In Reynolds’ classic experiment a fluid enters a straight tube through a rounded entrance and flows along it. To enable the flow to be visualized, a small stream of the same fluid, but dyed, enters the flow at the center of the tube from a small pipe. At lower velocities this flow is laminar (in which layers of fluid slide smoothly over each other without mixing, like cards in a deck), the dyed flow in the center marks out a straight line. As the velocity of the flow is gradually increased, a point is reached at which the dyed flow is seen to oscillate at a point downstream from the entry to the tube, and then very shortly downstream from this oscillation, the dye is seen to mix almost uniformly with the entire flow. The flow has made a transition from laminar to turbulent.

Were we to investigate this flow in detail, we would see that the boundary layer, the sluggish layer of fluid at the tube wall which has been slowed by its molecules’ many collisions with the wall, gradually increases in thickness the farther along the tube we look, and it develops in a non-uniform way. Eventually its thickness becomes sufficient that its presence generates irregularities, blobs of the thickened boundary layer are carried along, and the original smooth laminar flow is disrupted into a whirling mass of eddies. This is turbulent flow.

Although it might seem that laminar flow is more desirable than turbulent flow, many of the things we want to do with fluid flows would be quite impossible if they remained laminar.

Imagine air, flowing through a fuel injection throttle-body on its way into the cylinder of an engine. If this flow remained laminar, fuel droplets sprayed into it would tend to remain isolated in the layers of the flow they reached, and the result would be a very irregular fuel distribution. At the moment of ignition, what was passing between the spark plug’s electrodes would be a procession of rich and lean zones, with therefore many chances of a misfire, should the spark pass through only regions too rich or too lean to be ignited.

We are fortunate, therefore, that at the velocities occurring in engine intakes, only turbulent flow is present. Fuel injected into such a flow is vigorously mixed as the tumbling mass of eddies that make up the flow carry fuel into all parts of it.

As was demonstrated to my school class by a GM speaker in the late 1950s, a completely still mixture of air and fuel burns quite slowly. He produced a three-foot-long Plexiglas tube, plugged at one end, and with a gasoline-filled medicine dropper “carbureted” the air within. To mix air and fuel thoroughly, he placed a tennis ball in the tube, stoppered the open end, and tilted the tube back and forth, causing the tennis ball to roll end-to-end as a mixing device. Then he removed the stopper and the tennis ball and applied the flame from his cigarette lighter to the open end of the tube (seemingly all adults smoked in the 1950s).
Instead of an explosion, there was a drawn-out BORRRRP sound as the resulting flame front made its way from the open to the closed end of the tube. The flame velocity was one or two feet per second – slow!

Now think of a 4-inch bore engine at 6000-rpm. If its ignition is timed to fire a centrally-located spark plug at about 36-deg. BTDC, and if the flame ends at the cylinder wall about 36-deg. after TDC, then that flame has traveled two inches in 2/10 of a revolution. At 6000, the crank makes one revolution in .01 second, and 2/10 of that is two thousandths of a second. Going 2 inches in .002 second is 83 feet per second. Fast!

In a TZ250 Yamaha two-stroke with a bore of 54-mm and timing of 15-deg. BTDC at 12,000-rpm, we get a flame speed of 200 feet per second. Fast!

Why the big difference between one foot per second and 83 or 200? Trick gas? Special fast-burn blends might boost flame speed about 15%, but that only gets us from one foot per second to 13.8 inches per second. Compression? Sure, some effect – but not a factor of 200-to-one.

The biggest part of the answer is turbulence, which tears, shreds, and whirls the tiny flame kernel ignited at the spark plug into something with huge surface area. Then even the very small natural flame velocity will burn up the charge in the cylinder in a tiny fraction of a second. As we know, the turbulence necessary for fast combustion arises in two major ways – first, as a result of the high velocity of charge entering the cylinder, and second, as a result of squish – the high-velocity squirting-out of charge from regions in which the piston very nearly touches the cylinder head at TDC.

Turbulence not only makes gasoline-air combustion fast enough to make engines practical, but it can also make combustion fast enough to win the race against the accumulating in-cylinder chemical changes that eventually (given time enough) result in detonation.

Addendum:

The squish clearance thing - I want people to know that the only "right" squish for their engine is;

1) the minimum that controls detonation adequately and;
2) a geometry that places the very least volume of mixture in squish.

Under #1 are the people who have Gordon Jennings's 50% squish area, and it's too much for their engines, sending extra heat to coolant because combustion is too turbulent. I did this once with a TZ750 I thought I was building for Loudon. It didn't work. Therefore I have advised people to make up a bunch of heads with different squish percentages - the last of the TZ350s had only 8-10-mm-wide squish.

Think, under #2, of what a large percentage of the total mixture volume is compressed into the squish band by combustion pressure just after TDC. That part of the charge is going to burn late and will not be able to contribute to peak pressure (usually located at about 11-deg ATDC). I once worked out that 2% of the mixture is compressed into the piston ring crevice and top land clearance. Do we make so much power that we can afford to ignore what is trapped in squish?
Therefore my argument is that all squish should be at .027” vertical clearance, and what we should vary is the percentage of bore area that is devoted to squish - the less of it we can get away with, the better. .027” is a number that keeps coming up in this connection, but if a builder knows the value at which bright spots (indicating light contact at high revs) begin to appear on head and piston, he can use that plus .005” or so. On the old 54-mm-stroke Yamaha twins you’d get the bright spots at .018”, for example.

It makes me feel stupid to remember how I used those Kawasaki head gasket rings in various thicknesses to "vary compression", all the while not seeing all the other variables I was changing - and seldom for the better!

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Now we come to heat transfer. The most prominent fact we need here is that heat flows in proportion to the temperature difference between the hot and hold substances. If liquid coolant moves slowly enough through its passages inside the engine structure, it may in some degree remain laminar. This means that it will mostly be the layer of fluid in contact with the hot metal which itself becomes hot, while the bulk of the flow – many “layers” away – will pick up little heat. The boundary layer of stagnant fluid at the metal surface, and the slower-moving fluid immediately adjacent, will function as coolant, while the body of the coolant flow is just along for the ride.

We can feel the effect of the boundary layer in the bath tub. We settle happily into hot water and are comfortable for about five minutes. Then, feeling less heat from the water, we begin to wonder if we can turn on the hot water tap with our feet. But wait! Movement makes us feel warm again – pushing water to and fro brings comfort. What this does is to scour away the boundary layer next our skin. This boundary layer has cooled off in the act of warming us, so the water feels cooler. It is. But outside the cooled boundary layer is warmer water, and a little movement in the tub puts us in contact with it.

In some of the earliest liquid-cooled two-strokes – GP racing engines of Bultaco and Suzuki – there was no coolant pump. These systems relied upon the slight density difference between hotter and cooler water to push the flow through the radiator – the so-called “thermosyphon” system. Because the pressure difference available from this density gradient was so small, very large and streamlined water passages had to be provided. At first, designers were sure that surrounding the cylinders and heads of these engines with ever-bigger pots of water would solve their cooling problems of hot-spotting and detonation. After all, it only makes sense, right? More water must mean better cooling!

It did not. Slow-moving water generated thick boundary layers like the one that surrounds us in the bath tub. As those boundary layers heated up, heat transfer went down – because it is proportional to the temperature difference between warmer and cooler materials. The water next to the hot metal became very hot, but the rest of the coolant passing nearby did not. The hotter the water next to hot metal, the less heat could flow
between them. Engines boiled and detonated. One by one, these designs proved inadequate and their makers had to adopt coolant pumps.

The use of a pump sped up coolant movement, making it more turbulent and scouring down the thickness of the liquid boundary layer adhering to the hot metal. The continual swirling motion of turbulence brought cooler water from the body of the flow up against hot metal. The result was a large increase in temperature difference between hot metal and the coolant in contact with it.

Even today, some designers are still tempted by the idea that “putting more water around the cylinders” will cool them better. The result is the opposite. The thicker the water in the water jacket, the slower the coolant motion, the less its turbulence, and the slower heat transfer will be. This is why progressive designs have quite thin water jackets whose flow has been studied to ensure high coolant velocity over all hot surfaces.

Despite all this, we meet old timers who “know what they know” and are not persuaded. They tell of removing the thermostat from the cooling system of a dirt-track car and having it boil over.

“Y’see, the water’s movin’ through the engine so fast, it doesn’t have time to pick up the heat. But put that thermostat in there, the water slows down an’ she works good.”

Doesn’t have time to pick up heat. OK, here we are in the weather shack atop Mt. Washington in February. It’s 80 degrees below zero outside, and the wind is blowing 100 miles per hour. That’s a large temperature difference, but the wind is moving so fast that we should be able to take off all our clothes, go outside, and be toasty warm.

Hm, what ever happened to wind chill? Wind chill is the accelerating effect of wind on heat transfer from a warm person to the surrounding cooler air. Sounds a lot like turbulent heat transfer to me!

So what is happening in the dirt-track car’s cooling system? Its water pump was designed to operate with the restrictive thermostat in place. Without it, low pressure on the inlet side causes cavitation – pressure so low that the coolant pulls apart into vapor. With the pump partly windmilling in this vapor, circulation decreases and the engine overheats. I have often found that a little “porting” to the entry of a water pump – removing sharp edges or casting flash – dropped coolant temperature 5-deg C. Especially on motorcycles, where space is at a premium, designers like to place a 90-degree turn right at the entry to the pump – about the worst thing they could do in terms of inviting cavitation.

Detroit automakers have in recent years adopted what they call “strategic cooling”, which means directing the most rapid coolant flow onto the hottest parts of the engine. Hot new concept, right? It was therefore interesting to me to see, on drawings of German aircraft engines of World War One, designed 95 years ago, little tubes inside the
water jackets, directing coolant flow onto the material surrounding the hot exhaust valve seats.

For a long time, engineers took cooling for granted because at moderate levels of power density just surrounding the parts with simple water jacketing, and moving coolant through with the same old pump, worked fine. But as engines have made more and more power per cubic inch, this “It’ll be OK” system breaks down and engines overheat. This just means that designers have to wake up and actually engineer cooling systems on such engines.