Dr. Nancy McGuire / Contributing Editor and **Paul Michael**

Efficient hydraulic systems deliver the power

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Hydraulic fluid and system efficiency depends on the application, operating conditions and how hard your system is working.

KEY CONCEPTS

- Reliability and efficiency demand different properties of a hydraulic fluid.
- Overall efficiency is the product of volumetric efficiency and mechanical efficiency.
- The machine duty cycle affects the efficiency of power transmission by hydraulic fluids.

EACH YEAR FLUID POWER SYSTEMS CONSUME BETWEEN 2.25 and 3.0 quadrillion British thermal units of energy—roughly 1.2 for mobile applications, 1.7 for industrial applications and 0.1 for aerospace applications. The average efficiency of these fluid power systems is 21%. Could fluid optimization reduce energy consumption and improve the efficiency of hydraulic systems?

This article is based on the STLE Webinar "Efficient Hydraulic Systems and Fluids" presented by Paul Michael, research chemist at the Milwaukee School of Engineering Fluid Power Institute.

EFFICIENCY BASICS

Hydraulic systems convert rotary mechanical power from engines and electric motors to fluid power by turning the input shaft of a pump. Hydraulic control valves direct the pump flow to machine actuators that use cylinders and motors to convert fluid power back to mechanical power.

A hydraulic motor is like a pump that runs backward; it converts fluid power back to rotary mechanical power and it can generate the high-power densities required by mobile machines. Hydraulic motors turn the drum on a cement mixer, swing the boom on an excavator, drive the cutting blade on a rock-wheel, excite the eccentric on a paving machine or propel a skid-steer loader.

MEET THE PRESENTER

This article is based on a Webinar originally presented by STLE University on Feb. 5, 2015. "Efficient Hydraulic Systems and Fluids" is available at **www.stle.org**: $39 to STLE members, $59 for all others.

Paul Michael, a research chemist at the Milwaukee School of Engineering's Fluid Power Institute, has more than 35 years of experience in formulating and testing lubricants. His research interests include energy-efficient fluids, fluid compatibility, oil aeration, filtration, particle characterization and machine failure diagnosis.

He is active in standards committees for ASTM, the International Organization for Standardization and the National Fire Protection Association. He also serves as a lubrication subject matter expert for the U.S. military. Paul is the principal investigator for energy-efficient hydraulic fluids in the Center for Compact and Efficient Fluid Power, a National Science Foundation engineering research center in Minneapolis that brings together researchers, educators, students and industry representatives to develop more compact, efficient and effective hydraulic and pneumatic technology. You can reach Michael at **michael@msoe.edu**.

Paul Michael

Unlike centrifugal pumping systems, where the flow depends on pressure, hydraulic systems use positive displacement pumps and motors—where flow is independent of pressure. In reality no pump is 100% efficient, so pressure always influences flow to some extent.

Hydraulic systems produce kinetic energy in the form of flow and potential energy in the form of pressure. Thus, it is imperative to maintain separation between high-pressure and low-pressure zones in a hydraulic system. This requirement drives many of the design concepts in fluid power technology; moving machine components must seal at tribological interfaces to minimize leakage through gaps.

Internal leakage, the migration of fluids from high-pressure zones to low-pressure zones inside hydraulic components, reduces the amount of power that a system can deliver. As system pressures and temperatures increase, pressure-driven flow losses through internal gaps also increase. This effect is more significant in mobile applications—the smaller oil reservoirs and heat exchangers required for mobile hydraulic systems means that they operate at higher temperatures than industrial systems.

HOW DO WE MEASURE EFFICIENCY?

The overall efficiency of a hydraulic pump or motor is its volumetric efficiency multiplied by its mechanical efficiency. Volumetric efficiency relates to the output flow per revolution of the input shaft of a pump. It measures the pump's ability to minimize leakage between high-pressure and low-pressure regions. Mechanical efficiency relates to the output torque of a motor and is an indicator of the ability of the fluid to prevent friction.

At high pump pressures and low motor speeds, where most practical operations take place, volumetric efficiency increases rapidly with increasing pump speed (or fluid viscosity), and then levels off. Meanwhile, mechanical efficiency decreases nearly linearly as the pump speed (or the viscosity of the fluid) increases. This relationship is commonly illustrated using a Stribeck curve, which plots efficiency as a function of speed, viscosity and pressure (load) (*see Figure 1*).

FLUID REQUIREMENTS

Reliability and efficiency demand different properties of the hydraulic fluid. Reliability standards are well defined and required for all hydraulic fluids. These standards include viscosity, wear protection, thermal stability, corrosion inhibition, foam resistance, demulsibility, oxidation life and cleanliness. Pressure-dependent fluid properties, which include bulk modulus, density and traction, can have a large impact on hydraulic system efficiency, but these properties rarely appear in hydraulic fluid specifications.

Bulk modulus represents the ratio of volume change to pressure change in a liquid. As a rule of thumb, the volume of a hydraulic fluid decreases by about 0.5% for every 1,000 psi increase in pressure. A fluid's bulk modulus depends on pressure, temperature, chemistry and structural rigidity. Bulk mod-

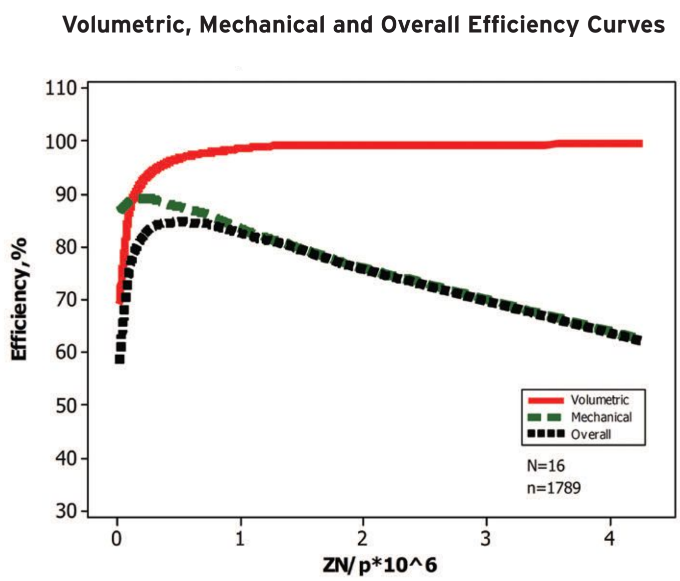

Figure 1 | **Stribeck curves plot efficiency in a hydraulic system as a function of Z (speed), N (viscosity) and p (load or pressure). Multiplying volumetric efficiency by mechanical efficiency yields the overall efficiency. In this plot, 16 gear pumps produced 1,789 data points.**

ulus can affect pump losses (efficiency), sound transmission (noise generation) and system bandwidth (dynamic response or how quickly the machine responds when you shut the valve). Bulk modulus also appears to affect leakage flow in the pump and control systems.

Density is a substance's mass per unit volume, and it is a function of intermolecular forces and chemical composition. An oil with a high bulk modulus is denser and, thus, less compressible than a conventional lubricant. Density factors can affect the pressure drop through valves and fluid conductors and, thus, system efficiency.

Traction is the shear force transmitted across a lubricating oil film, and it is the result of differences in velocity (which includes speed and direction) between the upper and lower surfaces of the film. A fluid's traction coefficient is the ratio of traction force to normal load. When a fluid has a low traction coefficient, it takes less energy to shear the fluid film between two surfaces that are moving with respect to each other. A fluid with a low traction coefficient can reduce a motor's low-speed torque losses (the difference between theoretical torque and actual torque caused by friction in the gaps).

FLUID EFFICIENCY

Hydraulic Motors. Hydraulic motor efficiency at low speeds or starting from a resting position often determines the design pressure and the size of the pump required in a hydraulic machine. This is particularly true for machines that must start under load—digging into a pile of dirt or lifting a shipping container, for example. Just as an automobile is least efficient when it is stopped or moving slowly through traffic, hydraulic motors also are inefficient at low speeds. Reducing motor friction at low speeds improves efficiency by increasing the power available to engage the payload. Improving the performance of the motor can significantly affect the efficiency of the whole system.

To illustrate how the characteristics of the hydraulic fluid can affect a system's performance, we compared five hydraulic fluids. Each of these fluids contains ashless antiwear additives.

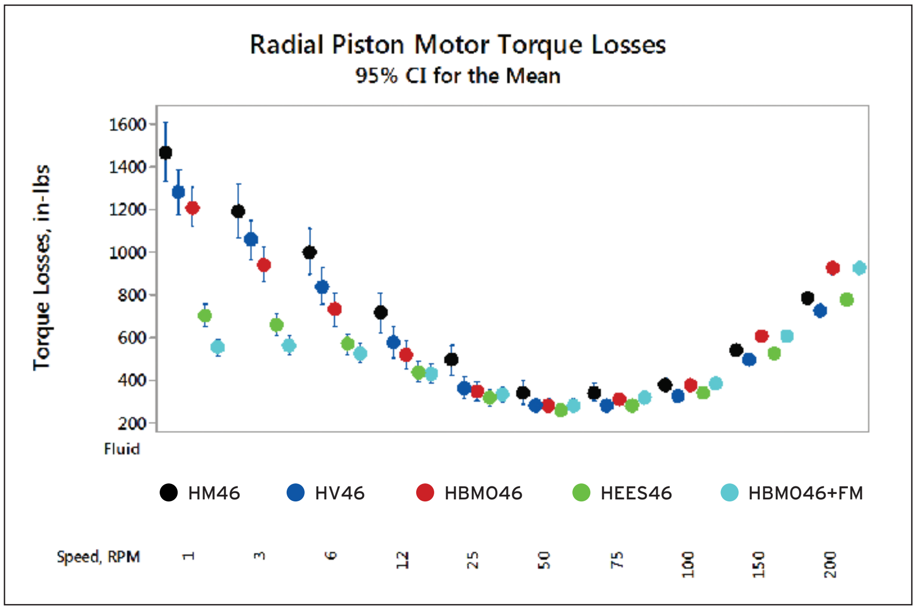

Figure 2 | **Torque losses for a radial piston motor operating at various speeds. Error bars represent the 95% confidence interval for the mean value over several tests.**

- **HM46**. A high-performance Group I mineral oil for use in high-pressure hydraulic systems operating under moderate to severe conditions in mobile and industrial applications.
- **HV46**. A high viscosity index Group III oil, for use in heavy-duty hydraulic systems, with a high viscosity index for improved temperature-viscosity performance.
- **HEES46**. A biodegradable oil based on synthetic esters, especially good for uses where an incidental oil leak could detrimentally impact water.
- **HBMO46**. A high bulk modulus oil based on Group V phenyl esters (aromatic compounds).
- **HBMO46+FM**. HBMO46 with a small amount of friction modifier additive. All properties other than traction coefficient are the same as for HBMO46.

These fluids were evaluated in axial piston, radial piston and orbital (geroler) motors, which show similar trends in torque losses as a function of motor speed. At low motor speeds, low-traction fluids (HEES46 and HBMO46+FM) exhibit half the low-speed torque losses of a conventional hydraulic fluid. Torque losses for all types of oil are similar at medium and high speeds; they decrease and level out as the motor speeds up then increase slightly at the highest speeds (*see Figure 2*).

Differences in mechanical efficiencies mirror the torque losses. Fluids without base stocks or additives that modify frictional characteristics exhibit lower mechanical efficiency at low-motor speeds. Efficiency increases with increasing speed up to a maximum, and tapers off at higher values (*see Figure 3*). The efficiencies of the fluids are similar at high speeds because hydrodynamic lubrication is at work and the fluids are the same ISO viscosity grade.

Hydraulic Pumps. *Piston pump –open loop:* In an axial piston pump, an input shaft rotates the cylinder barrel. As the cylinder barrel rotates, the slippers slide on the swash plate creating a reciprocating piston motion that fills and empties the cylinder bore as shown in Figure 4 on page 40. The fluid expelled by the piston is transmitted to the circuit through ports in the valve plate. The primary leakage flow gaps in an axial piston pump are located at the cylinder barrel/valve plate, slipper/swash plate and piston/cylinder bore interfaces.

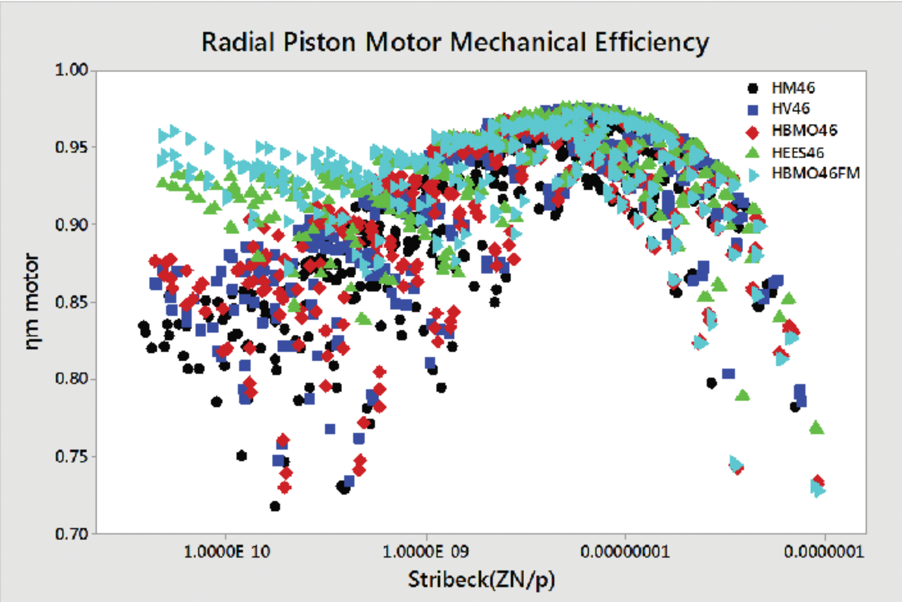

Figure 3 | **Mechanical efficiency for the radial piston motor test shown in Figure 2 as a function of motor speed (Z) at constant viscosity and load.**

In an axial piston pump with pressure compensation, the swash plate angle automatically adjusts to compensate for changes in pump outlet pressure. Hydraulically, pressure compensation reduces the volumetric efficiency of a pump by redirecting pump outlet flow to the compensator control system.

We compared the combined pump case and compensator flow losses for the five fluids described above. The HM46 oil was used as the reference fluid, and it was evaluated at the start, middle and end of the test sequence. The mean leakage flow rate for the HBMO fluid was 20% less than that of the baseline HM46 oil (*see Figure 5 on page 40*). The flow losses for HEES46 and HV46 also were less than the HM46 baseline. The flow losses of the HBMO46+FM fluid were slightly higher than that of the HBMO46 base fluid, possibly because of the addition of the friction modifier or another change in fluid properties. The high bulk modulus fluid also reduced pump power losses, but pumping losses were not proportional to flow losses.

Piston pump–closed loop: In a closed loop pump system, instead of a gravity feed, a charge-pump feeds the oil into the hydraulic pump. Closed loop systems are used in mobile equipment because the charge pressure prevents

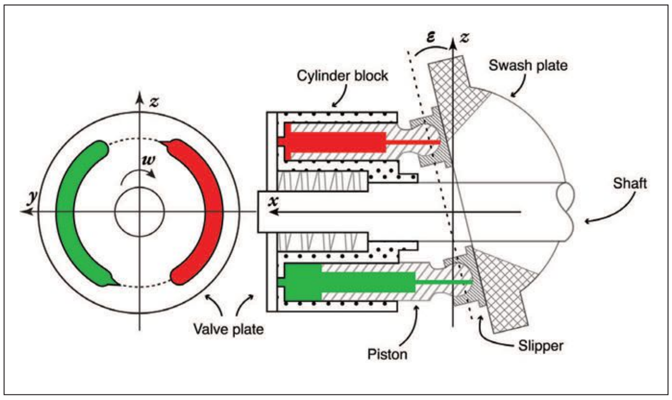

Figure 4 | **Schematic of the axial piston pump used to compare the performance of five hydraulic fluids.**

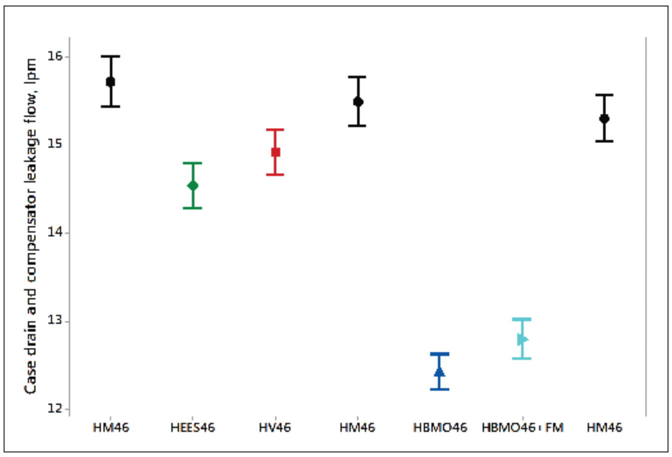

Figure 5 | **Case drain and compensator leakage flow in liters per minute for five hydraulic fluids for the open-loop piston pump system fluid comparison test. HM46 was used as a reference fluid and was checked at the beginning, middle and end of the run.**

efficiency losses caused by having an insufficient amount of oil coming into the pump.

In closed-loop pump testing, volumetric efficiency was found to depend on the pump case flow rate (*see Figure 6*). The volumetric efficiency decreased by about 5% when the pump case leakage flow increased from 0.55 to 1.05 gallons per minute. A half-gallon leakage flow doesn't sound like much, but it amounts to about a 0.5 kW reduction in power loss—about 25 gallons in diesel fuel or $75 in electrical power over 1,000 hours of operation.

Gear pump: In external gear pumps, the most widely used positive displacement machines, flow is produced by directing fluid around the perimeter of meshing gears (*see Figure 7*). We compared the average efficiencies of 16 external gear pumps from seven manufacturers, determined throughout the range of rated operating pressures and speeds. The average volumetric efficiency for the 16 pumps was greater at 50 C than at 80 C across the board (*see Figure 8 on page 42*), but

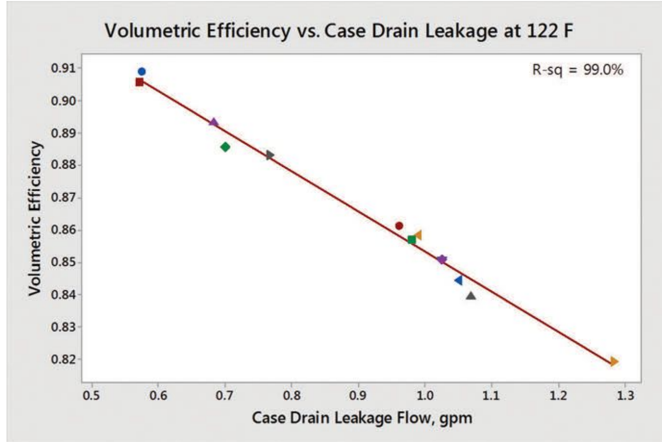

Figure 6 | **Volumetric efficiency as a function of case drain leakage flow in a closed-loop pump system.**

the mechanical efficiency of the pumps varied significantly between pump models (*see Figure 9 on page 42*).

Torque measurements as a function of pump speed produced some unexpected results. At low pressures (and thus low-torque values), the systems performed about the same at 50 C and 80 C. At higher pressures, however, there was less torque at 50 C than at 80 C at all pump speeds, contrary to what is predicted by most textbooks. Pump outlet flow rate as a function of pump outlet pressure was greater at 50 C than at 80 C, and the difference was greatest at higher flow rates and higher pressures, in agreement with textbook predictions. All of the gear pumps had a greater overall efficiency at the lower temperature.

PUTTING IT ALL TOGETHER

Choosing the right hydraulic fluid requires an evaluation of several interacting factors, including the size and type of equipment and operating conditions like temperature, pressure and maximum load. Some properties require a tradeoff to achieve an optimum balance—reliability versus efficiency

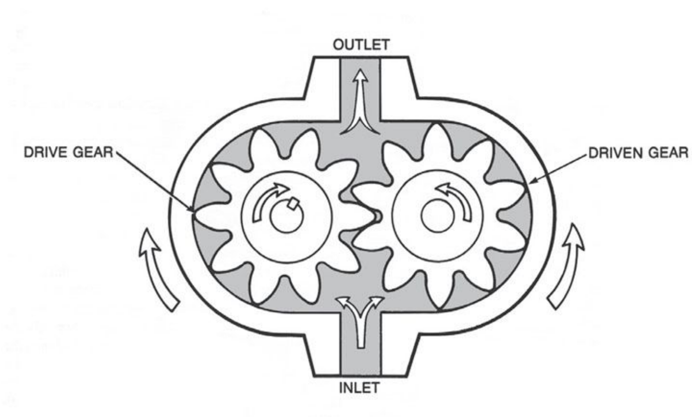

Figure 7 | **Schematic of an external gear pump, the most widely used positive displacement machine.**

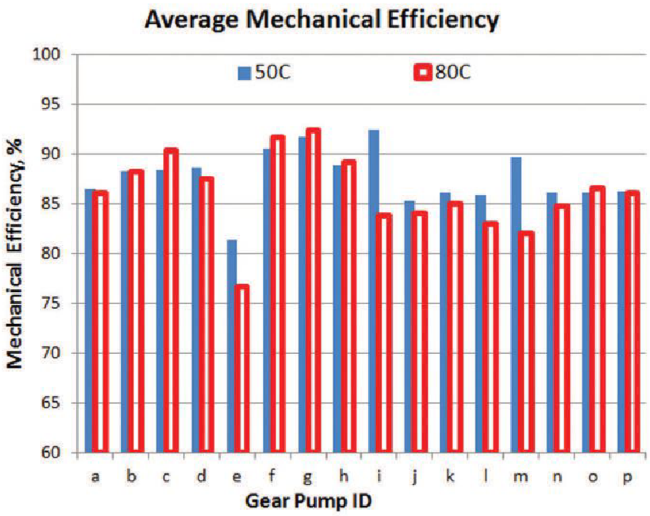

Figure 8 | **Average mechanical efficiencies of 16 different gear pumps (from seven manufacturers), measured at 50 C and 80 C throughout the range of rated operating pressures and speeds.**

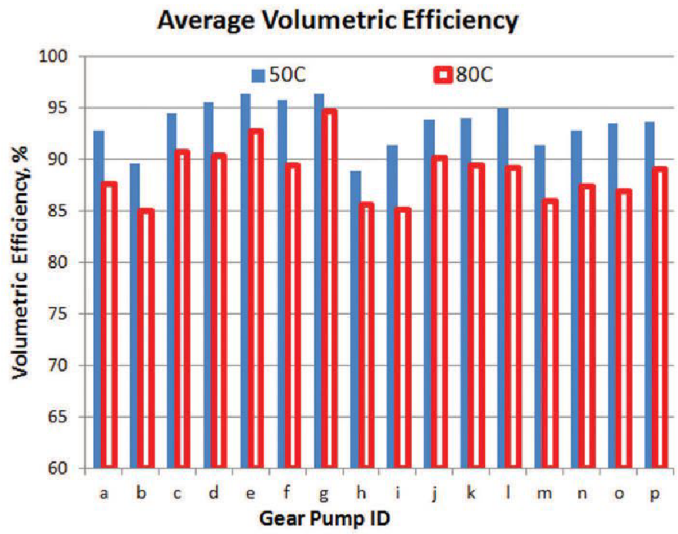

Figure 9 | **Average volumetric efficiencies of the 16 gear pumps shown in Figure 8, measured at 50 C and 80 C throughout the range of rated operating pressures and speeds.**

and mechanical efficiency versus volumetric efficiency, for example. The differences among various hydraulic fluids in efficiently transmitting power are most pronounced at the low motor speeds characteristic of digging a trench or lifting a shipping container, where performance is most critical. TLT

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