Kinetic theory and lift

I found Stuart 'Supercool' Sherlock's item about Isaac Newton and aerodynamics under the heading 'Fluid or Molecules' on page 63 in the February 2017 Aeromodeller very thought-provoking. Those who listen to Cabin Pressure on Radio 4 will remember the hapless Arthur telling the crew that no-one really knows how planes can fly. They all tell him he's wrong but don't explain why. In the end Arthur is given the classic explanation involving air speeding up over the longer upper surface causing a pressure drop and hence lift. He then says 'So 'planes can't fly up-side-down then?'. Let's try to answer Arthur's question.

Kinetic theory of gases and impulse

For those who are not familiar with this here is a brief summary. All gases are made up of tiny molecules, which we call particles. At sea level the volume of the particles is about one thousandth of the volume of the gas. They move at random, on average at the speed of sound. They bounce off each other and solid objects. The hotter the gas the faster the particles move. Gases store heat energy in the form of this kinetic energy which increases with the square of their speeds. The particles do not stick to each other but adhere a little to a solid surface. Hence the boundary layer on a wing. They bounce perfectly elastically, so no energy is lost that way.

Lift is a force. Stuart's idea was to analyse lift in terms of molecular motion as Isaac Newton apparently did. I started to wonder if this would help us understand lift better. Newton was fond of particles. He also said that light was particles, which made everyone fall about, until the discovery of photons.

Newton showed that force is the result of change in momentum. Momentum is mass times velocity mv. When a particle bounces off a solid boundary it imposes an impulse on it. An impulse, according to Newton, is a change in momentum and is equal to force times the time of contact. Newton's equation therefore is impulse Ft = mv. Divide through by t. As v/t is acceleration we get to the modern version of Newton's Second Law which is F = ma. Forces, like all vectors, can be resolved into two (or three) components at right angles to each other.

The atmosphere

We are at the bottom of a roughly 20 km deep sea of air. At sea level the forces from the air particles are high, though our bodies are adapted to it so we don't notice it. A cubic metre of air has a mass of about 1 kg. So a one square metre column of air 20 km high has a mass of 10 000 kg assuming the density steadily drops to zero. So each square metre has a pressure of about 100 000 pascals on it due to this air piled up on top of it. Each pascal is a newton per square metre. A newton (N) is the weight of a 100 g medium apple (nice!). A kilogram weighs ten newtons. So each square metre has 100 000 apples on it or 10 000 kg as suggested above. You can see that you only need a small change in this to create a large force. To generate a lift force of 1kg (10N) on a surface area of one square metre you only need a pressure difference between the upper and lower surfaces of 10/100 000 or a hundredth of one percent. A 5 kg model with a wing area of 0.5 m^2 will only need a 0.1% difference.

Yes, I had to check the data for that percentage figure again when I calculated it. So I tried again in old terms where atmospheric pressure is 14 lb/square inch. There are 1550 square inches in a square metre. So there are 1550 x 14 or about 22 000 lb force. There are 2.2 lb in a kg so the answer is again about 10 000 kg and 100 000 N. Phew!

It's all particles

From now on we will only think in terms of particles not pressure. Does this help our understanding? Each wing surface has a force on it from the sum of the particle impulses. Some particles hit vertically but most bounce at an angle. In this case a proportion of the force acts vertically on the surface, called a component. When stationary the upward and downward forces are the same so there is no lift. If there is to be lift the sum of these components acting down must be less than those acting up. This can be both from the number and the size of the impulses.

Particles in a hotter gas move faster. They can be speeded up by being hit by a surface moving towards them so increasing their speeds. That is how a diesel engine works. The rising piston hits and speeds up the particles. This heats the gas until it reaches the ignition temperature for the fuel. As the hot gas pushes the piston down the piston surface moving away means the particles bounce back more slowly. This lowers the gas temperature and and the piston absorbs the kinetic energy. It is also why the skin of a fast moving aircraft heats up.

Of course a wing has a thin stationary boundary layer attached to it. However it would seem logical to treat this layer as the surface of the wing as any impulses will be passed on at the speed of sound. This is similar to the fact that a surface that feels hard is actually mostly empty space made to feel hard by the repulsion between the outer layers of electrons on the surface and the finger pushing down on it.

Impulses on the wing

Let us look at the impulses on the lower surface. When it moves forward with an angle of attack there will be a small rise in the size of the force from the impulses. The particles will crash into the lower surface harder as the wing hits them. For an incidence angle of say four degrees the upward component will be about 7% of the force (sin 4°). For a surface with a drooping trailing edge the effect will be larger. Flaps will make it larger still. We notice that when we lower flaps and the model's nose starts to rise. If it didn't also slow this would be fine. In fact we have to lower the nose to keep up airspeed as the horizontal component of the impulses increase drag. There must also be a similar effect on the upward curve on the underside of the leading edge. Remember we only need a tiny change to generate lift.

What about the top surface? Classic theory from Bernoulli says that when a fluid, in this case air, is speeded up its pressure drops. Using kinetic theory this true fact can be viewed differently. The upper surface is longer. Therefore the particles are more spaced out. Therefore the impulses per unit area will be fewer and so will be the force per unit area, also known as pressure. Are there other effects at play? As a gas expands it cools. That is why you get condensation mist when you pop the cork from a champagne bottle. Perhaps the air above the wing is cooler than that below? The particles would then move more slowly and produce smaller impulses.

What about symmetrical aerofoils? Here clearly we have no lift due to the longer upper surface. All lift must be the result of angle of attack as described above. Extremely thin wings must rely on a modest angle of attack coupled with high forward speed. No doubt the air is heated below the wing as well which will increase lift.

Gliders sometimes use turbulators in the form of a thread just in front of the leading edge, or shapes sticking out of the wing surface. These cause controlled turbulence over the whole surface instead of only behind the point where laminar flow breaks up. Does turbulence reduce impulses? It is neither more nor less random than normal flow. Perhaps the only advantage of turbulence is that it is predictable so the glider can be trimmed to fly closer to stall without unpleasant surprises if its flight is disturbed. I can't get my head round this so maybe someone else can suggest ideas based on kinetic theory?

Conclusion

So after thinking about kinetic theory it seems that lift is not caused by a single pressure effect. It is the result of many different effects. The proportion of each in the total lift will depend on airspeed, wing cross-section including camber and leading edge, angle of attack and possibly even temperature changes. But all are the result of the frequency and magnitude of the vertical components of the many particle impulses.

And the answer to Arthur's question (which isn't in the radio programme) is that when an aerofoil is inverted it loses the effect of the curvature of the upper surface. In fact there will be some negative lift from that effect. The changed angle of attack and the forward speed produce higher impulses on the new under surface which more than compensate for this.