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Reversing Hydraulic Fan Drive Systems

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ABSTRACT

One challenge for today's machine or system designer is to consider all of the factors involved in determining the cooling system's fan drive. One large factor in this decision is determining if a fan reversing function is required. If reversing is required, a hydraulic fan drive is a top choice. This paper describes several of the basic systems currently in use for reversing fans as well as a newly optimized option seldom used in the past that is now more relevant due a new product development.

INTRODUCTION

This paper will take the reader through the evolution of hydraulically powered fan drives, where the function of reversing the fan direction is included. It will include a number of options and will review several key aspects of the systems including;

1. The impact on power loss of the fan drive and consequent increased need for heat rejection capability
2. The space claim differences, due to both the number and size of components and to their power density
3. Cost benefits related to parts count, assembly time and complexity requirements
4. Differences in system flexibility and controllability
5. The reliability differences due to the number of components, hydraulic connections and assembly steps required

The discussion will include open loop and closed loop options, as well as dedicated and shared flow source systems.

Once this review of several options is complete, the focus will turn to one in particular that is not commonly seen today, but can offer several benefits in size and efficiency.

MAIN SECTION

PART 1 - SYSTEM DESCRIPTIONS

The types of systems used in reversing, hydraulically driven, fan drives include a broad range of options that impact the system. The list below gives an overview of this range.

Open Loop Type Systems – **Dedicated Flow Source**

1) Fixed pump (typically a gear pump) and fixed motor (typically a gear or vane motor) with a directional control valve (DCV) in a separate manifold for reversing. One major concern with this type of system is the fast response of the typical DCV. For this reason, another valve is required in the system to reduce the pressure (and flow) supplied to the motor to reduce the fan speed and prevent fan failure from harsh direction changes.

2) Same system as above but with the DCV (and the speed control valve) integrated into the motor to reduce the assembly and reliability concerns of extra fittings and hoses.

3) Variable pump with a fixed motor and DCV (either integrated or not). The variable pump helps to address the concerns of sudden shifts at high fan speeds, as the pump can be used to reduce the fan speed before the DCV shift. This eliminates a need for the additional speed control valve and the consequent power loss that comes from pumping oil over a relief valve. These systems typically have higher pressure capabilities than the fixed pump systems, but not as high as typical closed loop systems, in part because of the pressure limits of the DCVs.

4) Fixed or variable pumps with a motor capable of reversing output direction without the use of a DCV. If used with a variable pump, this type of system has the lowest power loss of an open loop system, as it eliminates the pressure loss (and heat generation) associated with the DCVs. It also has the lowest losses for the speed control. Furthermore, by eliminating the valves completely, it has the potential to operate at higher pressures which can further increase the

efficiency and reduce product package size. This system will be the focus of the second part of this paper.

Open Loop System – **Shared Flow Source**

This type of system can be used with any one of the open loop pumps described above. It would utilize a variable displacement motor to produce the desired fan speed based on the pressure available. If the variable motor option is combined with the ability to internally reverse output direction, this system can also achieve reversing with a shared flow source and no DCVs.

Closed Loop System – **Dedicated Flow Source**

This type of system will typically use a variable displacement pump with a fixed motor. The fan speed is controlled via the pump displacement control, with feedback from the fan and/or cooling system. Closed loop systems typically use components with higher pressure ratings, thus giving higher power density capability. They do, however, have certain drawbacks, such as the requirement of a low pressure supply (charge) source, which will cause a loss of power and associated heat generation, and two sets of high pressure lines and fittings.

SYSTEM COMPARISONS

There are several aspects of a hydraulically driven fan system that a machine designer might be concerned with. These include:

1) Space claim
2) Effects on engine power availability and heat rejection systems
3) Cost – Initial cost and/or total cost of ownership
4) The ability to tailor the system response and/or performance – system flexibility
5) Impact on the machine assembly and service – system complexity, number of parts, etc.

This section will show some typical comparisons between the systems listed above. These comparisons will focus on fan systems in approximately the 25 and 50 kW fan power range.

<u>Space Claim</u>

Table 1, below, gives a comparison of volume space claim for the different types of systems discussed. The following definitions apply to the following tables:

GM = external gear type motor

PM = axial piston type motor

Table 1 Machine Space Claim for Various Systems

System Configuration	Lower Power System Volume (cm^3)	Higher Power System Volume (cm^3)
Fixed Pump Fixed Motor External Valves	5100 (GM) 6700 (PM)	8400 (GM) 11000 (PM)
Fixed Pump Fixed Motor Integral Valves	15000 (GM) 7300 (PM)*	17000 (GM) 7500 (PM)*
Variable Pump Fixed Motor External Valves	9200 (GM) 10800 (PM)	11500 (GM) 14500 (PM)
Variable Pump Fixed Motor Integral Valves	16100 (GM) 10700 (PM)*	17000 (GM) 12400 (PM)*
Variable Pump Reversing Motor	11900 (PM)**	11900 (PM)**
Closed Circuit Variable Pump Fixed Motor	11300	16200

*Data based on estimations – actual product does not exist to the author's knowledge

**Includes a new product recently developed for the market

The information in Table 1, except as noted, is based on actual products generally available to the market today and is based on basic length, width and height dimensions.

Engine Power Draw/Heat Generation

The following discussion considers a typical fan duty cycle as given below in Table 2.

Table 2 – Typical Fan Duty Cycle

Step	% of Duty Cycle	Motor Supply Pressure (bar)	Fan (Motor) Speed (rpm)
1	2	10	500
2	4	22.5	750
3	5	40	1000
4	12	62.5	1250
5	20	90	1500
6	20	122.5	1750
7	15	160	2000
8	12	202.5	2250
9	10	250	2500

Based on typical characteristics of a DCV sized per normal practice (which is the same DCV assumed in the space claim discussion above) and, on typical motor volumetric efficiencies, Table 3 shows the power loss caused by the DCV for the duty cycle listed above for two sizes of fan systems.

Table 3 – Power Loss due to DCV Pressure Drop

	25kW Power Gear Motor	50kW Power Gear Motor	25kW Power Piston Motor	50kW Power Piston Motor
Peak Fan Power (kW)	26	46.8	26	46.8
Weighted Duty Cycle Power (kW)	10.3	18.5	10.3	18.5
Peak Power Loss (kW)	2.8	3.1	2.0	2.2
Weighted Duty Cycle Power Loss (kW)	1.1	1.2	0.8	0.9
% Increase in Power Draw on Engine	9.3	5.7	7.4	4.6
% of Fan System Power Going to Heat Generation	8.5	5.4	6.9	4.4

The information summarized in Table 3 is shown in more detail in Figure 2 in the appendix.

Table 4, below, shows typical differences in power loss between a gear motor and piston motor for a fan drive system due to efficiency differences.

Table 4 – Power Loss Delta = Power Loss of Gear Motor-Power Loss of Piston Motor

	Low Power System	High Power System
Power Loss Delta at Peak Operation (kW)	1.2	2.6
Power Loss Delta for Weighted Duty Cycle (kW)	0.5	1.0

The following paragraph is not directly related to the reversing function, but could be of interest to the reader.

One difference between fixed pump (FP) and variable pump (VP) systems is the difference in power loss to achieve speed control. The same typical duty cycle discussed already would lead to an increase in engine power draw of 27% for a fixed pump system (due to losses across a proportional relief valve) and a 12% increase in power draw for a variable pump system (due to control losses). A modification to the traditional fixed pump system is to use two fixed pumps with a recirculating or unloading valve in one section. For this duty cycle, the optimum unloaded pump displacement would be 15% of the total pump displacement and would reduce the power draw increase to 16%. Further information on this is shown in Figure 3 in the appendix.

Cost – Up Front and Total Cost of Ownership

The first two topics in this section, “Space Claim” and “Power Loss”, clearly play a significant part in cost. Both play a major part in the initial machine design. Component size will make packaging more difficult and power loss will affect the sizing of cooling systems (which can further complicate packaging). ***Power loss***

also results in an ongoing additional cost for fuel and loss of productivity.

Another part of cost is the initial cost of the components. While this paper does not include actual price numbers, it does show relative differences in the systems discussed previously. The traditional system of a fixed pump (FP), gear motor (GM) and valve manifold is used as the baseline for the comparison. The numbers in Table 5 reflect not only the major components listed, but also items such as hoses, fittings and assembly costs.

Table 5 – Relative System Costs for Components

System Configuration	Lower Power System Volume (cm^3)	Higher Power System Volume (cm^3)
Fixed Pump Fixed Motor External Valves	1.00 (GM) 1.05 (PM)	1.00(GM) 1.10(PM)
Fixed Pump Fixed Motor Integral Valves	0.94 (GM) 0.85 (PM)*	0.87(GM) 0.84 (PM)*
Variable Pump Fixed Motor External Valves	1.34 (GM) 1.39 (PM)	1.36 (GM) 1.46 (PM)
Variable Pump Fixed Motor Integral Valves	1.20 (GM) 1.16 (PM)*	1.15 (GM) 1.19 (PM)*
Variable Pump Reversing Motor	1.14 (PM)**	1.17 (PM)**
Closed Circuit Variable Pump Fixed Motor	1.29	1.23

*Data based on estimations – actual product does not exist to the author's knowledge

**Includes a new product recently developed for the market

System Flexibility and Controllability

A statement of system flexibility relates to the flexibility in designing the system into the overall machine and in using the system to achieve the desired results.

Open circuit systems tend to be more flexible in designing into a machine since there is only one high pressure line to connect the pump and motor. The rest of the open circuit system (inlet and return lines) are low pressure and can be routed independently. A closed circuit system requires two high pressure lines between these two components.

A reversing motor with proportional input capability can be operated with a typical on/off type of signal, like a directional control valve, or it can be operated with a controlled current signal to better control the reversing process, if needed by the system.

System Assembly & Service

The main points of this discussion are around the number of components and the complexity of assembly and service, including troubleshooting.

Any of the systems mentioned include the basic requirements of a pump, a motor, a controller and hydraulic connections (hoses and fittings).

In open circuit systems, adding an external valve manifold not only adds that assembly, but also adds a second set of hoses and fittings, thus increasing assembly and service times and increasing the risk of failures of those processes resulting in leaks. Adding directional control valves and proportional relief valves (for speed control) to the pumps or motors can make those products more complex, add package size and increase the risk of leaks due to the interfaces of those valves to the base components.

Use of a variable pump with pressure control and a reversing-capable motor keeps the system complexity for assembly and service down to a level similar to the basic system. Troubleshooting becomes a simpler task and the risk of failure is reduced with a minimum of hydraulic sealing joints.

PART 2 – REVERSING MOTOR WITHOUT DCV

This system, using a variable pump and reversing motor, has not been a practical solution in the past because a cost effective motor did not exist. The only way to accomplish this previously would be to use a typical closed circuit pump equipped to act as a motor The ideal product for this type of application would be a simple two position axial piston motor capable of full displacement in both directions. This allows a combination of the benefits of a typical open circuit system (one high pressure line, true pressure control) with a typical closed circuit system (no directional control or speed control valves required and improved system operation control).

This type of motor would be spring biased to full displacement in the forward direction and then, when a reversal is desired, an integral valve in the motor would accept a signal from the system controller and, using internal system pressure, shift the motor to the reverse direction. When the reverse cycle is complete, the signal is removed and the motor returns to the forward direction. By incorporating the spring bias and using a proportional valve for the control, the control system can be designed to shift the motor as aggressively or slowly as desired. Also, the spring bias insures that a loss of signal to the motor would give full forward displacement, but do so in a way that the system is not damaged. This is accomplished by removing the shock loading and sudden reversals associated with DCV systems.

There is no required difference in the system architecture between a system using a DCV or a reversing motor. The reversing motor would accept the same digital signal used for a DCV or, as mentioned above, the system designer may choose to tailor the shift characteristics by using a proportional signal. Figure 1, below, shows a typical reversing cycle with a digital input. The second speed change in the trace is the return from reverse to forward operation. As the data shows, the inherent motor characteristics can protect the system from damage due to unexpected or uncontrolled reversals caused by electrical or controller issues.

The motor uses the pressure in the system line to shift direction, but is designed to operate at a minimal system pressures for maximum system flexibility.

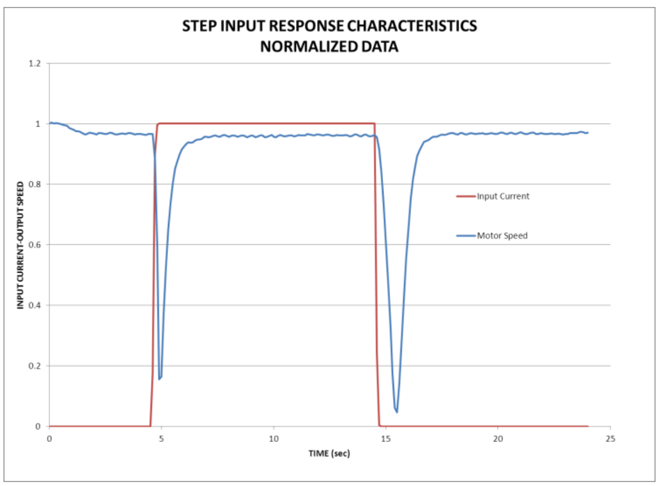

Figure 1 – Step Input Response

CONCLUSION

If a medium or high power reversing fan drive is required on a piece of equipment, a hydraulically driven fan is currently the top choice. There are several categories of systems, and a number of options within each category, for a system designer to choose from. There are several key factors to consider in making that choice.

In today's world of increasing focus on conservation of energy, resources, reliability and total cost of ownership, one system that stands out is the use of a variable pump and reversing capable motor (without the use of directional control valves). This system has the potential for the lowest power loss, highest reliability and the least system complexity (fewest components) of any open circuit system.

CONTACT

Steve Frantz earned his Bachelor of Science degree from Iowa State University in Mechanical Engineering with a focus on fluid power and turbine design.

Steve worked in the fluid power industry for 29 years with a focus on product development and has been involved in, or the lead on, several major product developments. He is currently a staff engineer with Danfoss Power Solutions working on product development in the Medium Power business area.

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ADDITIONAL SOURCES

Additional information on hydraulic fan drives can be found in the following documents.

1) Danfoss Power Solutions, "Hydraulic Fan Drive Systems Design Guidelines," Bulletin 520L0926 Revision BC, May 2013, available by document search at www.PowerSolutions.Danfoss.com

2) Danfoss Power Solutions, "Hydraulic Fan Drive Systems Technical Information," Bulletin 520L0824 Revision CC, November 2010, available by document search at www.PowerSolutions.Danfoss.com

APPENDIX

Figure 2 - Directional Control Valve Power Loss for Various Systems

Directional Control Valve Power Loss

Piston Motors		Motor Vol Effic		90%													
Motor Displacement (cc)		25						Motor Displacement (cc)		45							
Time (sec)	Pressure (dbar)	Speed (rpm)	Flow (lpm)	Motor Input Power (W)	Wtd Power (W)	DCV Pressure (bar)	DCV Loss (W)	Wtd Loss (W)	% Power Lost	Flow (lpm)	Motor Input Power (W)	Wtd Power (W)	DCV Pressure (bar)	DCV Loss (W)	Wtd Loss (W)	% Power Lost	
0	2.5	250	6.94	29	0	0.19	2.21	0.00	7.1%	12.50	52	0	0.12	2.52	0.00	4.6%	
2	10	500	13.89	231	463	0.81	18.64	37.27	7.5%	25.00	417	833	0.52	21.76	43.53	5.0%	
4	22.5	750	20.83	781	3125	1.83	63.69	254.76	7.5%	37.50	1406	5625	1.17	73.35	293.39	5.0%	
5	40	1000	27.78	1852	9259	3.28	151.77	758.85	7.6%	50.00	3333	16667	2.07	172.90	864.50	4.9%	
12	62.5	1250	34.72	3617	43403	5.14	297.28	3567.31	7.6%	62.50	6510	78125	3.23	336.05	4032.56	4.9%	
20	90	1500	41.67	6250	125000	7.41	514.61	10292.15	7.6%	75.00	11250	225000	4.63	578.41	11568.25	4.9%	
20	122.5	1750	48.61	9925	198495	10.10	818.17	16363.31	7.6%	87.50	17865	357292	6.28	915.62	18312.44	4.9%	
15	160	2000	55.56	14815	222222	13.20	1222.35	18335.27	7.6%	100.00	26667	400000	8.18	1363.30	20449.50	4.9%	
12	202.5	2250	62.50	21094	253125	16.72	1741.57	20898.78	7.6%	112.50	37969	455625	10.33	1937.07	23244.86	4.9%	
10	250	2500	69.44	28935	289352	20.65	2390.21	23902.08	7.6%	125.00	52083	520833	12.73	2652.56	26525.63	4.8%	
					11444.44	Duty Cycle Power Loss		944.10	7.6%	% of pump output lost		20600.00	Duty Cycle Power Loss		1053.35	4.9%	% of pump output lost
									8.2%	% additional power req'd						5.1%	% additional power req'd
Gear Motors		Motor Vol Effic		85%													
Motor Displacement (cc)		25						Motor Displacement (cc)		45							
Time (sec)	Pressure (dbar)	Speed (rpm)	Flow (lpm)	Motor Input Power (W)	Wtd Power (W)	DCV Pressure (bar)	DCV Loss (W)	Wtd Loss (W)	% Power Lost	Flow (lpm)	Motor Input Power (W)	Wtd Power (W)	DCV Pressure (bar)	DCV Loss (W)	Wtd Loss (W)	% Power Lost	
0	2.5	250	7.35	31	0	0.22	2.64	0.00	7.9%	13.24	55	0	0.14	3.04	0.00	5.2%	
2	10	500	14.71	245	490	0.90	22.17	44.35	8.3%	26.47	441	882	0.59	25.85	51.70	5.5%	
4	22.5	750	22.06	827	3309	2.06	75.70	302.79	8.4%	39.71	1489	5956	1.31	86.98	347.94	5.5%	
5	40	1000	29.41	1961	9804	3.68	180.31	901.54	8.4%	52.94	3529	17647	2.32	204.99	1024.94	5.5%	
12	62.5	1250	36.76	3830	45956	5.76	353.10	4237.15	8.4%	66.18	6893	82721	3.61	398.41	4780.89	5.5%	
20	90	1500	44.12	6618	132353	8.31	611.16	12223.16	8.5%	79.41	11912	238235	5.18	685.79	13715.86	5.4%	
20	122.5	1750	51.47	10509	210172	11.33	971.59	19431.75	8.5%	92.65	18915	378309	7.03	1085.69	21713.82	5.4%	
15	160	2000	58.82	15686	235294	14.81	1451.48	21772.19	8.5%	105.88	28235	423529	9.16	1616.65	24249.74	5.4%	
12	202.5	2250	66.18	22335	268015	18.75	2067.93	24815.12	8.5%	119.12	40202	482426	11.57	2297.22	27566.58	5.4%	
10	250	2500	73.53	30637	306373	23.16	2838.03	28380.25	8.5%	132.35	55147	551471	14.26	3145.94	31459.37	5.4%	
					12117.65	Duty Cycle Power Loss		1121.08	8.5%	% of pump output lost		21811.76	Duty Cycle Power Loss		1249.11	5.4%	% of pump output lost
									9.3%	% additional power req'd						5.7%	% additional power req'd

Figure 3 - Impact on Power Loss of Dual Displacement Fixed Pumps with Unloading Valves

Impact of 2 section fixed pump with unloading valve on power loss

Fixed Motors Motor Vol Effic 90%

Motor Displacement (cc) 25

Time (sec)	Pressure (dbar)	Speed (rpm)	Flow (lpm)	Motor Input Power (W)	Wtd Power (W)	Excess Flow (lpm)	Relief Valve Power (W)	Wtd Power (W)	Pump Vol Eff %	Pump Power Loss (W)	Wtd Power (W)
0	2.5	250	6.94	29	0	62.50	260.42	0.00	85%	5	0
2	10	500	13.89	231	463	55.56	925.93	1851.85	85%	41	82
4	22.5	750	20.83	781	3125	48.61	1822.92	7291.67	85%	138	551
5	40	1000	27.78	1852	9259	41.67	2777.78	13888.89	85%	327	1634
12	62.5	1250	34.72	3617	43403	34.72	3616.90	43402.78	85%	638	7659
20	90	1500	41.67	6250	125000	27.78	4166.67	83333.33	85%	1103	22059
20	122.5	1750	48.61	9925	198495	20.83	4253.47	85069.44	85%	1751	35029
15	160	2000	55.56	14815	222222	13.89	3703.70	55555.56	85%	2614	39216
12	202.5	2250	62.50	21094	253125	6.94	2343.75	28125.00	85%	3722	44669
10	250	2500	69.44	28935	289352	0.00	0.00	0.00	85%	5106	51062
								Relief Valve			Pump Excess
% of Motor Displ in unloaded section			0%		11444.44	Duty Cycle Power Loss		3185.19	21.8%		2019.61
									27.8%		

Motor Displacement (cc) 45

Time (sec)	Flow (lpm)	Motor Input Power (W)	Wtd Power (W)	Excess Flow (lpm)	Relief Valve Power (W)	Wtd Power (W)	Pump Vol Eff %	Pump Power Loss (W)	Wtd Power (W)
0	12.5	52	0	112.50	468.75	0.00	85%	9	0
2	25	417	833	100.00	1666.67	3333.33	85%	74	147
4	37.5	1406	5625	87.50	3281.25	13125.00	85%	248	993
5	50	3333	16667	75.00	5000.00	25000.00	85%	588	2941
12	62.5	6510	78125	62.50	6510.42	78125.00	85%	1149	13787
20	75	11250	225000	50.00	7500.00	150000.00	85%	1985	39706
20	87.5	17865	357292	37.50	7656.25	153125.00	85%	3153	63051
15	100	26667	400000	25.00	6666.67	100000.00	85%	4706	70588
12	112.5	37969	455625	12.50	4218.75	50625.00	85%	6700	80404
10	125	52083	520833	0.00	0.00	0.00	85%	9191	91912
						Relief Valve			Pump Excess
			20600.00	Duty Cycle Power Loss		5733.33	21.8%		3635.29
							27.8%		

Fixed Motors Motor Vol Effic 90%

Motor Displacement (cc) 25

Time (sec)	Pressure (dbar)	Speed (rpm)	Flow (lpm)	Motor Input Power (W)	Wtd Power (W)	Excess Flow (lpm)	Relief Valve Power (W)	Wtd Power (W)	Pump Vol Eff %	Pump Power Loss (W)	Wtd Power (W)
0	2.5	250	6.94	29	0	52.08	217.01	0.00	85%	5	0
2	10	500	13.89	231	463	45.14	752.31	1504.63	85%	41	82
4	22.5	750	20.83	781	3125	38.19	1432.29	5729.17	85%	138	551
5	40	1000	27.78	1852	9259	31.25	2083.33	10416.67	85%	327	1634
12	62.5	1250	34.72	3617	43403	24.31	2531.83	30381.94	85%	638	7659
20	90	1500	41.67	6250	125000	17.36	2604.17	52083.33	85%	1103	22059
20	122.5	1750	48.61	9925	198495	10.42	2126.74	42534.72	85%	1751	35029
15	160	2000	55.56	14815	222222	3.47	925.93	13888.89	85%	2614	39216
12	202.5	2250	62.50	21094	253125	6.94	2343.75	28125.00	85%	3722	44669
10	250	2500	69.44	28935	289352	0.00	0.00	0.00	85%	5106	51062
								Relief Valve			Pump Excess
% of Motor Displ in unloaded section			15%		11444.44	Duty Cycle Power Loss		1846.64	13.9%		2019.61
									16.1%		

Motor Displacement (cc) 45

Time (sec)	Flow (lpm)	Motor Input Power (W)	Wtd Power (W)	Excess Flow (lpm)	Relief Valve Power (W)	Wtd Power (W)	Pump Vol Eff %	Pump Power Loss (W)	Wtd Power (W)
0	12.5	52	0	93.75	390.63	0.00	85%	9	0
2	25	417	833	81.25	1354.17	2708.33	85%	74	147
4	37.5	1406	5625	68.75	2578.13	10312.50	85%	248	993
5	50	3333	16667	56.25	3750.00	18750.00	85%	588	2941
12	62.5	6510	78125	43.75	4557.29	54687.50	85%	1149	13787
20	75	11250	225000	31.25	4687.50	93750.00	85%	1985	39706
20	87.5	17865	357292	18.75	3828.13	76562.50	85%	3153	63051
15	100	26667	400000	6.25	1666.67	25000.00	85%	4706	70588
12	112.5	37969	455625	12.50	4218.75	50625.00	85%	6700	80404
10	125	52083	520833	0.00	0.00	0.00	85%	9191	91912
						Relief Valve			Pump Excess
			20600.00	Duty Cycle Power Loss		3323.96	13.9%		3635.29
							16.1%		