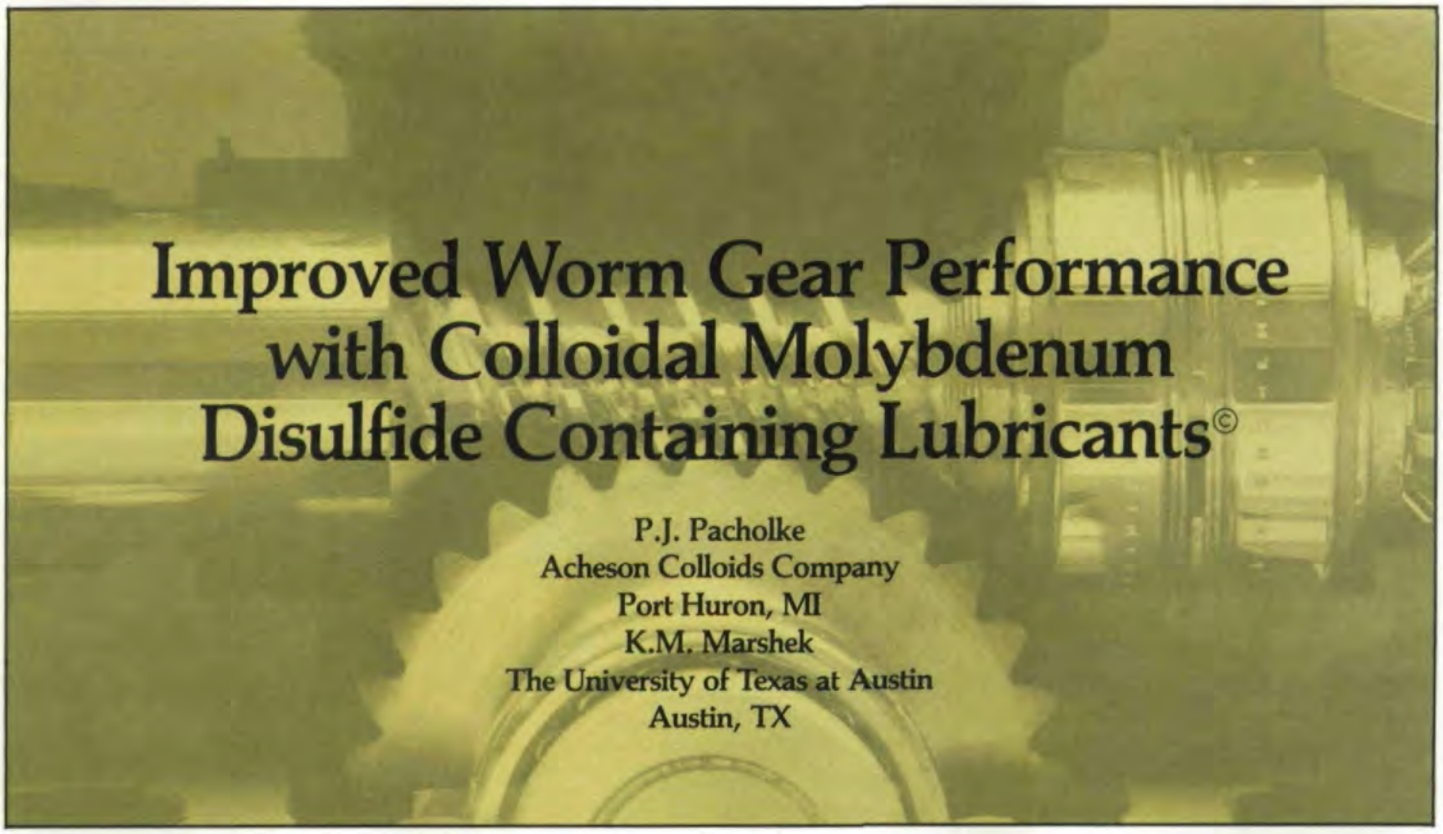

Improved Worm Gear Performance with Colloidal Molybdenum Disulfide Containing Lubricants©

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Abstract:

Worm gear speed reducers give the design engineer considerable options, but these gear systems present a challenge to the lubrication engineer. Heat energy generated by the high rate of sliding and friction in the contact zone causes worm gears to be relatively inefficient compared to other gear types. Because worm gears operate under a boundary or near-boundary lubrication regime, a satisfactory lubricant should contain a friction modifier to alleviate these conditions.

Experimental results show that the addition of speciallly formulated colloidal molybdenum disulfide containing additives to gear lubricants can increase efficiency, lower operating temperatures through sliding friction reduction and reduce gear wear and break-in time.

Introduction

Compactness, dependability, a wide selection of reduction ratios in a single unit, and lower cost compared to other speed reducers make worm gear drives a good design choice. The inefficiency of worm gear reducers has been ignored in recent years as the energy crisis of the early 1970s gave way to a relative abundance of fuel today.

Industry analysts have projected an annual energy cost savings of six billion dollars if worm gear lubricants contained just 1.0% colloidal MoS_2.[1] These calculations were based on the assumption that there are an estimated three million worm gear speed reducers rated at an average of 10 hp currently in service in the United States. If the efficiency of these units was increased by 5% (for example, from 68.8% to 72.2%) with 1.0% stable colloidal MoS_2, the energy savings would amount to 98 billion kW-h, which, at $0.06/kW-h, amount to six billion dollars. These data, based on AGMA (American Gear Manufacturers Association) estimates, do not even include the several million more worm gear reducers which are rated at less than 5 hp.

Even though energy conservation may not be receiving as much attention and priority today, the bottom-line savings that lubricants containing stable colloidal molybdenum disulfide can offer should not be ignored by a world faced with a finite energy supply.

The very design of worm gearing results in a high rate of sliding which generates a great deal of heat energy. There is a con-

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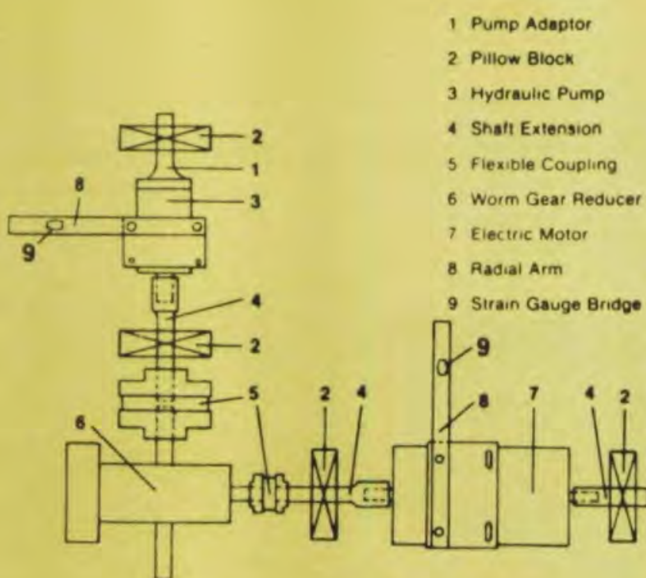

Fig. 1—Worm gear dynamometer test machine.

siderable loss of output power, primarily as thermal energy. (About 75% of the output power lost by worm gearing can be attributed to the generation of thermal energy by sliding friction. Minor power losses are due to churning, bearing friction and other miscellaneous causes.) Output power generated by worm gear reducers operating at high speeds, loads and reduction ratios is consequently limited by thermal constraints rather than mechanical limits.[2] Higher oil temperatures result in shortened lubricant life, and worm gear reducers often require external cooling to reduce oil temperatures to an acceptable level.

Worm gear efficiency is defined as the ratio of output power to input power and depends indirectly on speed-reducer reduction ratios. Efficiency in worm gear reducers ranges from 50-90%, compared to hypoid and similar gearing, which are 85-97% efficient. The relative inefficiency in worm gears is a result of the sliding friction created between the contacting surfaces of the worm and the driven gear, whereas, in spur and helical gearing, the contact between mating surfaces is predominately rolling. For low reduction ratios, worm gearing is between 70% and 90% efficient, but a high reduction ratio of 60:1 would have a rated efficiency of only about 50%.[3] In the higher reduction ratios, therefore, even a small percentage increase in efficiency would translate into fairly substantial energy savings.

Lubricants designed for worm gear reducers should perform two major functions:

1. Reduce friction and wear to improve efficiency and extend gear life.
2. Act as a heat transfer medium to conduct heat energy away from the contact zone.

Worm gears operate predominantly under boundary lubrication conditions. Hydrodynamic or thick film lubrication does not exist because of the high rate of sliding, high contact pressures and tooth geometry found in worm gears. Boundary lubrication conditions require the use of specialized additives which can provide the lubrication necessary to prevent metal-to-metal contact in the absence of a thick oil film.

The traditional worm gear lubricant is a high-viscosity oil compounded with "oiliness" or lubricity components, such as acidless tallow or synthesized fatty esters. These compounded oils function to relieve boundary lubrication conditions by providing an adsorbed layer of molecules which easily shear on the contacting surfaces of the gear teeth. Acidless tallow added to the oil reduces operating temperatures to acceptable levels, but the efficiency of the reducer is not significantly affected.

Studies have shown that dispersed solid lubricants, such as molybdenum disulfide or graphite, increase efficiency and, hence, reduce energy consumption in automotive engines and gearing.[3, 4, 5] Initial work by Smith and Marshek indicated that the use of 1.0% by weight of stable colloidal MoS_2 in worm gear lubricants improved efficiency and reduced oil temperatures in the baseline fluid studied. This work showed that oils blended with MoS_2 in stable colloidal form significantly improved worm gear performance, whereas, earlier studies had not detected this effect because the molybdenum disulfide powder was merely stirred into the test oil, where it immediately settled and was not available as a boundary friction modifier. With stable colloidal MoS_2, however, the molybdenum disulfide is available throughout the entire recommended oil change period and does not settle out in properly formulated lubricants.

Maintenance engineers have long expressed a desire for a more universal oil, one which would function in all types of gear systems and which would also provide the specialized lubrication required in worm gearing. The present study examined the concept of a "universal" gear oil, a lower viscosity base oil which would contain a specially designed package of stable, dispersed MoS_2 and oxidation inhibitors, and which would properly lubricate both worm gear speed reducers and other gear types.

Apparatus and Procedure

A worm gear dynamometer test machine was used to evaluate the various performance aspects of the worm gear speed reducer (Fig. 1). A 30:1 reduction ratio, fan-cooled unit was powered by a 1.5 hp, 1720 rpm, ac motor. The load on the reducer was supplied by a hydraulic gear pump circulating automatic transmission fluid through a closed loop. The fluid was circulated through a water-cooled heat exchanger to maintain a fluid temperature less than 56°C.

Both the motor and gear pump were supported by their shafts in pillow blocks to allow freedom of rotation. Connections between the system components were made with flexible couplings to minimize any effects of misalignment. A radial arm was bolted to the gear pump housing so that torque could be transmitted from the housing to the radial arm which provided the load on the worm gear reducer. The load was controlled by adjusting the back pressure in the gear pump hydraulic loop with a pressure control valve.

Output torque was measured by a strain gauge mounted on the radial arm in a full-bridge configuration. Input torque was measured in a similar way.

Thermal measurements were made by T-type (copper-constantan) thermocouples placed in the reducer sump, the hydraulic fluid reserve tank and in the ambient air.

All measurement transducers on the worm gear dynamometer were monitored by a data acquisition system controlled by a microcomputer. Interface cards accepted wiring from strain gauges and thermocouples for direct input into the acquisition system. Measured values were converted directly into engineering units by utilizing the microcomputer software. Output data were stored on floppy disk and hard copy provided by printer and plotter.

Test Parameters. Output torque was maintained at 113 N·m (1000 in·lbf), allowing input torque to vary as a function of lubricant performance. The ambient temperature was controlled at 25°C in an air-conditioned laboratory. Fan cooling was provided to keep the oil in the reducer sump below 95°C.

Break-in Test Procedure. This portion of the study was designed to characterize and compare the break-in of two identical worm gear sets using two lubricants — the factory-fill AGMA No. 8 compounded and AGMA No. 7 (uncompounded) containing 1.0% colloidal MoS_2 (by weight) as a specially formulated, stable additive package.

A new steel worm and bronze gear set was installed and properly aligned in the reducer for each test. One-half liter of test lubricant was prepared and placed in the reducer. All test parameters — input and output torque together with reducer oil sump, gear pump transmission fluid and ambient air temperatures — were monitored by the data acquisition system.

1. The reducer was run at 56.5 N·m (50 in·lbf), approximately half its rated output torque, until a steady-state temperature of <95°C was attained.
2. Output load was incrementally increased to a final output torque of 113 N·m (1000 in·lbf). The reducer was required to achieve steady-state operation; i.e., reducer oil sump temperature <95°C) before the load was increased to the next level.
3. Once the steady-state operation at 113 N·m output torque was attained, efficiency calculations were made.
4. Upon completing the prescribed break-in procedures, the test lubricant was removed from the reducer and the unit thoroughly flushed with solvent.

Performance Testing. Efficiency and other performance parameters of candidate worm gear lubricants were measured on a gear set installed in the worm gear test dynamometer and run in with AGMA No. 8 compounded oil to steady-state operating conditions. Output torque was held constant at 113 N·m, and oil sump temperatures were required to be less than 95°C whenever possible.

1. The test lubricant was prepared as necessary. For tests with lubricants containing MoS_2, specially formulated dispersion packages were blended into the lubricant prior to filling the reducer sump.
2. One-half liter of test lubricant was added to the reducer sump, and the reducer was started with no applied output load.
3. The back pressure control valve on the gear pump reserve fluid tank was slowly closed to bring the output torque to the 113 N·m test load.
4. The reducer was allowed to achieve steady-state operation. (Steady-state operation in this study is defined as: output torque = 113 N·m and reducer oil sump temperature constant and <95°C.) Once the unit had reached the steady-state condition, the load on the strain gauges was removed and unstrained readings taken for both strain gauge bridges.
5. Output torque was returned to 113 N·m and the steady-state conditions.
6. Monitoring of the test parameters was initiated by the data acquisition unit and continued throughout the two-hour test period. One hundred measurements from each transducer were averaged every 146 seconds during the test.
7. The microcomputer then calculated and printed a table of the mean values and standard deviations of the test parameters.
8. The test lubricant was drained from the reducer and sump. The unit was then double-flushed with a volatile solvent to minimize any possible carry-over effects from individual lubricants. This process was considered sufficient to remove mechanically occluded MoS_2 contained in conventional mineral-oil-based lubricants as determined by previous work.

Test Lubricants. The test lubricants and molybdenum disulfide dispersion packages evaluated in this study are described in Tables 1 and 2, respectively. The selected lubricants were chosen to represent:

1. A typical factory-fill worm gear oil – AGMA No. 8 compounded
2. AGMA No. 8 compounded with 1.0% colloidal MoS_2 (by weight)
3. A lower viscosity oil – uncompounded AGMA No. 7 with 1.0% colloidal MoS_2 as a boundary friction modifier
4. Two synthetic lubricants – polyalphaolefin and polyalkylene glycol.

Results and Discussion

Break-in Studies. AGMA No. 7 (uncompounded) gear oil containing 1.0% colloidal MoS_2 substantially reduced the time necessary to achieve steady-state operating conditions in the worm gear test apparatus, when compared to the same procedure carried out using the manufacturer's recommended AGMA No. 8 compounded oil. This reduction is clearly shown in Fig. 2. Accompanying the reduced time to

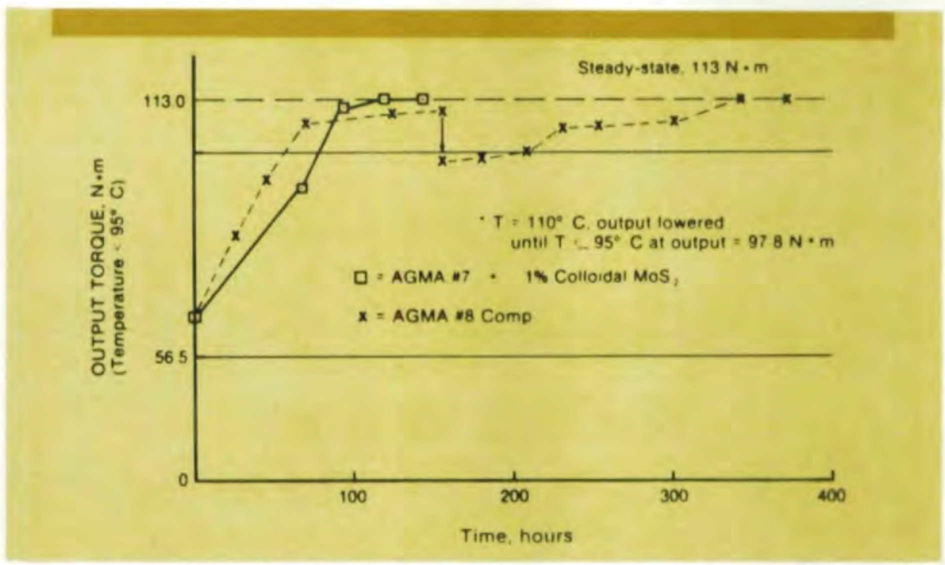

Fig. 2 – Comparison of time to achieve steady-state operation (output torque = 113 N·m, oil sump temperature <95°C).

Table 1—Description of Worm Gear Test Lubricants

Fluid ID	Description	Kinematic Viscosity, cSt 40°C	Kinematic Viscosity, cSt 100°C	Viscosity* Index
A	AGMA No. 8 Comp	631.7	32.75	80
B	AGMA No. 8 Comp + 1.0% Colloidal MoS_2 as Dispersion Package 1	642.9	33.75	84
C	AGMA No. 7 + 1.0% Colloidal MoS_2 as Dispersion Package 1	466.6	29.97	92
D	AGMA No. 7	458.5	29.50	92
E	AGMA No. 7 + Additive Package 2 (Package 1 without MoS_2)	433.5	28.40	92
F	Synthetic No. 1, Polyalphaolefin	62.38	10.25	134
G	Synthetic No. 1 + 1.0% Colloidal MoS_2 as Dispersion Package 3	66.24	9.975	125
H	Synthetic No. 2, Polyalkylene Glycol	59.56	10.92	145
I	Synthetic No. 2 + 1.0% Colloidal MoS_2 as Dispersion Package 4	61.68	10.34	136

*Calculated as per ASTM D-2270

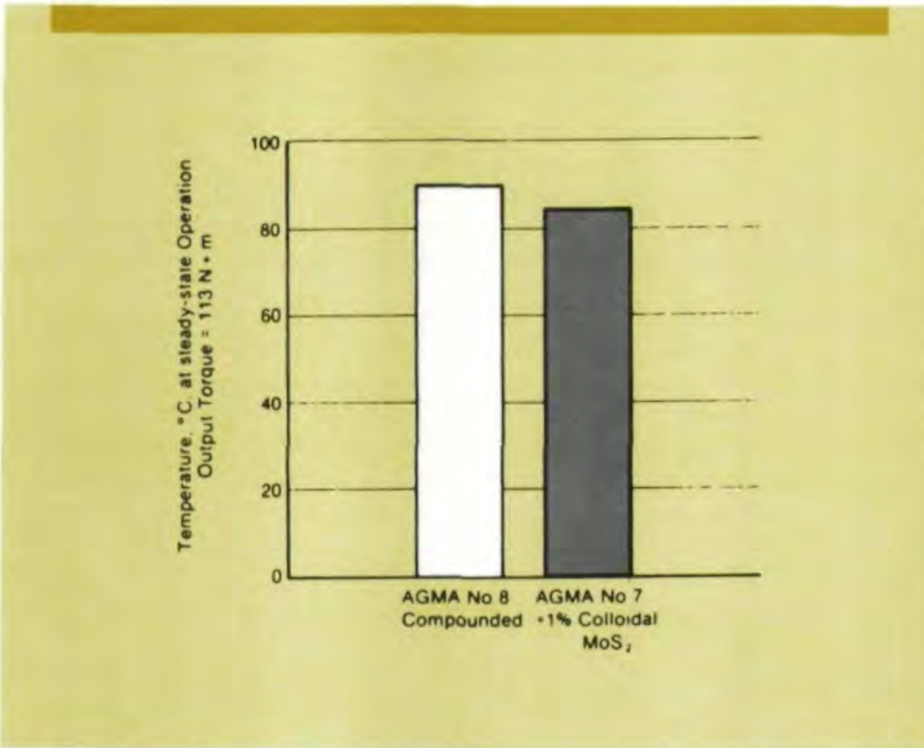

Fig. 3 – Comparison of oil sump temperature at steady-state operation: AGMA No. 7 + 1.0% colloidal MoS_2 vs AGMA No. 8 compounded.

reach operating conditions of 113 N·m and oil temperatures less than 95°C with the use of the MoS_2-containing AGMA No. 7, was a significant reduction in oil sump temperatures at a constant level of output torque. Fig. 3 compares the temperatures of the two break-in test oils at steady-state operation.

Performance Evaluations. The performance criteria of interest were input torque and calculated efficiency as an indication of the energy expenditure effects of each lubricant. Oil sump temperatures were examined as an indication of the heat transfer ability of the lubricant. The addition of stable dispersed molybdenum disulfide to test lubricants lowered the input torque needed to drive the worm gear test reducer at a standard output torque of 113 N·m. Table 3 describes the performance characteristics of all the fluids: mean input torque, efficiency and oil sump temperatures. The most dramatic increase in efficiency and decreased operating oil sump temperatures in a test lubricant formulated with 1.0% colloidal MoS_2 by weight was exhibited by the synthetic lubricants – Fluids F, G, H and I. Fig. 4 compares the efficiencies of test lubricants with and without 1.0% stable colloidal MoS_2.

Efficiency Studies. Test lubricant F, the the polyalphaolefin without MoS_2, had an efficiency similar to that of Fluid B (AGMA No. 8 compounded plus 1.0% coloidal MoS_2). The addition of 1.0% MoS_2 as a PAO-based additive package (Fluid G) increased the efficiency of this PAO lubricant from 63.2% to 67.8%, a 7.3% increase in efficiency.

Synthetic No. 2, the polyalkylene glycol Fluid H, ran less efficiently than any lubricant tested. However, the addition of MoS_2 in a polyalkylene glycol-based dispersion package improved efficiency by 5.3% – from 61.8% to 65.1% efficiency.

Fluids D and E were control lubricants used to examine any possible effect soluble components of the dispersion additive packages might have on worm gear performance. Neither lubricant D nor E gave the same level of efficiency or the reduced input torque exhibited by Fluid C (AGMA No. 7 base oil with 1.0% colloidal MoS_2). Both Fluid D and Fluid E performed comparably to Fluid A, the factory-fill AGMA No. 8 compounded gear oil. These test results indicate that a lower viscosity oil, blended with a stable MoS_2 additive package, provides the necessary friction modification to improve power transmission efficiency by reducing sliding friction. Fluid C (No. 7 plus 1.0% colloidal MoS_2) had a mean efficiency of 64.0%, whereas, the conventionally compounded No. 8 oil (Fluid A) operated at a mean efficiency of only 62.6%. This improvement translates to a 2.2% increase in efficiency.

Statistical analysis showed that the probability that these differences in performance are real exceeds 99.99%.

Temperature Effects. No statistically signficant variations in oil temperatures were observed in the group of high-viscosity AGMA No. 7 (uncompounded) and No. 8 (compounded) fluids. This apparent lack of differentiation between oils containing dispersed MoS_2 and untreated oils is most likely due to the heat energy generated by the excessive churning of the lubricant and the generally poor heat transfer capabilities of high-viscosity fluids. The lone exception to this generality is Fluid E, which had been tested after the synthetic plus MoS_2 Fluid G. Despite stringent measures to eliminate carryover between test fluids, the baseline oil, run just before and after the PAO series of fluids, indicated a consistent and significant decrease in oil tempertures (<90°C) similar to those developed by Fluid B during the last one hour of its test period. The esta-

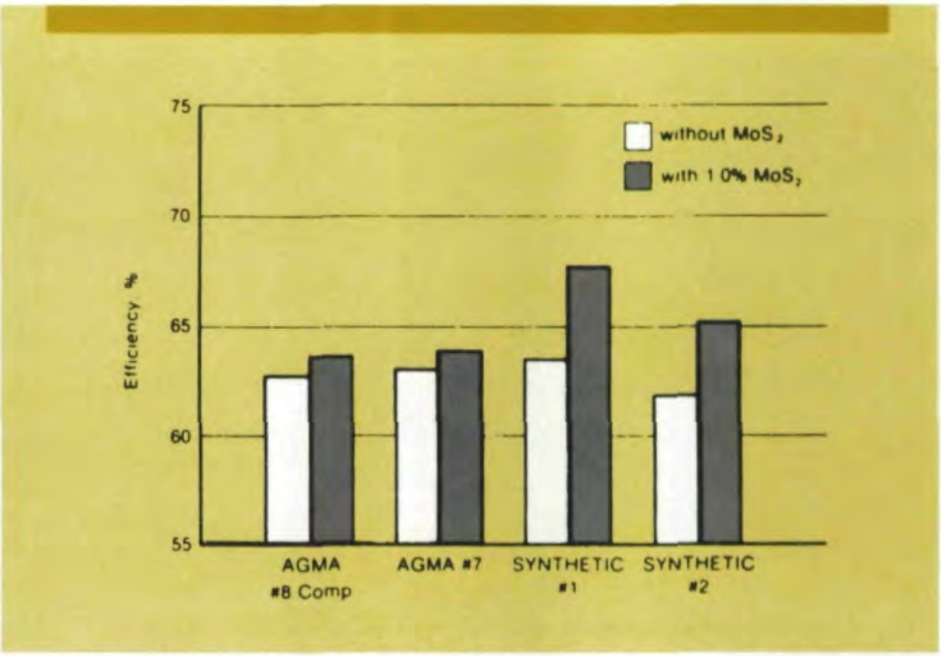

Fig. 4 – Efficiency comparison of test lubricants with and without 1.0% stable colloidal MoS_2.

Table 2—Description of Stable Colloidal MoS_2 Additive Packages	
Dispersion Package	Description
1	MoS_2 Dispersed in 150 Solvent Neutral Oil
2	Package 1 without MoS_2
3	MoS_2 Dispersed in Polyalphaolefin
4	MoS_2 Dispersed in Polyalkylene Glycol

Table 3—Results of Worm Gear Dynamometer Tests

		Performance Parameters Output Torque = 113 N·m			
Fluid ID	Description	Mean Input Torque, N·m	Std. Dev.	Percent Efficiency	Mean Oil Sump Temperature, °C
A	AGMA No. 8 Comp	6.02	0.054	62.6	92.1
B	AGMA No. 8 Comp + 1.0% Colloidal MoS_2 Dispersion Additive 1	5.92	0.107	63.6	95.5
C	AGMA No. 7 + 1% MoS_2 as Dispersion Additive 1	5.89	0.079	64.0	93.4
D	AGMA No. 7	6.05	0.075	62.3	93.6
E	AGMA No. 7 + Additive 2 (Additive 1 Package without MoS_2)	5.99	0.080	62.9	86.5*
F	Synthetic No. 1, Polyalphaolefin	5.96	0.110	63.2	97.5
G	Synthetic No. 1 + 1% Colloidal MoS_2 as Dispersion Additive 3	5.56	0.017	67.8	91.0
H	Synthetic No. 2, Polyalkylene Glycol	6.09	0.080	61.8	108.8
I	Synthetic No. 2 + 1% Colloidal MoS_2 as Dispersion Additive 4	5.79	0.117	65.1	88.4

*Lower temperature attributed to minor Fluid G carry-over. See text.

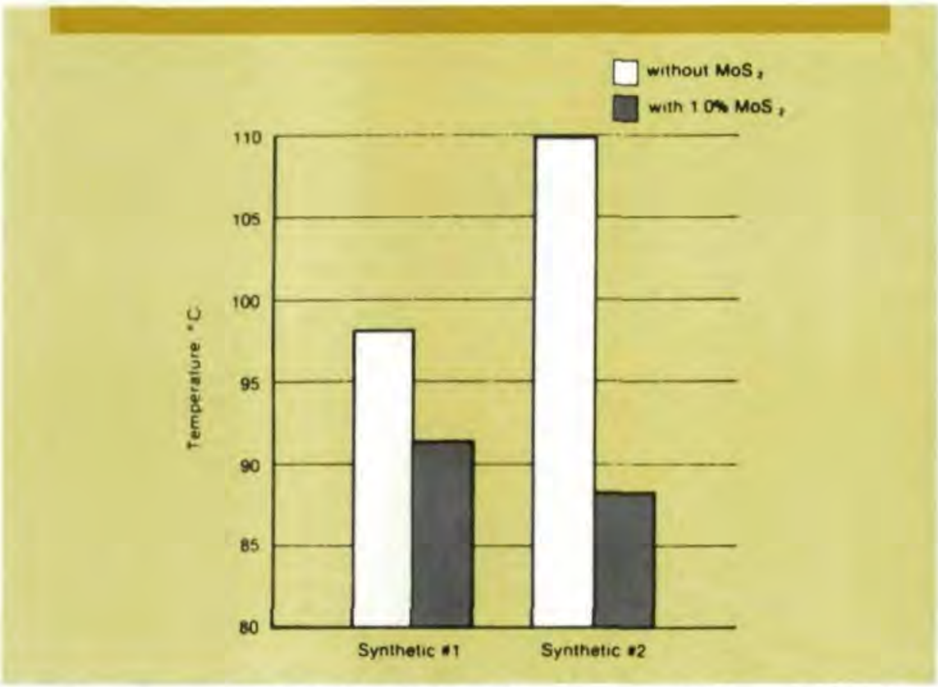

Fig. 5 – Temperature-reduction effects of the addition of 1.0% stable, dispersed MoS_2 to synthetic lubricants 1 and 2.

blished input torque baseline data allowed the calculation of an appropriate input torque correction factor to be applied to the input torque values of Fluid E.

The temperature reduction benefits of 1.0% colloidal molybdenum disulfide in lubricants are clearly observed in the two synthetic fluids. Both Synthetic No. 1 and Synthetic No. 2 are considerably lower in viscosity (Table 1) than any of Fluids A – E. Although the synthetic fluids have higher viscosity indexes compared to most petroleum-based oils, they do not always provide adequate boundary friction lubrication. In the PAO series, Fluids F and G, the addition of 1.0% stable, dispersed MoS_2 reduced the mean operating oil temperature by 6.5°C: from 97.5°C for Fluid F to 91.0°C for Fluid G as shown in Fig. 5. It should also be noted that the oil sump temperatures for Fluid G were substantially lower during the last hour of the efficiency test.

An even greater decrease in mean oil sump temperatures was observed with the polyalkylene glycols. Fig. 5 shows that the addition of 1.0% colloidal MoS_2 resulted in a 20.4°C decrease in mean oil sump temperatures. Fluid H had a mean temperature of 108.8°C, whereas Fluid I, which contained MoS_2, had a mean temperature of 88.4°C. There is a probability that the decreases in oil sump temperatures observed with the synthetic lubricants containing colloidal MoS_2 are real exceed 99.99%.

Conclusions

This study showed that the addition of 1.0% molybdenum disulfide (as a stable, colloidal dispersion package) to an AGMA No. 7 gear oil reduced the time required to break in a gear set to an output power equivalent to the factory-fill AGMA No. 8 compounded oil by 60.2%: 139 hours for the AGMA No. 7 plus colloidal MoS_2 to reach an output of 113 N·m, compared to the 349 hours required for the AGMA No. 8 compounded to reach the same conditions. A significant reduction in the final steady-state operating temperature was also observed: 90°C for the AGMA No. 8 compounded versus 84.4°C for the AGMA No. 7 plus 1.0% colloidal MoS_2.

The addition of colloidal MoS_2 to worm gear lubricants also significantly increased power transmission efficiency by reducing sliding friction and allowing the reducer to operate at the same level of output power for a smaller expenditure of input power. This decreased input power requirement appeared to be the case for conventional oils containing MoS_2, as well as with similarly treated synthetic lubricants. There is greater than a 99.9% certainty that these improvements are real.

The treatment of high-viscosity oils with 1.0% colloidal MoS_2 (AGMA No. 8 compounded and AGMA No. 7) did not appear to have a measureable effect on oil temperatures because of the poor heat energy transfer properties of such oils. However, lower viscosity fluids of high-viscosity index, such as the synthetic polyalphaolefins and polyalkylene glycols, when blended with 1.0% colloidal MoS_2, exhibited real and significant reductions of operating oil tempertures.

It can then be reasonably presumed that 1.0% colloidal molybdenum disulfide can increase the performance in worm gear speed reducers with considerable cost savings in energy consumption, and can also reduce operating temperatures in certain lubricants and extend lubricant life by reducing the rate of oil oxidation. Only the lubricants containing stable colloidal MoS_2 offered these performance benefits. In such stable lubricant systems, the molybdenum disulfide particles remain in suspension throughout the normal lubricant lifespan, whereas, noncolloidal MoS_2, simply stirred into lubricants, flocculates and settles almost immediately to the bottom of the gear box and is not available as a solid lubricant friction modifier. All these parameters of worm gear performance can be correlated to reduced friction due to the improved boundary lubrication conditions resulting in less wear, quieter operation and longer lubricant and gear box life.

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