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## Getting the Most Out of Your Die

# Key Performance Criteria of Water-Glycol Hydraulic Fluids

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## Introduction

Hydraulic fluids are the lifeblood of a die casting machine, and a quality fluid must meet many stringent performance demands. Their primary function is for energy transmission to the die casting machine, but they also function as heat transfer fluid within the hydraulic system. Furthermore, hydraulic fluids provide lubrication and corrosion protection within the hydraulic system. The hydraulic system of a die casting machine is subject to high fluid pressure. These pressures lead to the failure of the system's parts and lines and results in fluid leaks. This potential for a fluid leak, in close proximity to the molten metal, has necessitated the use of fire resistant hydraulic fluids in die casting plants. Fire resistant hydraulic fluids are classified as HF by ISO 6743-4:1999, "Lubricants, Industrial Oils and Related Products (Class L)-Classification-Part 4: Family H (Hydraulic Systems). This article will focus only on fire resistant hydraulic fluids, with primary focus on water-glycol hydraulic fluids.

## Hydraulic Equipment and Fluid Functions

All hydraulic systems have the following basic components:

- Hydraulic fluid
- Hydraulic fluid reservoir
- Pump, for hydraulic fluid flow
- Accumulators and Actuator
- Control valves and fluid piping

Hydraulic fluid must be compatible with all system components as it interacts with the entire system. All fluids are not created equal, so the fluid must offer a reasonable price to performance ratio. The main functions that hydraulic fluid performs in the system are:

- Energy transmission
- Lubrication of critical components
- Provide sealing on metal-to-metal joints for leak prevention
- Corrosion protection

The primary function of hydraulic fluid is energy transmission. A prime mover (like a motor) drives the pump, which sends the fluid through piping to valves that control actuators. The fluid must efficiently transfer the input energy to the actuator so that work can be performed.

Hydraulic fluid also provides lubrication to all moving parts within the system. There are very small clearances between the moving parts in hydraulic systems which can lead to extreme wear if moving parts are not lubricated adequately. The industry standard for testing the lubrication characteristic of a fluid is the ASTM D-7043 test method. This test method calls for Vickers V-104 rotary vane pump. In this test method, 18.9 liters of fluid is circulated for 100 hours at 1200 rpm and with pump outlet pressure of 2000 PSI. Temperature of fluid at pump inlet is maintained at 66°C during the test. At the end of the test, mass loss of the ring and vanes are measured to determine amount of wear. A fluid that exhibits high mass loss will lead to higher wear during in-field use and cause premature pump failure.

The next important function that a fluid serves is to seal the system. There are many metal-to-metal sealing fits in pumps and valves that present opportunities for fluid to leak. Hydraulic fluid must form a strong enough film over these joints to prevent leaks. Thin fluids can leak through these joints, thereby reducing efficiency of the system. High viscosity fluids will minimize this leakage. However, overly thick fluids can also have some detrimental side effects which will be discussed later in this paper.

## Types of Fluids

In the die casting industry, fire resistant fluids are customary due to close proximity of hydraulic fluid to molten metal, which can pose a major fire hazard if flammable fluids are used. There are many types of hydraulic fluids which are fire resistant. The International Organization for Standardization (ISO) has established a hydraulic fluid classification system, ISO 6743-4, "Lubricants, Industrial Oils and Related Products (class L)-classification-Part 4: Family H (Hydraulic Systems)". The common thread among fire resistant hydraulic fluids is that they are difficult to ignite and do not propagate flame when ignited. These fluids are referred to as HF fluids, where "H" refers to hydraulic and "F" refers to fire resistant. These fluids are classified under three generic descriptions, namely, oil-water emulsions, water-polymer systems and anhydrous synthetics. These broad classifications are further subdivided into the following classifications:

- HFA: Oil-in-Water emulsions, typically with more than 80% water content
- HFB- Water-in-Oil emulsions, typically with more than 40% water content
- HFC-Water-Glycol solutions, typically with more than 35% water content
- HFD: Synthetic anhydrous fluids, for example, fluids based on phosphate esters, polyol esters

There are further sub classifications to the above categories; for example, HFA is further subdivided into HFAE, oil-in-water emulsions, and HFAS, synthetic aqueous fluids. A brief summary of these sub classifications is presented below in Table 1.

HFAE fluids usually have high water content, up to 95%, and are commonly supplied as a blend of surfactants and oil by suppliers. They are mixed on-site with water by the end user. This results in oil droplets which are water dispersible. Since the water is in high quantity and is the continuous phase, these emulsions usually have very low viscosity. HFAS are fluids with at least 80% water content with the remaining fluid being composed of synthetic polymer, additives, etc. In HFAS fluids, synthetic polymers serve the purpose served by oil in HFAE. The synthetic polymers employed in HFAS fluids can either work through an associative mechanism or through water soluble mechanism. Both HFAE and HFAS have a continuous water phase. HFB fluids are used extensively in the mining industry and contain water emulsified in oil, with oil as the continuous phase. These fluids are supplied as ready to use (unlike HFAE fluids) by the suppliers. Both HFAE and HFB fluids typically use mineral oils. HFB type fluids are classified as non-flammable as they burn slower than pure mineral oil fluids (not discussed in this article). Both HFA and HFB type fluids are usually not used in die casting plants due to their low pressure rating.

Water-Glycol (HFC) fluids are the work horses of the die casting industry due to their inherent fire resistance. These fluids are typically composed of water (>35%), glycol (mainly diethylene glycol), polymeric thickener (polyoxyalkylene glycol), additives, etc. They are an attractive alternative to mineral oil hydraulic fluids (not discussed in this article) in medium to high pressure hydraulic systems. This, coupled with their attractive performance-cost ratio and ease of maintenance, has made them the fluids of choice in die casting industry. They are appropriate for medium pressure systems that are common in the die casting industry. HFC fluids will be discussed further in later sections of this paper.

HFD fluids are based on synthetic materials and do not contain any water. They are sub-classified into two categories as outlined in Table 1. The primary uses for these expensive fluids are in the mining and aviation industries as they offer excellent hydraulic performance. More information about HFD's can be found in published literature.[3]

The remainder of this paper will discuss HFC fluids in detail.

## Key Critical Characteristics of Water-glycol Fluids

There are a number of test methods that are followed to qualify and monitor the hydraulic fluids. An exhaustive list of all applicable tests can be found in SAE MS 1005 standard. A selected few critical tests are discussed below:

### Viscosity

Viscosity is one of the most important fluid properties; every fluid is designed to perform optimally within a certain viscosity range. A fluid outside of this optimum range can lead to premature replacement of hydraulic system components. Viscosity for HFC fluids is measured using ASTM D-445. Most equipment manufacturers specify a viscosity range for their fluid. Choice of viscosity range is a compromise, a fluid must be thin enough to flow and provide high efficiency, yet not thin enough to generate too much bypass. It must be thick enough to provide seal and lubrication, yet not thick enough to induce cavitation and reduce pump efficiency. During start-up, temperature is low so the viscosity of fluid is high, whereas when the fluid warms up the viscosity decreases. The high-end of the viscosity range is

*Table 1 – Various Types of Fire Resistant Hydraulic Fluids.*

| ISO Classification | Sub-Category | Composition | Typical Water Content[1] | Operating Range[1] | Comments |
|---|---|---|---|---|---|
| HFA | HFAE | Oil-Water emulsions | >80% | 5° to 50°C | Low cost, reasonable performance, equipment must be specially designed, good for low pressure systems[2] up to 1500 PSI |
| | HFAS | Synthetic Aqueous Fluids | >80% | 5° to 50°C | |
| HFB | | Water-Oil emulsions | >40% | 5° to 50°C | Higher cost, reasonable performance, good for low pressure systems[2] up to 1500 PSI |
| HFC | | Water-Glycol solutions | >35% | -20° to 50°C | Higher cost, workhorse of die casting industry, good price to performance ratio, good for medium pressure systems up to 2500 PSI |
| HFD* | HFDR | Phosphate esters | 0 | -20° to 70°C | Highest cost, good for high pressure systems[2] up to 4500 PSI |
| | HFDU | Synthetic anhydrous fluids, other than phosphate esters | 0 | -20° to 70°C | |

* Other two fluids covered by HFD classification are based on chlorinated materials, and have been discontinued by majority of suppliers due to environmental reasons and hence not shown in this classification

an important monitoring point. If the fluid is too thick, the pump inlet will not be fully supplied from the reservoir which will result in pump damage due to cavitation. This is especially true in cold weather start-ups.

### Particle Count

Cleanliness of fluid is very important as dirt/wear particles present in fluid will cause excessive wear of the hydraulic fluid pump. This can lead to frequent maintenance and expensive part replacement. These particles can be attributed to items such as external contamination, component wear, corrosion, etc. Such particles are extremely hard and damaging to hydraulic components. Particle count can be measured using particle counters or optical microscopy using ISO cleanliness code ISO 4406. This provides a meaningful and unambiguous way to classify the size and number of particles in a fluid. This standard specifies counting of particles bigger than 4 µm, 6 µm and 14 µm, in a unit volume of fluid and assigns a correlating ISO-number for number of particles per unit volume of fluid. These ISO-numbers range from 0.7 to 30 for numbers of particles in 1 milliliter of fluid. For example ISO-number 1 represents particle population of less than 0.02 per milliliter, whereas an ISO-number 16 represents a maximum of 640 particles per unit volume. A subset of ISO Range Number Table is shown below in Table 2.

Table 2: Sub-section of ISO Code 4406

| Particle Concentration up to & including (per milliliter) | Range Number |
|---|---|
| 40000 | 22 |
| 20000 | 21 |
| 10000 | 20 |
| 5000 | 19 |
| 2500 | 18 |
| 1300 | 17 |
| 640 | 16 |
| 320 | 15 |
| 160 | 14 |
| 80 | 13 |
| 40 | 12 |
| 20 | 11 |
| 10 | 10 |
| 5 | 9 |
| 2.5 | 8 |
| 1.3 | 7 |
| 0.64 | 6 |
| 0.32 | 5 |
| 0.16 | 4 |
| 0.08 | 3 |
| 0.04 | 2 |
| 0.02 | 1 |

Another common nomenclature is the use of 2 ISO-numbers, in which particle count is assigned on the basis of the number of particles per unit volume for particles greater than 5 µm and 15 µm in size.

Hydraulic fluid users should exercise every effort to minimize this contamination through qualification of a clean fluid, proper filtration and by preventing ingression of contaminants in the hydraulic system. Hydraulic equipment suppliers recommend the minimum cleanliness standards, and these should be strictly adhered to by the user[4].

### Air Entrapment and Cavitation

Air entrapment within hydraulic fluid systems is an extremely serious problem that results in excessive equipment wear, fluid degradation, increase in compressibility (thus lower power transmission) and increased equipment downtime. Air is present in hydraulic system in three different forms, namely, air pockets, entrained air and dissolved air. Air pocket refers to a pocket of air that is trapped somewhere in the system such as hydraulic lines. Entrained air refers to air bubbles that are suspended in hydraulic fluid. Presence of entrained air leads to a hazy/cloudy appearing hydraulic fluid. A fluid with entrained air under pressure will lead to foaming when this fluid is brought to atmospheric pressure. Excessive foaming can then lead to non-lubricated hot-spots, resulting in excessive pump wear and cavitation. All fluids have a small propensity to dissolve gasses, air is no exception.

The amount of air dissolved in hydraulic fluid is a function of fluid chemistry, operating temperature and pressure. Higher temperatures can lead to less dissolved air whereas higher pressures can lead to more dissolved air. For the common classes of hydraulic fluids, it has been shown that water-glycol fluids exhibit one of the lowest air solubility followed by phosphate esters, oil-in-water emulsions, with mineral oils being the highest[5].

All three forms of air in a hydraulic system can potentially lead to cavitation and excessive wear of hydraulic fluid pumps. Cavitation is defined as the "dynamic process of gas cavity growth and collapse in a fluid" [6]. During cavitation, an air/gas bubble entrapped within the fluid starts to collapse on pump metal surfaces due to high pressures. This results in a fluid micro-jet, which impinges on the metal surface at high velocity. Repeated impingement of these micro-jets on a metal surface will result in erosion of the metal surfaces within the pump. This leads to increased wear of parts due to wear particles, eventually leading to pump failure. This cavitation process is showed pictorially in Figure 1.

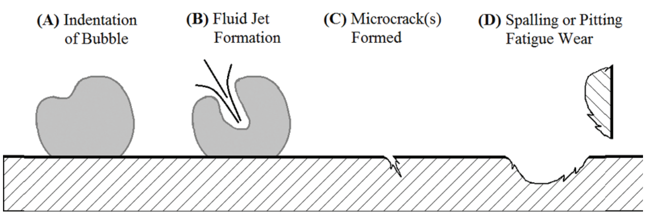


*Figure 1 – Cavitation Process.*

### Water Content

Water content is one of the most significant variables on water-glycol hydraulic fluid performance. All water-glycol fluids are designed to yield optimum performance within a certain viscosity range and most fluids are formulated with 35-40% water. The reason being that below 35% water, fluid viscosity is too high to yield good pump efficiency and amount of water is too low to provide fire resistance. In contrast, high water content results in severe pump wear[7].

Low water content results in higher HF viscosity and thus lower pump throughput and consequently lower pump efficiency. High water content leads to lower HF viscosity and thereby increased wear of pump components due to lower load bearing capability of the HF film on moving parts within the pump. It has been shown earlier[7] that pump wear rates increase dramatically fast after water content increases beyond 40%. Thus water content in a water-glycol fluid should be maintained within a narrow range recommended by fluid manufacturer. During normal use of water-glycols fluids there is water loss due to evaporation. This can be readily monitored by either using analytical methods like refractive index, Karl-Fisher titration, or by monitoring kinematic viscosity using ASTM D-445. Only distilled or de-ionized water should be used as make-up water. This is important as polyvalent ions ($Ca^{++}$, $Mg^{++}$, etc.) in hard water will react with anti-wear additives, leading to increased pump wear. It is important to note that low viscosity can also be due to thermo-oxidative causes discussed in the section below.

### Reserve Alkalinity, pH and Corrosion

Amine based corrosion inhibitors are used in water-glycol hydraulic fluids to provide corrosion protection to metal parts within the hydraulic system. Their concentration is referred to as reserve alkalinity, and usually reported as milliliters of 0.1N hydrochloric acid to titrate 10 milliliter of water-glycol fluid to a pH of 5.5. All hydraulic fluids, including water-glycol, are usually exposed for short intervals to temperatures higher than their recommended maximum operating temperatures due to localized heating encountered in hydraulic systems. This exposure to elevated temperatures results in formation of degradation by-products of glycol and thickener. Thermal and oxidative degradation of thickener and glycols occurs through formation of peroxide species[8], referred to as ROOH, where R refers to the preceding organic group. Metal ions such as Iron (II) and Iron (III) and Copper (II) catalyze the degradation of peroxide species. The free radical thus produced, RO*, can undergo further reactions to breakdown glycol and thickeners. Following generalized reaction scheme shows this:

$$Fe^{2+} + ROOH \rightarrow Fe^{3+} + RO^* + OH^-$$

$$RO^* + RH \rightarrow ROH + R^*$$

This process leads to formation of low molecular weight carboxylic acids, like formic acid and acetic acid, thus reducing reserve alkalinity and thereby increasing corrosion. This process eventually leads to increased pump wear. Thus monitoring of reserve alkalinity is a critical preventive maintenance step.

It is important to evaluate a fluid, in both the liquid and vapor phases, for corrosion performance on all possible construction contact points for the fluid. Corrosion tests are run at operating temperatures in accordance with ASTM D130 and ASTM D665A and B. They measure the effect of fluid on corrosion of steel, aluminum, and yellow metals in liquid and vapor phase. Details can be found in ASTM test procedures referred to earlier.

## Summary

Consideration of many characteristics is an important step in selecting a good water-glycol fluid for hydraulic systems. Water-glycol fluids play a critical role in system reliability, and need to be chosen and monitored carefully. Due to space restrictions, other important properties were not discussed in this article. An exhaustive list of appropriate test procedures can be found in SAE MS 1005 standard. Understanding of selection criteria for water-glycol fluids is the first step in ensuring the maximum performance and reliability of hydraulic systems. It is possible to ensure maximum system reliability by establishing and adhering to a rigorous maintenance schedule.

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