorting mechanism hence the entropy decreases in the exit flow. This sorting process at the exit selects particles that will give a lower pressure when that pressure is measured at an orifice whose plane is parallel to the flow, like a manometer connection.

Vortex fluid motion

As a fluid stream passes through an opening in a wall, eddies appear behind the wall. Consider the state of the fluid as the flow begins. Behind the wall the distribution of velocities of the particles of the fluid in a small volume is spherically symmetric (except for the effect of gravity) and the mean of the distribution is a function of the Kelvin temperature.

For example, let the lower half of the *y-z* plane be a barrier in the fluid. The velocity of the flow will be superimposed on the random motion due to heat. As the flow begins, say from minus to plus in the *x*-direction, the mean of the distribution of the velocities of those particles in the flow will be shifted toward positive v_x. As these particles pass the barrier, they collide with fluid particles that have a velocity distribution with zero mean, i.e. the particles are stagnant.

Call an impact parameter positive if the location of the impact point with a particle in the flow is a positive distance in *y* from the center of one of these particles. If it passes the edge of the barrier with sufficient speed, a flow particle is likely to hit a particle behind the barrier with a positive impact parameter. This will result in the stagnant particle being knocked back behind the barrier (See Fig. 2a below.). The flow particle will be deflected up into the flow, with reduced momentum where it will be deflected by other particles in the flow and eventually be knocked back, away from the flow (Fig. 2b). These particles still have an *x*-component of velocity that is larger than their *y-z* velocities but as they interact with each other and other particles in the flow in the way described above, they will move on a circular path; "go a little, turn a little" and their energy will be decreased. This process repeated statistically with various impact parameters results in a vortex. We will call it the *vortex process*.

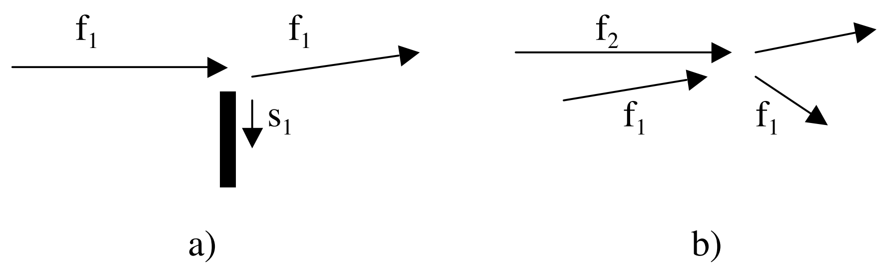


Figure 2

Consider a velocity coordinate system local to a flow particle that passes very close to the barrier and with its *x*-axis in the flow direction. Initially, that system will be aligned with the coordinates mentioned above. As time goes on after the particle has passed the *y*-*z* plane, the local system will, on average, rotate around its *y*-axis. One can see in this way that the effects of this interaction with the stagnant molecules will propagate into the flow on the downstream side of the barrier. The result, for a sufficiently high flow velocity, is a vortex.

Vortex refrigerator

A device called a vortex refrigerator consists of a cylindrical chamber into which a gas is injected tangentially. Gas is then drawn off, cold, from the axis of the cylinder and hot from its periphery. The cold molecules are separated from the hot by the process outlined above for vortex flow in Figure 2 above.

The low-energy particles are sorted from the rest by the process that creates and sustains the vortex. This means that the pressure in the center of the vortex is lower than the static pressure outside. The centers of hurricanes are regions of low pressure. In the great hurricane of 1900 that struck Galveston, Texas, the pressure was the lowest ever recorded up to that time. If the hurricane is over water, this low pressure causes what is called "storm surge." The water in the center of the hurricane is pushed up because of the low pressure there and the higher pressure outside the center. In the case of Galveston, this storm surge caused most of the damage to the city.

Behavior around obstacles

When free-stream flow encounters a barrier, the flow ceases there, i.e. the distribution of velocities is spherically symmetric, at least far from any exit around the barrier. Upstream, the pressure behind the barrier is higher than the pressure behind the exit. For a fast flow, a particle on a streamline just grazing the barrier encounters particles behind that barrier whose mean velocities are zero. Downstream of the barrier, the result of collisions with these stagnant particles is the slowing of a flow particle as well as its deflection back into the flow. (See Figure 2 above.) The question now is, what are the circumstances for vortex formation?

The thermal particle will, on average, be deflected away from the flow if the speed of the flow is

$$v_S \geq \delta \times \frac{v_T}{r}$$

where

δ = the mean free path in the flow,
v_T = the thermal speed of stagnant particles,
r = particle radius,
v_S = the speed of the flow.

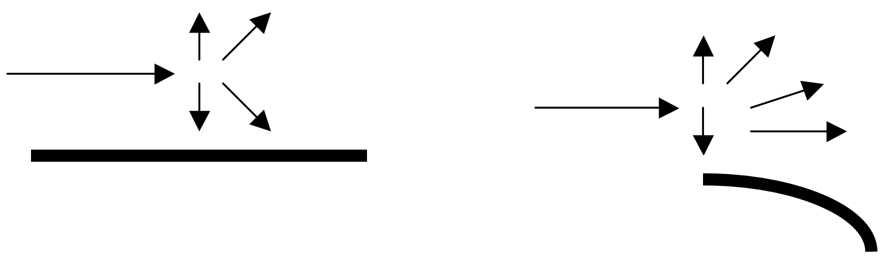
In this case a vortex will form.

Consider two particles with radii $r = 6.2 \times 10^{-10}$ m: a stream particle and a stagnant particle. The stagnant particle moves due to thermal agitation at $v_T = 8.6 \times 10^{-2}$ m/sec (at a Kelvin temperature of 292°) and has a mean free path of about $\delta = 10^{-7}$ m (at 1 atm. pressure). At this temperature, then, the speed of the flow would have to exceed about 1.4 m/sec in order for a vortex to be formed. The reasoning is as follows. Under these conditions, a stagnant particle moving normal into the flow, which has just missed being hit by a stream particle, will be hit by another stream particle at an impact parameter greater than zero. If the flow speed is much greater than the thermal velocity in the stagnant region, the stagnant particle will be deflected away from the flow at a speed not much different from its speed before the collision. The impacting stream particle will be deflected into the flow but at a speed less than the flow speed, i.e. it has given some of its energy to the particle that was deflected out of the stream. It will then be hit from behind by other flow particle(s) at a positive impact parameter.

The greater the difference between the flow velocity and the thermal velocities of the stagnant particles, the closer to 90° from the flow direction will be the directions of the stagnant particles after the collisions. Thus the interaction between the stream and the stagnant region serves to sort out the colder stagnant particles and force them away from the flow. The vortex heat pump described above uses this principle.

As the stream particles that have suffered collisions with stagnant particles are hit by faster ones in the stream, they too are deflected with a velocity component normal to the stream velocity. As they continue after being deflected away from the stream, they hit other stagnant particles, forcing them toward the same center. The result is that part of the flow is changed into a vortex. If the obstruction is a hole in a plate, some of the energy of the flow is trapped in the form of a vortex ring. If the flow is a pulse, this ring follows in its wake.

Fluid Flow over a Curved Surface: The Coanda Effect



a) b)

Figure 3

In a steady flow over a surface, stream particles have only thermal velocity components normal to the surface. If the surface is flat, the particles that collide with boundary layer particles are as likely to knock them out of the boundary layer as to knock others in, i.e. the boundary layer population is not changed and the pressure on the surface is the same as if there were no flow. If, however, the surface is curved in a convex shape, the particles in the flow will tend to take directions tangent to the surface, i.e. away from the surface, obeying Newton's first law. As these particles flow away from the surface, their collisions with the boundary layer thermal particles tend to "blow" those particles away from the surface. What this means is that if all impact parameters are equally likely, there are more ways a collision can result in a depletion of the boundary layer than an increase in the boundary layer population. The boundary layer will tend to increase in thickness and to depopulate; the pressure will reduce there. Those particles in the flow that do interact with the stagnant boundary layer will give some of their energy to particles there. As they are deflected back into the flow by collisions with boundary layer particles, they are, in turn, struck by faster particles in the flow and struck at positive impact parameters. They are thus forced back toward the surface. This is how the flow is “attracted” to the surface, the Coanda effect[9].

The flow shears past the surface (where the fluid velocity vanishes) and the fluid velocity as a function of the distance normal to the surface is a smooth function of this distance. The curve parameters are constants depending on the physical characteristics of the surface and the particles making up the fluid. In any case, as the flow velocity increases, separation points will begin to appear. These are the points on the surface where the derivative of the fluid velocity with respect to the normal distance vanishes. As the fluid velocity increases even further, the derivatives at the separation points actually reverse sign, there is backward flow on the surface. Vortices have formed downstream from these stagnation points. All this is in the language of fluids. What is going on at the particle level though?

The curved part of the surface acts as the obstruction mentioned in the explanation of vortex rings because it presents stagnant particles to the flow. The flowing particles as they approach the surface interact with these particles and with the surface itself. Some populate the “boundary layer” and then interact as stagnant particles with other particles in the flow. There is a constant interchange of particles between the boundary layer and the flow. As these interactions take place the process described above tends to cause the flow to envelop the surface. When the surface curves away from the flow, the flow particles, obeying Newton’s first law, tend to travel on trajectories tangent to the surface and thus leave its vicinity. The particles in the boundary layer that would escape to infinity if there were no flow now escape more into the flow, they are “blown away.” There are fewer collisions with the surface and hence less drag force and more lift due to pressure from the other side of the surface.

Stalling wing

As the flow velocity increases, the “secondary” collisions that affect the flow particles slowed by collisions with boundary layer particles cause the slowed flow particles to be more violently knocked back toward the surface by the main flow. When they start to hit the surface itself, the forces on the surface there increase.

[9] This explanation suggests experiments exploring the structure at the edge of the main flow that is away from the wall. The explanation of the mechanism by which the flow is “attracted” to the wall implies how the flow should behave at its other edge too.

The wing is stalling. As the velocity increases still further, the flow near[10] the surface reverses itself and flows back along the wing and also increases the boundary layer population there. The flow is said to separate at the point where the backward flow rate equals the forward fluid velocity there. Downstream from this point, a vortex has formed.

Vortex Street formed behind a Cylinder

The following two pictures from the URL below show the von Karman vortex street phenomenon. The wind starts at the dark areas.

http://www.space.com/scienceastronomy/planetearth/vortex_street_001213.htm l

[10] At the surface the flow velocity is zero. The derivative of the flow velocity in the direction normal to the surface vanishes at the so-called separation point on the surface. Downstream of this point the particles just above the surface are flowing in reverse of the flow.

Using the particle approach as outlined above, let us see what is happening. We always have to keep in mind that these effects are caused by the interaction of the particle flow with the solid object and with itself. See Figure 4 below for a drawing of a cylinder in a flow.

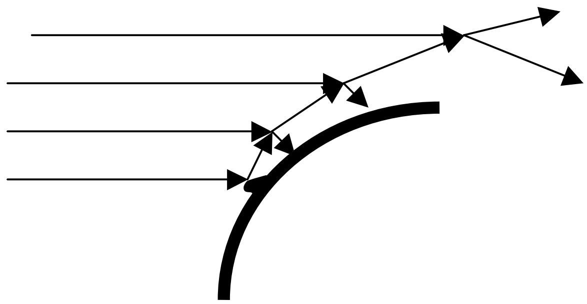


Figure 4