COOLING FOR POWER THEORY

THE BALANCE BETWEEN CREATING COMBUSTION HEAT AND REGULATING ITS EFFECTS IS KEY TO OPTIMIZING POWER AND PARTS LIFE

TEXT AND GRAPHICS BY JIM MCFARLAND

Editor's Note: This story is compiled as an assembly of information about internal combustion engines and their cooling systems. It neither advocates nor suggests one system or method as superior to another. Rather, it is intended to stimulate thoughts and point to peripheral areas involving cooling-system performance worth considering when optimizing race engine power.

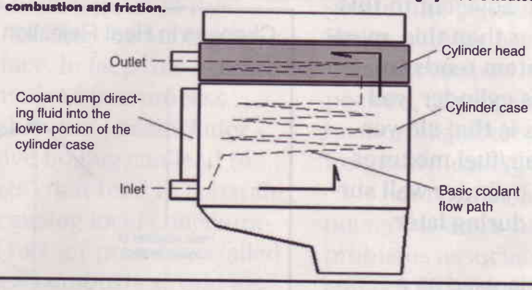
For the moment, direct your attention to an engine's combustion space. It's the heart of this story and focal point for the production of heat (power). Ideally, we'd like to optimize the containment and conversion of this heat into useable crankshaft torque while minimizing heat lost to the cooling system. Clearly oversimplified, this is the platform on which the following paragraphs are built. Internal combustion engines, particularly those used for racing, are a complex network of compromises. The balance between maximizing heat and minimizing its loss to cooling is among these compromises.

IT'S NOT JUST ABOUT COOLING HOT PARTS

Overheated lubricants cannot provide proper lubrication. Reasons include both chemical and physical breakdown of oil and a reduction of film strength. Results from this condition include thermally overstressed parts (particularly pistons), increased losses from friction horsepower, and mechanical failures. In the process, higher piston crown temperatures can lead to either pre-ignition, detonation, or both. Although pre-ignition and detonation event periods may be brief when compared to normal combustion cycles, additional heat can result from these conditions, too.

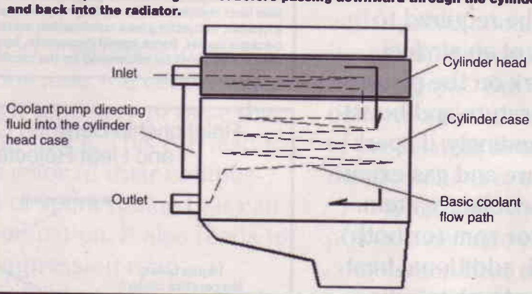
"Normal" Flow Cooling System

NOTE: This type of system typically introduces coolant in the cylinder case first, circulating it upward into the cylinder head. In this fashion, cylinder head coolant is "pre-heated" by having passed through the cylinder case containing cylinders heated by combustion and friction.



"Reverse" Flow Cooling System

NOTE: This type of system typically introduces coolant first in the cylinder head, circulating it downward into the cylinder case. In this fashion, cylinder head coolant enters the hottest part of the engine first before passing downward through the cylinder block and back into the radiator.



Torque output, a function of volumetric efficiency, can also suffer. This comes from increased air/fuel charge temperature, caused by what is called the "heat transfer effect" whereby heat is added to otherwise cooler mixtures, decreasing mixture density and reducing net volumetric efficiency. Conversely, a reduction in charge temperature tends to increase density and improve volumetric efficiency, suggesting a cooling system (or inlet manifold) design that routes heated coolant away from the inlet path. An example of this can be found in so-called "air gap" intake manifolds or by the elimination of a coolant crossover passage in V-type engines. Short of lowering engine mounting locations, this also provides for a lower overall engine profile for increased frontal area and improved race car aerodynamics.

HEAT TRANSFER AND THE NEED FOR COOLING

Arguably, most combustion heat created in a piston crown travels into cylinder walls by way of the piston rings. Unless proper cylinder wall cooling is provided, an abnormal wall temperature will reverse this path and lead to overheated piston crowns. Even if pre-ignition or detonation are not induced, the material strength of pistons may come into question, increasing the importance of cylinder wall cooling that is adequate but not a "sink" for reducing needed combustion heat (power). Again, a necessary balance between heat containment and transfer rears its head.

Cylinder head temperature control is also vital to optimizing power. While it is generally desirable to keep maximum head temperature below 400-450 degrees F, failure to do so can lead to overheated exhaust valves and spark plugs, either of which can produce pre-ignition, detonation, and damage.

Furthermore, it has been determined that even though combustion and the hot gases it produces are high in temperature, these gases are not good radiators. As a result, a process called "convection" creates major cylinder wall temperature or the transfer of heat from hot combustion gas-to-wall material by motion of the gases themselves. While this process may appear of little consequence to the importance of proper cooling, it is the primary means by which increases in horsepower require improved cooling efficiency, whether by coolant path, system design, coolant choice, or a combination of these.

ENGINE CONDITIONS AFFECTING COOLING SYSTEM REQUIREMENTS

Specific engine heat output can be affected by various operating factors. In one way or another, each of the following issues can have an impact on cooling system requirements.

Mechanical compression ratio—Because of a greater expansion of combustion gases near and at TDC piston position during the firing cycle, an increase in compression ratio will boost cylinder wall temperature during this time. However, near BDC on the power stroke, when an increased amount of cylinder wall surface area is exposed to the combustion gas, there is typically a reduction in its temperature (EGT) during early stages of the exhaust cycle (blow-down).

Any increase in cooling temperature (heat rejected to this system) will occur at or near TDC during combustion, thereby increasing an engine's sensitivity to detonation, spark timing, and cooling system efficiency. In terms of cooling system design, if a means were to exist that provided increased uniformity and control of temperature in and around the combustion area, an opportunity could arise that allowed higher mechanical compression ratios to be used without incurring abnormal combustion (note the paragraphs on normal- and reverse-flow cooling systems).

Air/fuel charge ratio—Both combustion flame speed and combustion temperatures fluctuate with changes in air/fuel ratio. Generally, a ratio of about 13:1 will produce the highest combustion gas temperature, therefore affecting the differential between the combustion space and cooling system adjacent to this area. At air/fuel ratios somewhat richer than this, maximum heat rejection to the cooling system tends to occur earlier in the burn and with less cylinder wall exposure. An accepted reason for this is that slower flame speeds associated with leaner air/fuel mixtures tend to expose increased amounts of cylinder wall surface over which to "spread" the burn during later stages of the combustion process.

Spark advance—If ignition spark is used as a "crutch" to overcome other deficiencies in an engine's combustion process, it is possible to create additional heat. For example, given poor mixture quality (homogeneity), additional spark timing may be required to adequately burn the "leaner" portions of an air/fuel charge. This tends to add pre-TDC work on the piston, thereby increasing combustion temperature and boosting the cooling requirement. Correspondingly, if spark timing is too retarded, cylinder pressure and gas expansion beyond TDC will add heat to the cooling system.

Power output—As either power or rpm (or both) increase, all other factors being equal, additional heat will be rejected to the cooling system. As piston displacement increases, the amount of combustion surface area increases accordingly, thereby providing more surface area over which to distribute combustion temperature. Therefore, "large" engines tend to lose less heat per unit area to cylinder walls than those of smaller displacement.

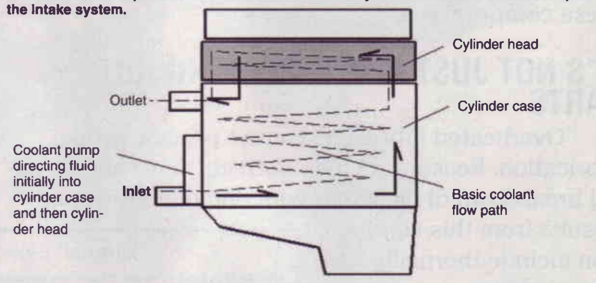
DEMANDS PLACED ON COOLING SYSTEMS

Discussion of how the foregoing factors affect engine heat is necessary to appreciate the benefits of cooling system design. Generally, of the total amount of heat produced in the combustion process, about 50 percent flows into the cylinder head and valve seats, 30 percent into the cylinder walls, and 20 percent into the exhaust port. Heating of intake ports can be largely identified as coming from heated coolant. More specifically, about 50 percent of the heat rejected to the cooling system is created during the compression, combustion, and expansion phases of the overall combustion process. In many instances, a higher overall percentage than this is lost when comparing the potential energy available from a given air/fuel charge and what finally becomes useable crankshaft torque.

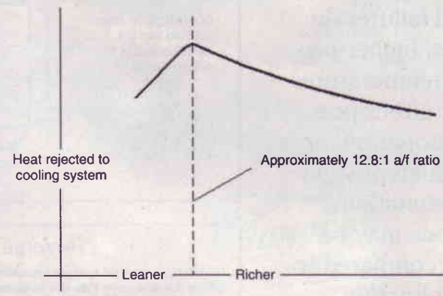
Whether cylinders are cooled before cylinder heads or heads before cylinders, there can be effects on engine performance and options available for optimizing combustion efficiency and power. In this regard, it may be helpful to also be aware that combustion flame control and power output is influenced by environmental temperature in the combustion space. In other words, the hotter the environment, the greater

"Modified-Reverse" Flow Cooling System

NOTE: This type of system typically introduces coolant first into the cylinder case, then into the cylinder head, subsequently circulating it downward back into the cylinder case and out. In this fashion, cylinder head coolant enters the cylinder case and is routed to the hottest part of the engine before passing downward through the cylinder block and back into the radiator to prevent the flow of hot coolant away from and reduce its effects upon the intake system.

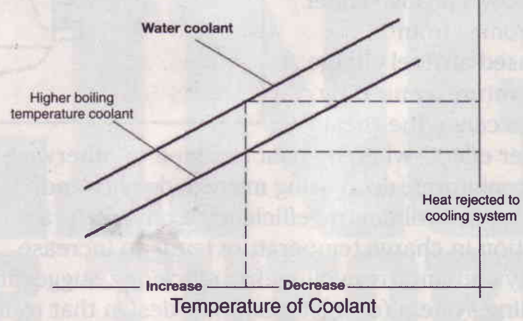


Changes in Heat Rejection As a Function of Air/Fuel Ratio



NOTE: The purpose of this graph is to show how enrichment affects the amount of combustion heat rejected to the cooling system. As mixtures become richer, flame speed begins to increase, subjecting less combustion surface area to heat. Correspondingly, as mixtures become leaner, flame speed decreases, but so does the amount of combustion heat produced that must be addressed by the cooling system.

Relationship Between Coolant Boiling Temperature and Heat Rejected to Cooling System



NOTE: As coolant boiling temperature is increased by choice of coolant composition, the amount of heat rejected to the cooling system decreases. In other words, more combustion heat is available for conversion into power than with lower boiling point coolants.

the tendency of (and compensation for) abnormal combustion and the problems encountered when trying to optimize engine performance.

"NORMAL" FLOW COOLING SYSTEMS

Common practice is to introduce engine coolant from the lower part of a radiator or heat exchanger into the cylinder block's jacket, upward into the cylinder head(s), and back into the upper part of the radiator. A thermostat is used to cause coolant retention in the engine until a pre-determined temperature is reached, at which time flow throughout this system is allowed, circulated by a pump. This is basic stuff.

Coolant in contact with the inner surfaces of coolant passages is directly exposed to heated metal surfaces. Depending upon the boiling point of the coolant and system pressure, "boiling" or bubble formation will occur at this interface. In fact, this event is evidence that the coolant is involved in a process called "nucleate boiling" and absorbing heat. Under certain circumstances, excessive boiling can lead to the formation of "steam pockets" that tend to separate coolant and heated surfaces, causing local concentrations of overheated metal and further problems (failed parts, abnormal or uncontrolled combustion, and lost power). So coolant boiling point, system pressure, and flow rate are among features that combine to efficiently absorb, remove, and control combustion- and friction-generated heat.

Regardless, this direction of flow tends to bring "preheated" coolant to locations near the combustion area. One condition created is a tendency to raise the temperature of the combustion space. This can lead to the heating of air/fuel charges prior to their combustion, thus limiting the amount of spark timing that can be used short of abnormal combustion. It also tends to place limits on mechanical compression ratio.

As a result, particularly in light of contemporary airflow technology and combustion techniques, such "tools" as specific mixture motion in the inlet path and combustion space have combined to improve burn efficiency, in part intended to overcome certain normal coolant flow problems. This has resulted in various improvements in engine output, whether directed to increased power (torque), on-track fuel economy, or parts durability. It has also given rise to exploration to identify and refine coolants other than water, particularly those with higher boiling points.

"REVERSE" FLOW COOLING SYSTEMS

It is known to the art that introducing coolant to the area of greatest engine heat (typically the combustion space) before passing it into cylinder block jackets ("top-down" flow) offers the potential for improved combustion efficiency and/or power. Among the benefits is the opportunity to revisit ignition spark timing parameters, notably the possibility of increased spark timing and power, absent abnormal combustion.

However, there have traditionally been problems associated with the introduction of coolant in a "downward" direction (e.g., from the cylinder head area downward into the cylinder block). One difficulty has been how to deal with formation of vapor and pressures in the upper part of the cooling system. The solution to this problem, given proper vapor venting, has allowed the reverse-flow cooling technique to become an "enabler" for companion engine modifications previously suggested.

In particular, it's worthwhile to understand some of the events that take place within an engine's cooling system in order to further appreciate the potential of reverse flow. For example, the higher the coolant temperature in proximity to the combustion space, the greater the possibility for steam pockets to develop. Steam pockets become "insulators" to the transfer of combustion heat into the coolant. The presence of these pockets, often located around the exhaust side of combustion chambers, can make a bad problem worse . . . frequently leading to abnormal combustion and damage.

For normal flow systems ("bottom-up" flow), numerous areas have been explored to resolve the problems associated with steam pocket development and resulting power limitations. These include "mapping" of coolant flow rates, flow volume, and distribution patterns. Juggling of coolant transfer holes in cylinder head gaskets has also been employed, along with special coolant pump features, enhanced radiator design, and chemical blends intended to raise coolant boiling point. But the fact remains—when coolant is delivered to the combustion area following a measure of pre-heating in the cylinder block, certain efficiency disadvantages are created.

What's the message here? To optimize engine power, a balance should be created between maximizing combustion heat and minimizing its adverse thermal and mechanical effects on parts. Short of abnormal combustion (primarily detonation), building and containing as much heat as possible within the combustion space can lead to increased horsepower. Of its jobs, the cooling system (including its contents) must help maintain combustion space temperature at a level that provides maximum heat release (power) during combustion without allowing the process to degrade into an uncontrolled burn. If this is accomplished, mechanical damage to engine parts sensitive to heat absorption will be minimized, thus extending the life span of these parts.

As previously suggested, an engine's components are a blend of functional compromises. Cooling system capability should be matched to engine characteristics and output. By installing a larger radiator, increasing system pressure, providing a greater volume of cooling air, or finding a high-output coolant pump, a given problem may be avoided or solved. It is likely more important to thoroughly understand their function and view cooling systems as "enablers" to optimizing power and extending parts life, treating them accordingly. **EM**