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Irrigation Pumping Plant Efficiencies—High Plains and Trans-Pecos Areas of Texas[1]

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Abstract

Three hundred sixty irrigation pumping plants were efficiency tested in the High Plains and Trans-Pecos areas of Texas. Pump efficiency averaged 58.9% but with large geographic variations. Pumps in the North Plains averaged 65.4%; but in the South and Trans-Pecos areas combined, the average efficiency was only 55.1%. Natural-gas-powered engines averaged 20.5%, but the average was biased by a popular industrial engine. Sixty-one of these engine efficiencies averaged 3% higher than the combined average of 179 other engines. The efficiency of 26 diesel engines averaged 31.2%; and the absence of low-efficiency diesel engines was notable. For 94 electric-powered pumping plants, the average efficiency was 47.0%. Grouped by motor type, the average efficiencies were 52.9% for pumping plants with vertical hollow-shaft motors, 40.9% for pumping plants with submersible motors, and 35.4% for pumping plants with horizontal motors connected by V-belts to right angle drives.

Introduction

In the Southern High Plains, surface water supplies are scarce, and most irrigation water is pumped from the Ogallala Aquifer. Pumping lifts can be as much as 600 ft, and irrigation pumping costs are a significant percentage of total crop production costs. To minimize the pumping costs requires high-efficiency pumping equipment. The Nebraska performance criteria for irrigation pumping plants are well accepted as the maximum practical efficiencies for irrigation pumping equipment (5). The criteria utilize a 75% deep-well, turbine pump efficiency and an 88% electric motor efficiency. Combining these two values gives a performance criteria for electric-powered pumping plants of 66% efficiency. Engine-powered pumping plants also utilize the 75% pump efficiency and a right-angle gear drive efficiency of 95%. When natural gas has an energy content of 1,000 BTU/scf, the criteria for natural-gas-powered engines is 24% efficiency. Corresponding efficiency for a natural-gas-powered pumping plant is 17%. The diesel engine performance criteria given by Schleusener and Sulek (5) has been upgraded by the University of Nebraska (8). With the new criteria and a diesel fuel energy content of 135,000 BTU/gal, the criteria for diesel engines is 33% efficiency. The corresponding diesel-powered pumping plant efficiency is 24%.

The Agricultural Engineering Department at Texas Tech University published an irrigation pumping plant efficiency study for the Southern High Plains in 1968 (2). The average efficiency of 134 pumps was 52.2%, and the average thermal efficiency of 46 natural-gas-powered engines was 19.8%. Sixteen engines powered by liquefied petroleum have had an average thermal efficiency of only 15.7%. At that time, much of the area was newly developed for irrigation, energy costs were low, and total pumping costs were quite low. Since then, the cost of energy for irrigation pumping has increased as much as tenfold. At the same time, fewer new wells and pumping plants have been added. Because of these divergent forces, pumping equipment efficiencies reported in 1968 may not be applicable today.

The results of more recent irrigation pumping plant efficiency studies in the area have been inconsistent. Abernathy, Cook, and Dean (1) tested 390 irrigation pumping plants in New Mexico and reported pump and natural-gas-powered engine efficiencies of 52 and 22%, respectively. In Texas, the High Plains Underground Water Conservation District (7) reported the average efficiency for 249 pumps to be 43%. Average thermal efficiency of 91 natural-gas-powered engines was 21%. In this study, benchmark efficiencies were determined for

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irrigation pumping equipment in the High Plains and Trans-Pecos areas of Texas. A sufficient number of pumping plants were tested to show geographic variations across the area. Comparison with the date published in 1968 (2) shows temporal trends. The data are representative of more than 71,000 irrigation pumping plants used to irrigate as many as 6.1 million acres (3) in the Texas High Plains.

Procedure

Standard procedure was to test the irrigation pumping plants during the irrigation season under normal operating conditions. County agents in 28 counties overlying the Ogallala aquifer and 6 counties in the Trans-Pecos area selected the individual test locations. Electricity, natural gas, and diesel were used to power the pumping plants. Data were collected during the irrigation seasons from 1977 through 1981.

Both the overall efficiency of the pumping plants and the efficiency of the pump and power unit were measured. Overall pumping plant efficiency is the combined efficiency of the power unit, pump, and gear drive (if one is used). The individual component efficiencies are needed to calculate the economic feasibility of upgrading either the pump or power unit or both.

Commercially available instruments and equipment were used to measure the water power output of the pumping plants. Pumping rates were measured with a portable propeller meter installed either at the pump or in an aluminum irrigation pipeline. If an airline was installed in the well casing, it was used to measure the pumping water level. Otherwise, pumping water levels were measured with an electric water level indicator. The pump discharge pressures were measured with Bourdon pressure gauges.

Natural gas measurements were made with a commercially available diaphragm meter fitted with quick-connect hoses for portable use. Gas pressure was measured on the discharge side of the meter and gas volumes were corrected to standard pressure. Diesel fuel consumption was measured volumetrically with a calibrated cylinder made of plexiglass. For the fuel consumption measurement, the calibrated cylinder replaced the permanent fuel tank.

For electric-powered pumping plants, motor efficiencies approved by the National Electrical Manufacturers Association were used and pump efficiency was calculated directly from pumping plant efficiency. This is standard practice since electric motor efficiencies do not vary appreciably from the design efficiency. The motor efficiencies used were within the individual manufacturers' ratings.

For the engine-powered pumping plants, engine power was measured with a torque meter and shaft speed counter installed as a unit in a U-joint drive line (2). During the power measurements, the instrumented drive line replaced the permanent U-joint drive line. The right-angle gear drive efficiency was estimated as 95% from manufacturers' data. The engine power adjusted for gear drive efficiency was the power input to the pump.

Pump, pumping plant, and engine efficiencies are reported as a percent of the theoretically attainable efficiency. Although specific fuel consumption is usually preferred by automotive engineers as an indicator of fuel efficiency (4), specific fuel consumption was converted to thermal efficiency for easier data interpretation. Comparison of thermal efficiencies of engines powered by natural gas and diesel is more meaningful. Thermal efficiencies can be converted to any desired specific fuel consumption using the heating value of the fuel. In addition, the results can be directly compared to earlier irrigation pumping efficiency studies. A detailed analysis of the engines was reported separately (6).

To obtain heating values, the higher heating value of diesel fuel was measured, and power companies provided standard, natural gas higher heating values. Long-term calorimeter measurements of processed natural gas in the Texas High Plains have shown a consistent higher heating value of 1000 BTU/scf. For unprocessed wellhead gas, the higher heating value is 1200 BTU/scf. For diesel fuel, a higher heating value of 135,000 BTU/gal was measured with a standard calorimeter.

Results and Discussion

Average operating data for tthe 360 pumping plants tested during the study are listed in Table 1. The data are averaged for 134 pumping plants located in 7 North Plains counties, for 198 pumping plants located in 21 South Plains counties, and for 28 pumping plants located in 6 Trans-Pecos area counties. Well drilling practices, pumping equipment, and operating conditions are sufficiently different to justify this breakdown.

Operating characteristics for the pumping plants varied over a wide range. Pumping rate ranged from 20 gal/min to 1,400 gal/min, pumping lift ranged from 42 ft. to 590 ft., and total dynamic head ranged from 70 ft. to 689 ft. With this wide range in pumping rates and lifts, power input to the pumps varied markedly. Electric motors had the largest variation in power outputs, with a range of 3 hp to 218 hp. Pump power provided by natural-gas-powered engines ranged from 15 hp to 202 hp. For the diesel-powered pumping plants, engine power output ranged from 20 hp to 173 hp.

Average pumping equipment efficiencies measured in the three geographic areas and for the combined areas are listed in Table 2. The efficiency of 94 electric-, 240 natural gas-, and 26 diesel-powered pumping plants was measured.

The efficiencies of individual pumping equipment varied appreciably except for diesel engines. Pump efficiency ranged from 13.7 to 82.7% or sixfold. Thermal efficiency of natural gas engines ranged from 7.8 to 28.9% or almost fourfold. Overall efficiency of electric-powered pumping plants ranged from 16.8 to 70.6%. Thermal efficiency of diesel engines only ranged from 26.0 to 34.8%, however.

Pumps

Pump efficiency of 360 pumps, both line-shaft and sumbersible, averaged 58.9%. This efficiency is higher than that reported for other studies in the area (1,2,7). The higher average efficiency is due to the more efficient pumps in the North Plains that were not as well represented in other reports.

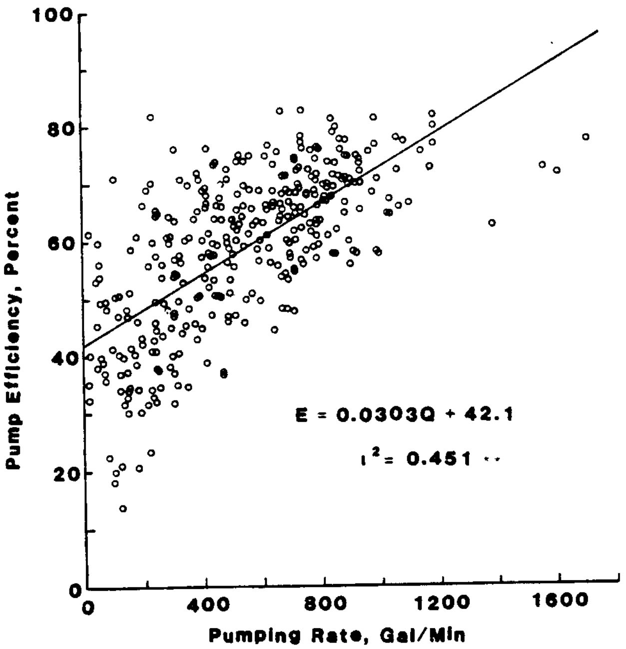

Figure 1. The effect of pumping rate on pump efficiency for all pumps.

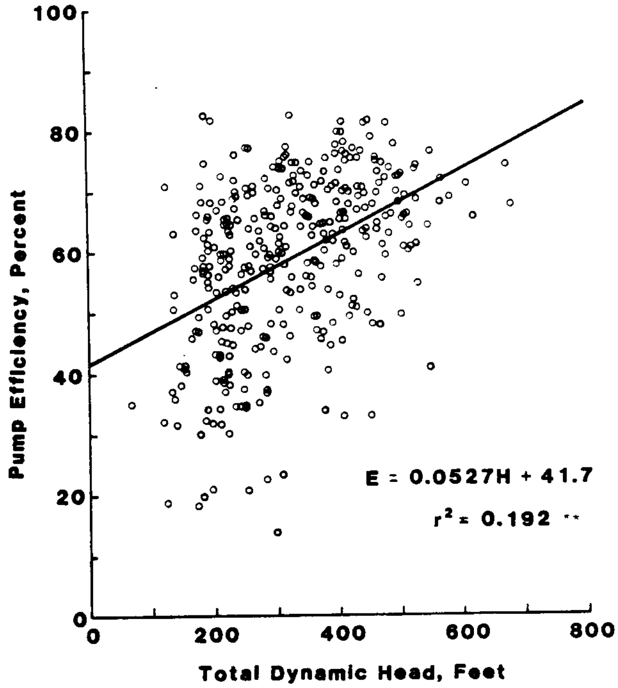

Figure 2. The effect of total dynamic head on pump efficiency for all pumps.

Pump efficiency was directly correlated with both pumping rate and total dynamic head, Figures 1 and 2. For every gallon-per-minute increase in pumping rate, the average pump efficiency increased 0.03%, Figure 1. The coefficient of determination shows that 45% of the variability in pump efficiency can be attributed to variations in pumping rate. For every one-foot increase in the total dynamic head, the average pump efficiency increased 0.05%. The coefficient of determination was 0.192 for the data in Figure 2. Pumping power varies with both the pumping rate and the total dynamic head. Therefore, pump efficiency is also directly correlated with the water horsepower of the pumping plants. From a practical viewpoint, pump efficiency increased directly with the fuel consumption rate of an individual pumping plant.

Electric-Powered Pumping Plants

Efficiency of the electric-powered pumping plants ranged from 16.8 to 70.6%. The lowest efficiencies tended to be in low producing wells, with many having submersible pumps. Higher efficiencies tended to be in higher producing wells with greater pumping lifts.

Efficiency of electric-powered pumping plants was lowest in the South Plains and highest in the North Plains. In the North Plains, only 10 electric-powered pumping plants were tested, and pumping rates and pumping lifts were larger than average. Low efficiency in the South Plains is the result of smaller pumping plants, especially a number of small submersible pumps.

Average pumping plant efficiencies for pumping plants equipped with sumbersible and vertical hollow-shaft motors were 40.9 and 52.9%, respectively. This reflects, to some extent, the inherently lower efficiency of both submersible motors and the small diameter turbine pumps coupled to the motors. The lower efficiency of submersible pumps is a factor in selection of electric-powered pumps. Submersible pumps are best suited for pumping plants with low discharge rates, an application for which line-shaft pumps are less efficient.

The least efficient electric-powered pumping plants were those with horizontal electric motors connected with V-belts to right-angle gear drives. Average efficiency of 11 pumping plants was only 35.4%, and two pumping plants were less than 20% efficient. These pumping plants were only located in the South Plains, where the water table decline of the Ogallala aquifer has been greatest. The belt drives reduce the speed of oversized pumps so that the pumping rate is reduced to prevent surging in low discharge wells. A more efficient alternative is installation of a correctly sized pump.

Natural-Gas-Powered Pumping Plants

Overall efficiency of the natural-gas-powered pumping plants ranged from 2.2 to 21.6% and averaged 11.7%. The lowest efficiencies were on pumping plants that grossly overdesigned or over equipped for the current yield of the well. Highest efficiencies were on higher producing wells with larger pumping lifts.

Thermal efficiency of natural-gas-powered engines averaged 20.5% and ranged from 7.8 to 28.9%. The wide range of efficiencies for these engines is similar to that reported in the literature (1, 2, 7) for the same area. In all studies, a small percentage of natural-gas-powered engines had extremely low efficiencies and could be conomically repaired or replaced.

Natural-gas-powered engine efficiency was significantly influenced by a popular brand and model industrial engine used on larger pumping plants. Sixty-one of these engines

Table 1. Average operating data for pumping plants in the three geographic areas. Numbers in parentheses are sample size.

	North Plains	South Plains	Trans-Pecos	All pumping plants
Pumping lift, ft	328 (134)	238 (198)	339 (28)	279 (360)
Total dynamic head, ft	402 (134)	272 (198)	364 (28)	328 (360)
Total dynamic head, furrow irrigated, ft	378 (55)	268 (152)	368 (24)	305 (231)
Total dynamic head, sprinkler irrigated, ft	419 (79)	287 (46)	339 (4)	369 (129)
Pumping rate, gal/min	726 (134)	443 (198)	527 (28)	555 (360)
Water power, hp	73 (134)	32 (198)	48 (28)	49 (360)
Engine power, natural-gas-powered, hp	115 (105)	68 (127)	103 (8)	90 (240)
Engine power, diesel, hp	130 (19)	47 (7)	(0)	108 (26)

Table 2. Average pumping equipment efficiencies from this study and those reported by Texas Tech University (2). Numbers in parentheses are sample size.

Equipment type	North Plains	South Plains	Trans-Pecos	All pumping plants	Texas Tech University
	%				
Pumps, turbine	65.4 (134)	55.1 (198)	54.9 (28)	58.9 (360)	52.2 (134)
Engine, natural-gas powered	21.1 (105)	19.7 (127)	22.1 (8)	20.5 (240)	19.8 (46)
Engine, diesel	31.6 (19)	30.0 (7)	(0)	31.2 (26)	(0)
Pumping plant, natural-gas powered	13.1 (105)	10.7 (127)	10.9 (8)	11.7 (240)	10.8 (46)
Pumping plant, diesel powered	20.6 (19)	18.1 (7)	(0)	19.9 (26)	(0)
Pumping plant, electric	60.8 (10)	44.2 (64)	49.1 (20)	47.0 (94)	43.0 (72)
Pumping plant, electric, vertical hollow-shaft motor	60.8 (10)	50.4 (32)	53.1 (11)	52.9 (53)	48.6 (41)
Pumping plant, electric, submersible motor	(0)	39.5 (21)	44.3 (9)	40.9 (30)	35.6 (31)
Pumping plant, electric horizontal motor with V-belt drive to right-angle gear drive	(0)	35.4 (11)	(0)	35.4 (11)	(0)

were tested, and the efficiency averaged 3% higher than the combined average of 179 other engines. These 61 engines were primarily located in the North Plains and Trans-Pecos areas. For this reason, the efficiency of natural-gas-powered engines in these two areas was higher than in the South Plains.

Diesel-Powered Pumping Plants

The overall efficiency of diesel-powered pumping plants averaged 19.9% and ranged from 13.7 to 24.5%. This average pumping plant efficiency is 70% higher than the average for natural-gas-powered pumping plants. Diesel engines are inherently more efficient than natural-gas-powered engines, but the diesel-powered pumps were also more efficient. Pumps powered by diesel averaged 67.2% compared to 59.0% for those powered by natural gas.

Thermal efficiency of diesel engines averaged 31.2% and ranged from 26.0 to 34.8%. When compared to natural-gas-powered engines, diesel engines were more efficient, and the range of efficiencies was smaller. The smaller efficiency range is caused by the absence of low efficiency diesel engines. The data showed that diesel engines are more likely to maintain their theoretically high efficiencies under field operating condtions.

Efficiency Variations Within Study Areas

The most notable difference between the three study areas was the turbine pump efficiency. In the North Plains, turbine pump efficiency averaged 65.4%. Average efficiencies in the South Plains and Trans-Pecos areas were 55.1 and 54.9%, respectively. Figure 3 illustrates the distribution of pump efficiencies in the North Plains. Since the average pump efficiencies for the South Plains and Trans-Pecos areas are nearly equal, the two areas are combined in Figure 4 to illustrate the distribution. The lower average pump efficiency for the South Plains and Trans-Pecos areas is due to the greater number of low efficiency pumps rather than to an absence of high efficiencies. Only 7.5% of the pumps in the North Plains were less than 50% efficient. For the South Plains and Trans-Pecos areas, 35.8% of the pumps were less than 50% efficient. This suggests that a large number of the turbine pumps in the South Plains and Trans-Pecos areas could be economically repaired or replaced.

The higher pump efficiencies in the North Plains are believed to be the result of five factors. Almost all wells in the North Plains are gravel packed; thus, the wells produce little or no sand to damage the pumps. In addition, pumps in the North Plains had larger pumping rates and total dynamic heads than the other two areas. In the study, pump efficiency was positively correlated with both of these factors. Also, the North Plains was developed for irrigation after the South Plains; thus, the average pump was newer in the North Plains. Finally, none of the low efficiency pumps powered by horizontal meters connected by V-belts to right angle drives or submersible meters were located in the North Plains.

Other differences in pumping eqipment efficiency existed among the three areas, but they were not as large as the differences for turbine pumps. A popular industrial engine caused the natural-gas-powered engine efficiencies in the

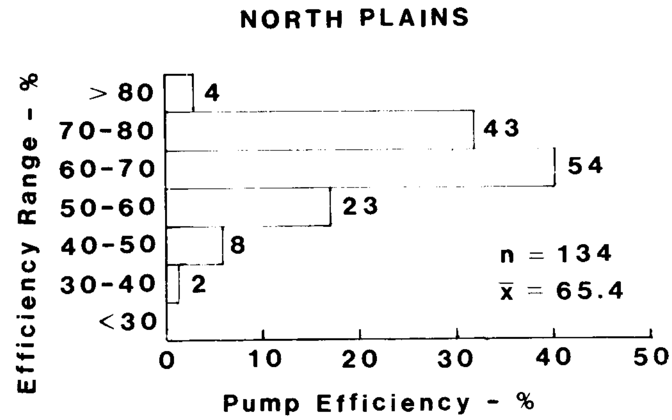

Figure 3. Efficiency distribution for pumps in the North Plains.

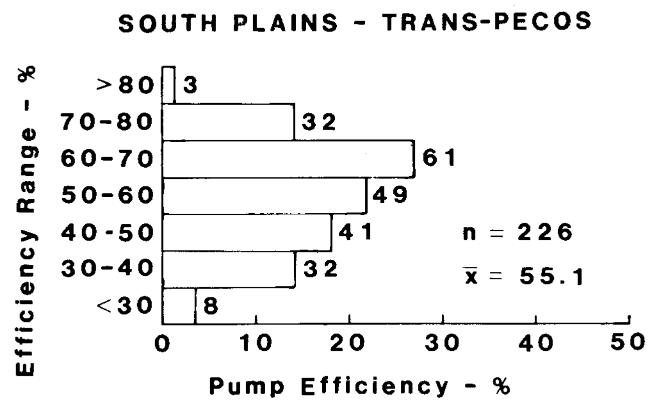

Figure 4. Efficiency distribution for pumps in the South Plains and Trans-Pecos areas combined.

North Plains and Trans-Pecos areas to be higher than for the South Plains. The combined higher pump and engine efficiencies in the North Plains caused the average natural-gas-powered pumping plants efficiency for the area to be appreciably higher than for the other two areas. Diesel engines in the North Plains were slightly more efficient than in the South Plains. Thus, the diesel-powered pumping plants in the North Plains were also more efficient. Electric-powered pumping plants in the North Plains were much more efficient than for the other two areas. Only 10 electric-powered pumps were tested in the North Plains, and they were newer installations with high pumping rates and pumping lifts.

Temporal Changes in Irrigation Pumping Plant Efficiencies

Several of the pumping equipment efficiencies can be directly compared with the study published by Texas Tech University in 1968 (2), Table 2. Average pump efficiency in the Texas Tech study was 52.2% compared with an average efficiency of 58.9% in this study. However, the higher efficiency in this study is primarily due to the high efficiency pumps in the North Plains. Average efficiency of natural-gas-powered engines was essentially the same in the two studies. Engine efficiency averaged 19.8% in the Texas Tech University study. In this study, it averaged

20.5%. Average efficiency of natural-gas-powered pumping plants was higher in this study, but this was due to higher efficiency pumps.

Electric-powered pumping plants were more efficient in this study for both vertical hollow-shaft and sumbersible motors. For pumps with vertical hollow-shaft motors, average pumping plant efficiency increased from 48.6 in the Texas Tech University study to 52.9% in this study. For pumps with submersible motors, average pumping plant efficiency increased from 35.6 to 40.9%. The electric-powered pumping plants in this study were also influenced by the higher pump efficiencies. Thus, the major change in pumping equipment efficiency between the two studies was for turbine pumps, especially those in the North Plains.

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