

HISTORY OF REVISIONS

Table of Revisions

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| | | |
|--------------------------------------|---|----|
| INTRODUCTION | Abstract..... | 5 |
| | Overview | 5 |
| | Principles of operation | 5 |
| | Power savings | 6 |
| | Modulation preferred over on/off fan speed control..... | 6 |
| FAN DRIVE DESIGN | Design considerations..... | 7 |
| | Fan drive element selection | 8 |
| FAN DRIVE COMPONENTS | Estimate of maximum input torque to the pump | 9 |
| | Sizing | 10 |
| SYSTEM DESIGN PARAMETERS | Sizing equations | 12 |
| | Pumps | 12 |
| | Motors..... | 12 |
| | Variables..... | 12 |
| | Axial flow fan power formula..... | 13 |
| | Power to system parameter relationships | 13 |
| | Engine details | 14 |
| | Power steering..... | 14 |
| | Fan information..... | 14 |
| | Control preference..... | 15 |
| | Reservoir..... | 15 |
| | Fluid..... | 15 |
| | Filtration..... | 15 |
| | Pump drive | 16 |
| | Pump drive data form | 16 |
| | Technical features | 17 |
| | Maximum pump speed..... | 17 |
| | Minimum pump and motor speed | 17 |
| | Motor starting pressure | 17 |
| | Motor free run pressure | 18 |
| | Input torque ratings | 18 |
| | Pump drive conditions | 18 |
| | Tapered shaft and hub connections..... | 19 |
| | Pump suction..... | 19 |
| | Case drain pressure | 19 |
| | Filtration..... | 20 |
| | Operating temperatures..... | 20 |
| | Fluids..... | 20 |
| | Mounting..... | 20 |
| | Axial thrust motors | 21 |
| | Piping..... | 21 |
| | Reservoir..... | 22 |
| Cavitation and aeration damage | 23 | |
| Cooling..... | 23 | |
| Pressure protection and ratings..... | 23 | |
| Bearing life expectancy..... | 23 | |

| | | |
|---|--|----|
| GLOSSARY | Terminology | 24 |
| APPENDIX A-FAN PERFORMANCE | Fans | 25 |
| | Fan performance | 25 |
| | Axial thrust..... | 26 |
| | Fan laws..... | 27 |
| APPENDIX B-FAN DRIVE SIZING EQUATIONS | Fan drive sizing equations and derivations | 32 |
| | Hydraulic system comparisons..... | 34 |
| APPENDIX C-FAN DRIVE SIZING EQUATIONS, USING VARIABLE DISPLACEMENT MOTORS | Hydraulic systems with 2 position, variable displacement motors, equations and derivations | 36 |
| | Spreadsheet to calculate optimum minimum displacement for two position variable motor | 38 |
| APPENDIX D-PRESSURE CHANGE DUE TO TRANSIENT FLOW IN A PASSAGE | Pressure change due to transient flow in a passage, equations and derivations | 39 |
| APPENDIX E-INFLUENCE OF BYPASS VALVE PRESSURE DROP | Influence of bypass valve pressure drop on fan trim speed, in applications using fixed displacement pumps, equations and derivations | 41 |
| APPENDIX F1-INFLUENCE OF TEMPERATURE, PRESSURE AND RELATIVE HUMIDITY ON SPECIFIC WEIGHT OF AIR | Influence of temperature, pressure and relative humidity on specific weight of air | 45 |
| APPENDIX F2-INFLUENCE OF ALTITUDE ON ATMOSPHERIC PRESSURE | Influence of altitude on atmospheric pressure | 46 |
| APPENDIX G-INFLUENCE OF REVERSED FAN PERFORMANCE ON SYSTEM PERFORMANCE | Influence of generic altitude on atmospheric pressure | 47 |
| APPENDIX H-SYSTEM CONSIDERATIONS FOR H1 FAN DRIVES WITH REVERSED FAN ROTATION | Influence of reversed fan rotation on system performance | 48 |

ABSTRACT

Fan drive system sizing relies heavily on the input received from the customer. All system sizing calculations are based on the required *fan power @ trim speed* data given to the hydraulic system design engineer. This data is a statement of the fan drive motor shaft power that is required to turn a fan at the required speed to push, or pull, a required volume of air across coolers/radiators. The usual sequence of events is:

For a detailed definition of terms in this document, refer to *Terminology* on page 24.

- The engine manufacturer advises the customer, or cooling system designer, of the heat dissipation required from the cooling system, charge air cooler etc. This information is combined with the heat rejection data for any accessories and work functions on the machine (such as : transmission cooler, hydraulic cooler, and A/C condenser) to determine the maximum heat rejection profile for the system.
- The customer's cooling pack manufacturer uses this data to size the cooling package and generally recommends a fan to suit this need, providing the rated fan power, rated fan speed, and the fan speed required to satisfy the cooling needs of the system.
- With this information, knowing the minimum engine speed at which maximum fan speed needs to occur, the hydraulic system designer can size the hydraulic fan drive system.

OVERVIEW

One goal of this document is to provide the reader with the equations and formulae needed to size a hydraulic fan drive, given that they are provided with the following information:

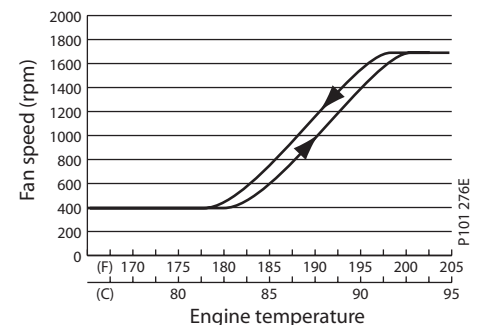
- Rated fan power.
- Rated fan speed.
- Fan speed required to meet the maximum cooling needs of the cooling system.
- Engine speed at which maximum system cooling is required.

This document also provides an explanation of the terms and factors used in the derivation of the sizing equations. In addition, the reader is provided with recommendations of simple system design solutions that will help provide a viable system with satisfactory performance.

PRINCIPLES OF OPERATION

The vehicle's cooling fan is driven by a hydraulic motor, which in turn, is driven by a hydraulic pump. The hydraulic pump can be driven directly off of the engine supplied PTO (Power Take Off), or with a belt drive. A thermostatically, or electrically, controlled proportional pressure control valve modulates the fan speed depending on a temperature reading. In a cold condition, the fan idles with very low power consumption. During the hot condition, the maximum fan speed is controlled by a pressure control valve, which adjusts the fan speed to meet the cooling needs of the total system. Every system has a temperature, which allows for the most efficient performance. The thermovalve, or an electronic control system, attempts to maintain the system at the optimum design temperature, which the system integrator selects during the design phase of the project.

Fan speed vs engine temperature



PRINCIPLES OF OPERATION (continued)

To optimize the cooling system operation in various environmental conditions and to minimize parasitic losses, the Sauer-Danfoss modulating fan drive system enables the fan cycle to be designed to specific heat rejection requirements for a wide range of environmental conditions. Vehicle manufacturers have complete control of the fan cycle by choosing the appropriate temperature limit.

The Sauer-Danfoss modulating fan drive system remains at idle speed until conditions require increased fan speeds. By regulating the pressure drop across the hydraulic motor, modulation of fan speed occurs above this point and over-cooling is prevented.

POWER SAVINGS

In the **fan off** condition, the fan may idle at approximately 30% of rated speed, but it will only consume about 3% of rated power. The Sauer-Danfoss modulating fan drive system allows the system designer to size the fan for the engine speed at which maximum heat rejection occurs. The fan speed will remain essentially constant at all higher engine speeds. Consequently, the fan will not require excessive parasitic losses as engine speed increases. In systems where the engine speed at maximum heat rejection is 80% of the governed speed, the reduction in parasitic power loss due to over-speeding a mechanically driven fan can be as high as 95%.

MODULATION PREFERRED OVER ON/OFF FAN SPEED CONTROL

Fan speed modulation occurs over a temperature range chosen by the system's designer. This eliminates the sudden changes in speed that cause dramatic changes in noise levels. Similarly, large accelerations of components, which may limit the reliability for long-term operation, are eliminated. Modulation also allows intermediate levels of cooling without unnecessary cycling of the fan between minimum and maximum speed. The calibration temperature, operating range, and ramp times can be varied independently by the system designer to achieve the desired level of temperature control.

DESIGN CONSIDERATIONS

- Parasitic losses from excessive fan speed are high. Power consumed by a fan is proportional to fan speed cubed (speed³).
- Heat rejection to the atmosphere does not increase linearly with engine speed.
- Overheating and/or over cooling the system will result in loss of efficiency and productivity.
- Overheating, and/or over cooling the engine can result in increased emissions to the environment.
- The proportion of operating time during which full fan speed (maximum fan power) is needed is typically about 20% and can be as low as 5%.
- Mounting the fan directly to the engine requires large fan blade tip clearances due to normal engine vibration and movement. This leads to loss of fan performance. Mounting the fan directly to a hydraulic motor can minimize tip clearance and boost fan performance significantly.

Hydraulic fan drive system designers select components for unique combinations of engine, fan, and application parameters. Do not exchange/change fan system components indiscriminately. Design factors which determine the selection of the fan drive system for a particular engine, or vehicle, include:

- Engine set point and maximum heat rejection
- Pump rotation
- Pump input torque limitations
- Maximum applied pressure and speed limits for the individual components
- Fit-up and available installation space
- Pump support structure requirements for individual engine/compressor combinations
- Specific engine and accessory temperature control limits

Fan drive element selection

| Fan drive Element | Design parameter | Design flexibility | Design champion |
|----------------------|--|--------------------|-------------------------------------|
| Engine & accessories | Power, speed, total heat rejection and duty cycle | Yes | OEM |
| PTO & Gearing | Engine to pump gear ratio | Sometimes | OEM's choice of engine supplier |
| Pump(s) | Displacement, pressure, speed, fixed pump or variable pump, mounting & drive line | Yes | S-D technical representative, & OEM |
| Fan drive control | Sensor input(s), control output, number of control elements | Yes | S-D technical representative, & OEM |
| Motor(s) | Displacement, pressure, speed, fixed motor or variable motor, mounting & coupling | Yes | S-D technical representative, & OEM |
| Fan(s) | Fan rated power @ rated speed, fan diameter, number of blades, blade pitch, proximity of blades to heat exchanger, direction of air flow | Yes | OEM & cooling specialists |
| Shroud(s) | Type of shroud (flat plate, short duct, venturi), blade axial position in shroud, tip clearance | Yes | OEM & cooling specialists |
| Air flow stream(s) | Air flow rate & static pressure across heat exchanger(s), maximum ambient air temperature, minimum atmospheric pressure, hot air recirculation, baffles, louvres & obstructions | Sometimes | OEM & cooling specialists |
| Heat exchangers | Physical size, height & width, number of heat exchangers in air flow stream, side-by-side, axial stack, materials selected, construction, number and types of tubes, tube configuration, fin density | Yes | OEM & cooling specialists |

FAN DRIVE ELEMENT SELECTION

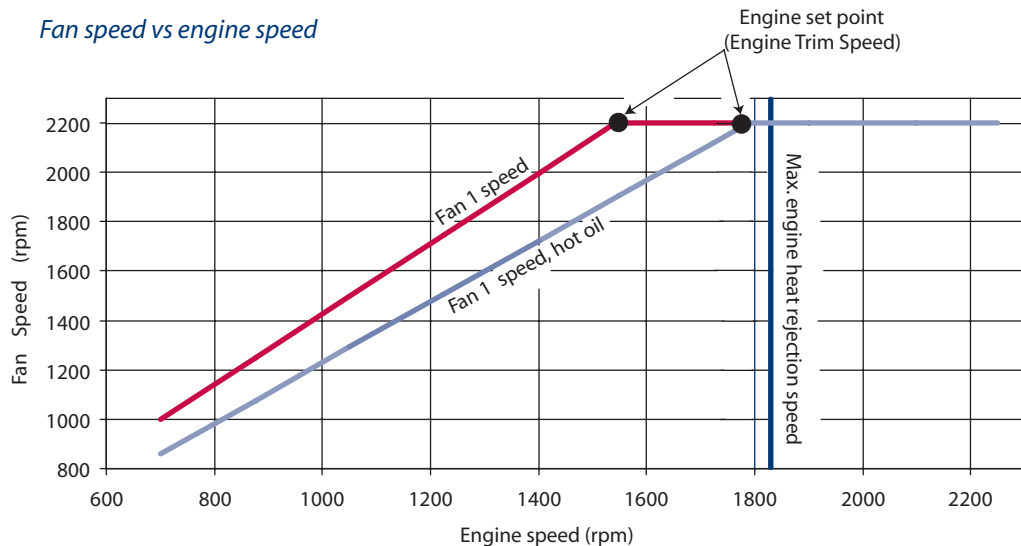
Optimizing the size of fan drive elements depends on selecting the correct components and gear ratios. By matching these components to the fan power requirements, the required unit sizes can be quickly determined. The pump and motor displacements, input gear ratios, engine set point, and pressure limits can be adjusted to provide some optimization of component size. Along with the sizing equations presented in this article, a Sauer-Danfoss fan drive sizing computer tool is available to assist with sizing the hydraulic components.

Many modulating hydraulic fan drives rely on dedicated pumps to provide flow to the fan circuit for optimum sizing. Other circuits are available that provide additional flow for power assisted steering and other accessory systems. In these, and many other circuits, the sizing equations and fan drive sizing tool may still be used to select the required components. Note that the design limits for associated design elements are not identified in this article. They may be reviewed by referring to the Sauer-Danfoss technical information for the components being considered. Machine designers should verify that all design parameters are met for all drive line components.

While the methods described in this article may be useful, they do not represent the only approach to sizing hydraulic components. Contact your Sauer-Danfoss representative if questions of interpretation exist.

Collect the application sizing parameters as identified on [pages 14, 15, and 16](#) of this document. Pay particular attention to the minimum engine speed at which maximum heat rejection to the atmosphere is required. When sizing the pump for the application, the system designer should ensure that the engine set point under hot oil condition is less than the engine speed at which maximum heat rejection occurs. Failure to do this can result in a condition where the cooling system may not provide adequate cooling when maximum work loading and maximum ambient conditions occur simultaneously.

Fan speed vs engine speed



Sample graph, performance prediction will vary depending on choice of input parameters.

**FAN DRIVE ELEMENT
 SELECTION (continued)**

One of the first things that the systems designer should consider is whether the maximum pump torque needed will exceed the input torque limitation of the pump drive. One way to calculate this is to divide the fan power requirement by an estimate of the hydraulic system's overall efficiency and then determine the input torque requirement at the pump speed that is equivalent to the maximum heat rejection speed of the engine.

**ESTIMATE OF MAXIMUM
 INPUT TORQUE TO THE
 PUMP**

Compare the estimated maximum input torque to the maximum available input torque at the pump drive; this will determine the design margin that is available to the designer. The hydraulic system designer should consult with the vehicle system's designer, and/or the prime mover's technical support staff for assistance, if required.

SI system

$$\text{Pump torque, } T_{p(N\cdot m)} \approx \left[\frac{\left(\frac{P_{f_{kW}}}{0.7} \right) \cdot (9549.0)}{(N_e \cdot R)} \right] \quad (N\cdot m)$$

English system

$$\text{Pump torque, } T_{p(lb\cdot in)} \approx \left[\frac{\left(\frac{P_{f_{hp}}}{0.7} \right) \cdot (63025)}{(N_e \cdot R)} \right] \quad (lb\cdot in)$$

Where:

- $P_{f_{kW}}$ = Max power, kW [hp]
- $(N_e \cdot R)$ = Pump speed, rpm
- R = Pump/Engine ratio

Converting terms

$$\text{Pump torque, } T_{p(lb\cdot in)} = T_{p(N\cdot m)} \cdot 8.8507 \quad (lb\cdot in)$$

$$\text{Pump torque, } T_{p(lb\cdot ft)} = T_{p(N\cdot m)} \cdot 0.7376 \quad (lb\cdot ft)$$

$$\text{Pump torque, } T_{p(N\cdot m)} = \left(\frac{T_{p(lb\cdot in)}}{8.8507} \right) \quad (N\cdot m)$$

$$\text{Pump torque, } T_{p(lb\cdot ft)} = \left(\frac{T_{p(lb\cdot in)}}{12.0} \right) \quad (lb\cdot ft)$$

SIZING

Fan drive system sizing relies heavily on the input received from the customer. All system sizing calculations are based on the required *fan power @ trim speed* data given to the hydraulic system design engineer. This data is a statement of the fan drive motor shaft power that is required to turn a fan at the required speed to push, or pull, a required volume of air across coolers/radiators. The usual sequence of events is:

- The engine manufacturer advises the customer, or cooling system designer, of the heat dissipation required from the cooling system, charge air cooler etc. This information is combined with the heat rejection data for any accessories and work functions on the machine (such as : transmission cooler, hydraulic cooler, and A/C condenser) to determine the maximum heat rejection profile for the system.
- The customer’s cooling pack manufacturer will then use this data to size the cooling package and will generally recommend a fan to suit this need, providing the rated fan power, rated fan speed, and the fan speed required to satisfy the cooling needs of the system.
- With this information, knowing the minimum engine speed at which maximum fan speed needs to occur, the hydraulic system designer can size the hydraulic fan drive system.

To completely understand any fan drive system is to understand the fan load characteristics. Fans are unique in that the power to drive the fan changes with the cube of the fan speed, as follows:

$$Pf = k \cdot (N_f)^3$$

$$\frac{Pf_1}{Pf_2} = \left(\frac{N_1}{N_2} \right)^3$$

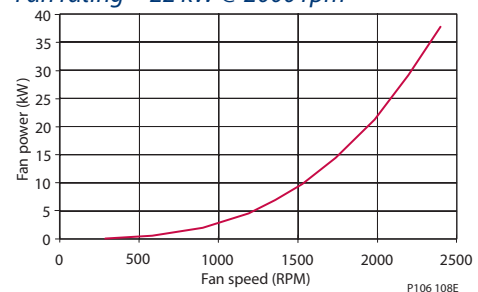
Where:

- Pf = fan power (kW, hp)
- N = fan speed (rpm)
- 1,2 = subscripts for two different conditions
- k = Fan power coefficient

Fan power is defined as the power required to drive the shaft connected to the fan and is equal to the output power of the motor.

When a given fan speed is doubled; the required power to drive the fan increases by a factor of 8.

Fan power requirements (Example)
Fan rating = 22 kW @ 2000 rpm



SIZING (continued)

Since fan horsepower is a function of both pressure and flow (fan speed), it follows that the relationship between fan speed and system pressure is

$$\frac{\Delta P_1}{\Delta P_2} = \left(\frac{N_1}{N_2}\right)^2$$

Where: ΔP = delta pressure across the hydraulic motor (bar, psid)

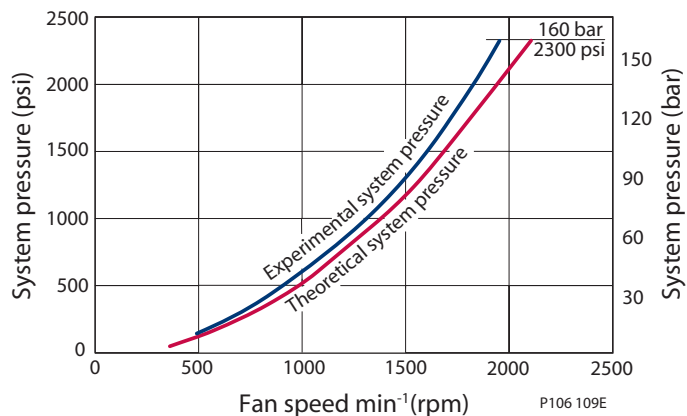
An accurate value of the fan rating is critical to the correct selection of components and their settings.

Although the cubic relationship between fan power and fan speed has been consistently verified experimentally, it is still an approximation of the fan behavior. Therefore, to avoid significant errors in predicting power requirements, the fan power rating should be taken at a speed representative of typical fan operation.

For example, for a system in which the fan usually operates in a speed range of 1800-2200 rpm, a fan rating specified at 2000 rpm will yield more accurate results than a rating specified at, say, 1500 or 2500 rpm.

Fan curves provided by the fan manufacturer are often developed under ideal conditions. It is unlikely that a fan will exhibit exactly the same performance in an actual application (because of: shrouding, heat exchange airflow characteristics, and air density). Only through test data taken on the actual vehicle can a fan's performance characteristics be accurately determined. The curve below illustrates the differences between predicted performance and actual performance of a fan installed in a vehicle. The system designer/integrator is encouraged to confirm their performance predictions via test over the entire operating speed range of the engine, and to refine their prediction model with a revised **fan power coefficient** when they rerun the sizing calculations.

Fan power requirements (example)
 Fan rating = 22 kW @ 2000 rpm



SIZING EQUATIONS

Pumps

Based on SI units

$$\text{Output flow } Q = \frac{V_g \cdot n \cdot \eta_v}{1000} \quad (\text{l/min})$$

$$\text{Input torque } M = \frac{V_g \cdot \Delta p}{20 \cdot \pi \cdot \eta_m} \quad (\text{N}\cdot\text{m})$$

$$\text{Input power } P = \frac{V_g \cdot n \cdot \Delta p}{600\,000 \cdot \eta_m} \quad (\text{kW})$$

Based on English units

$$\text{Output flow } Q = \frac{V_g \cdot n \cdot \eta_v}{231} \quad (\text{US gal/min})$$

$$\text{Input torque } M = \frac{V_g \cdot \Delta p}{2 \cdot \pi \cdot \eta_m} \quad (\text{lbf}\cdot\text{in})$$

$$\text{Input power } P = \frac{V_g \cdot n \cdot \Delta p}{396\,000 \cdot \eta_m} \quad (\text{hp})$$

Motors

Based on SI units

$$\text{Output torque } M = \frac{V_g \cdot \Delta p \cdot \eta_m}{20 \cdot \pi} \quad (\text{N}\cdot\text{m})$$

$$\text{Output power } P = \frac{Q \cdot \Delta p \cdot \eta_t}{600} \quad (\text{kW})$$

Based on English units

$$\text{Output torque } M = \frac{V_g \cdot \Delta p \cdot \eta_m}{2 \cdot \pi} \quad (\text{lbf}\cdot\text{in})$$

$$\text{Output power } P = \frac{Q \cdot \Delta p \cdot \eta_t}{1714} \quad (\text{hp})$$

Variables

SI units [English units]

- V_g = Displacement per revolution cm^3/rev [in^3/rev]
- p_o = Outlet pressure bar [psi]
- p_i = Inlet pressure bar [psi]
- Δp = $p_o - p_i$ (system pressure) bar [psi]
- n = Speed min^{-1} (rpm)
- η_v = Volumetric efficiency
- η_m = Mechanical efficiency
- η_t = Overall efficiency ($\eta_v \cdot \eta_m$)

SI unit formulas are based on cm, bar, N, N·m, W.
English formulas are based on in, psi, lbf·in, hp.

**AXIAL FLOW FAN POWER
FORMULA**

Power to system parameter relationships

$$\frac{Pf_2}{Pf_1} = \frac{(N_2)^3 \cdot (D_2)^5 \cdot v_2}{(N_1)^3 \cdot (D_1)^5 \cdot v_1}$$

$$\frac{Pf_2}{Pf_1} = \frac{\rho_2}{\rho_1} \cdot \left(\frac{N_2}{N_1}\right)^3 \cdot \left(\frac{D_2}{D_1}\right)^5 = \frac{v_2}{v_1} \cdot \left(\frac{N_2}{N_1}\right)^3 \cdot \left(\frac{D_2}{D_1}\right)^5$$

$$\frac{\dot{V}_2}{\dot{V}_1} = \left(\frac{D_2}{D_1}\right)^3 \cdot \left(\frac{N_2}{N_1}\right)$$

$$\frac{\Delta P_2}{\Delta P_1} = \frac{\rho_2}{\rho_1} \cdot \left(\frac{D_2}{D_1}\right)^2 \cdot \left(\frac{N_2}{N_1}\right)^2 = \frac{v_2}{v_1} \cdot \left(\frac{D_2}{D_1}\right)^2 \cdot \left(\frac{N_2}{N_1}\right)^2$$

- Pf₁ = Power of fan at known condition #1
- Pf₂ = Power of fan at condition #2
- N₁ = Fan speed at condition #1
- N₂ = Fan speed at condition #2
- D₁ = Fan diameter at condition #1
- D₂ = Fan diameter at condition #2
- v₁ = Specific weight of air at condition #1
- v₂ = Specific weight of air at condition #2
- ρ₁ = Density of air at condition #1
- ρ₂ = Density of air at condition #2
- ΔP₁ = Hydraulic and/or Static Pressure at condition #1
- ΔP₂ = Hydraulic and/or Static Pressure at condition #2
- Ṁ₁ = Flow rate of air at condition #1
- Ṁ₂ = Flow rate of air at condition #2

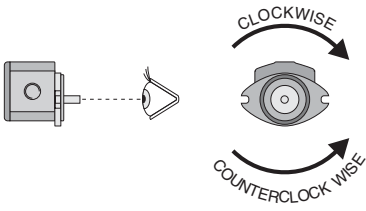
ENGINE DETAILS

Manufacturer _____ **Model or Series** _____

Pump Drive Engine PTO Ratio _____ :1 Input torque
Belt Drive (engine to pump) limit: _____

Pump Rotation Clockwise, Right hand
Counterclockwise, Anti-clockwise, Left hand

Speeds Low Idle _____ RPM (rated)
Governed _____ RPM (rated)
High Idle _____ RPM (max speed)



P106 110E

POWER STEERING

(if applicable)

Controlled Flow Requirement _____ US gal/min l/min

Steering Pressure _____ psi bar
(maximum)

P104 376E

FAN INFORMATION

Manufacturer _____ **Model or Series** _____

Fan Diameter _____ in mm

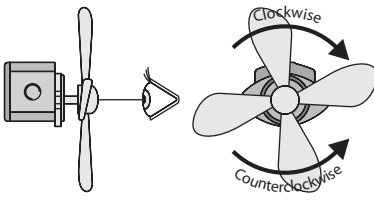
Fan Input Power _____ HP kW At speed _____ rpm

Fan Rotation (viewed on motor shaft, see illustration) **Clockwise**
Counterclockwise

Fan Trim Speed _____ rpm
(viewed on motor shaft, see illustration)

Set Point at Fan Trim Speed _____ rpm
(engine speed where max heat load occurs)

Coolant Temperature at Fan Trim Speed _____ °F _____ °C
(coolant temp where max fan speed is required)



Note: To properly size and specify a fan drive system, fan power requirements must be stated as accurately as possible. Fan power requirements can be determined from fan curves supplied by the manufacturer. Radiator and cooler manufacturers will supply air flow requirements based on heat loads. Air flow information must include accurate air flow and static pressure to determine correct fan power requirements.

P101 344E

CONTROL PREFERENCE

| | | |
|--------------------------------|--|---------------------------------|
| Wax Capsule ThermoValve | Electro-Hydraulic Modulating | Electro-Hydraulic ON/OFF |
| | Single Input <input type="checkbox"/> | <input type="checkbox"/> |
| | Multiple Inputs <input type="checkbox"/> | <input type="checkbox"/> |

P104 377E

RESERVOIR

Reservoir Capacity _____ US gal liter

P104 378E

FLUID

Hydraulic Fluid Type _____

Viscosity _____ at 40° C [104°F] cSt SUS

_____ at 100° C [212°F]

Maximum Fluid Temperature _____ °C _____ °F

P104 379E

FILTRATION

| | | | |
|------------------------|--|--------------------|---------------------------------------|
| Filter Position | Inlet Line <input type="checkbox"/> | Filter Flow | Full Flow <input type="checkbox"/> |
| | Pressure Line <input type="checkbox"/> | | Partial Flow <input type="checkbox"/> |
| | Return Line <input type="checkbox"/> | | |

(recommended)

Filter Rating _____ micron _____ x ratio

Note: Do not locate the filter cartridge inside the reservoir. This reduces the reservoir capacity and reduces the dwell time (the time the oil spends in the reservoir). It also increases the potential for damage to the hydraulic components due to aeration of the oil.

P104 380E

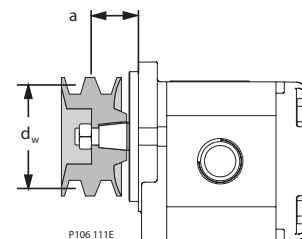
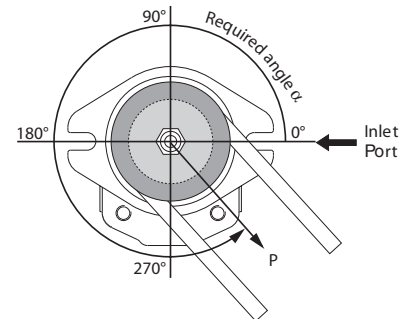
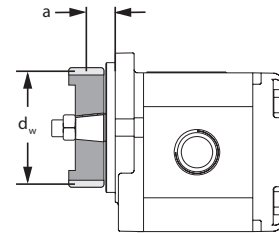
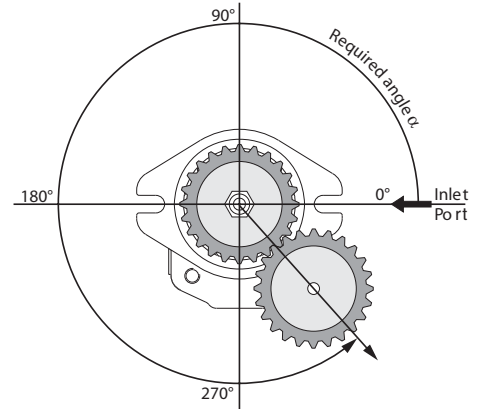
PUMP DRIVE

Pump drive data form

Photo copy this page and send the completed form to your Sauer-Danfoss representative for assistance in applying pumps with belt or gear drive.

Application data

| | | |
|--|----------|----------------------------|
| Pump displacement | | cc/rev |
| Rated system pressure | | ↑ bar ↑ psi |
| Relief valve setting | | ↑ bar ↑ psi |
| Pump shaft rotation | | ↑ left ↑ right |
| Pump minimum speed | | min ⁻¹ (rpm) |
| Pump maximum speed | | min ⁻¹ (rpm) |
| Drive gear pressure angle | | degrees |
| Drive gear helix angle (gear drive only) | | degrees |
| Belt type (belt drive only) | | ↑ V ↑ Notch/Cog |
| Belt tension (belt drive only) | P | ↑ N ↑ lbf |
| Angular orientation of gear or belt to inlet port | α | degrees |
| Pitch diameter of gear or pulley | d_w | ↑ mm ↑ in |
| Distance from flange to center of gear or pulley | a | ↑ mm ↑ in |



TECHNICAL FEATURES

In this document, we introduce the equations that are used to size the components of a modulating fan drive system. In addition to these principles, there are several other factors to consider to ensure that the hydraulic system performs to expectations. Following are some considerations you are encouraged to address during the design phase.

MAXIMUM PUMP SPEED

Gear tooth surface speeds and centrifugal filling of the pumping chamber limit maximum pump speed. Unless otherwise specified, maximum rated pump speeds are based on operation at sea level with hydraulic fluids having a specific gravity of 0.9 and a viscosity of 120 SUS (25 cSt) at 122° F (50° C). Speed limits for a particular application depend on the absolute pressure and oil viscosity. Speed limits for individual products may be found in their respective technical information bulletins. Consult a Sauer-Danfoss representative for operation outside of these published limits. For pumps, the minimum recommended operating speed at 2500 Psi (170 bar) is 600 min⁻¹(rpm). Volumetric efficiency limits minimum pump speed. If lower than recommended starting or operating speeds are required, contact a Sauer-Danfoss representative for assistance.

MINIMUM PUMP AND MOTOR SPEED

For motors, the minimum speeds listed in the technical bulletins are for continuous operation at rated pressure. Motors may be started from zero speed on fan drives, where torque will increase with speed. Repeated starts under highly loaded conditions are not recommended.

MOTOR STARTING PRESSURE

No-load motor start-up pressures may range from 220 to 725 psi (15 to 50 bar), depending on displacement. This property of the motor is dependent on motor design parameters, the CSF (Coefficient of Static Friction), and it is inversely proportional to motor displacement. For example: The starting torque for any given motor is largely dependent on the diameter of the gears and the CSF. Within any given frame size (Group 1, Group 2, or Group 3) the gear diameter is the same and the displacement is determined by changing the width (thickness) of the gears. Since torque is dependent on the product of pressure and displacement, and starting torque is essentially constant for any given frame size; starting pressure will be dependent on displacement, in an inverse relationship. To minimize starting pressure, select the smallest frame size for the required motor displacement.

Besides displacement, there are several factors which also effect motor starting pressure. They include: pressure rise rate (pressure gradient), temperature, fluid viscosity, motor return pressure (back pressure), fan inertia, pump flow rate, and piece-to-piece variation between motors.

MOTOR FREE RUN PRESSURE

Free run pressure is the minimum delta pressure across the motor that is required to keep the motor turning when there is no cooling demand. Free run pressure is dependent on motor displacement and shaft speed.

If the delta pressure across the motor is allowed to fall below the free run pressure; the motor will stop, and it will be necessary for the motor to go through the starting condition (start-up procedure) when cooling is needed again. In most applications, it is desirable to initiate fan rotation when the engine starts and prevent the motor from stopping, while the engine is running.

INPUT TORQUE RATINGS

When applying pumps in multiple configurations, ensure the input torque limitations are met for each section and for cumulative sections. Refer to individual product technical information bulletins for specific product torque limits. Always ensure that any individual pump in a multiple unit does not exceed its respective torque rating.

⚠ Caution

Torques in excess of recommended values may cause premature input shaft, or unit, failure.

PUMP DRIVE CONDITIONS

Most Sauer-Danfoss products are available with SAE and metric, standard spline, tapered key, or cylindrical keyed drive shafts for direct or indirect drive applications. An intermediate coupling is the preferred method for direct drives, thereby eliminating radial and axial loading. Direct Drive (or plug-in or rigid) spline drives can impose severe radial loads on the pump shaft when the mating spline is rigidly supported. Increased spline clearance does not alleviate this condition. The use of direct drive (plug-in, or rigid) spline drives is permissible providing that the concentricity between the mating spline and its pilot diameter are within 0.004 in (0.10 mm) TIR (Total Indicator Reading). Both concentricity and angular alignment of shafts are important to pump life. Misalignment can induce excessive side loads on bearings and seals, causing premature failure.

Overhung load drives (chain, belt, or gear) are permissible. Contact Sauer-Danfoss for assistance, especially for applications using tandem pumps. The allowable radial shaft loads are a function of the load magnitude, the load position, the load orientation, and the operating pressure of the hydraulic pump. All external shaft loads will have an effect on bearing life and may affect pump performance. In applications where external shaft loads cannot be avoided; optimizing the position, orientation, and magnitude of the radial load can minimize their influence on the pump. A tapered input shaft is recommended for applications where radial shaft loads are present. (Spline shafts are not recommended for belt or gear drive applications, the clearance between the mating splines will prevent accurate alignment of the drive elements and will contribute to excessive wear of the spline.) For belt drive applications, a spring loaded belt-tensioning device is recommended to avoid excessive radial loads on the input shaft.

TAPERED SHAFT AND HUB CONNECTIONS

Tapered shaft/hub connections provide excellent control of both axial and radial position of the drive coupling or fan assembly. When using the tapered connection, additional effort should be used to insure that there is adequate axial clamping load between the hub and the shaft. The designer is encouraged to establish that there is:

- Adequate clearance under the bolt/nut to insure full axial load may be applied to the taper without bottoming out.
- Adequate clearance between the top of the key and the bottom of the keyway in the hub. Interference between the top of the key and the bottom of the keyway will prevent the hub from seating onto the taper of the shaft. This will compromise the ability of the shaft to transmit its full torque capacity, and may result in failure of the shaft.

PUMP SUCTION

For maximum pump life, the inlet pressure should not drop below 0.8 bar absolute [6 in. Hg vac.] at the pump inlet port.

For cold start conditions, inlet pressure down to 0.6 bar absolute [12 in. Hg vac.] is acceptable for short durations. The possibility of damage due to fluid cavitation and aeration is proportional to decreases in inlet pressure. In addition, oil film lubrication may be disrupted by low inlet pressure. These factors, either singularly or combined, may contribute to a decrease in pump life. Multiple changes in either diameter or direction can have a significant effect on the resistance to flow in inlet passages and can result in a substantial increase in the effective length of the inlet line. For this reason, Sauer-Danfoss recommends that the inlet line contain a minimum number of adaptor fittings, tees, and elbows; as each are a source of additional restriction and, potentially, a source of leakage.

⚠ Caution

Continuous operation with inlet pressures below 0.8 bar absolute [6 in. Hg vac.] can cause premature unit failure. Ensure adequate flow/pressure head at the pump inlet at all times.

CASE DRAIN PRESSURE

Maximum pressure limitations for both case drain and inlet passages are available by consulting the appropriate technical information bulletin for the products being applied. Both line length and diameter influence the pressure drop of the fluid in these passages as it flows to/from the reservoir. In addition, both steady state flow velocity and transient conditions, which can accelerate the fluid in these passages, must be considered when determining their correct size. Of the two design parameters: line length and diameter, diameter has the most influence on the success of the design. Increasing line diameter can decrease both the steady state and the transient pressure drops exponentially. For additional information on steady state pressure drops in hydraulic passages, the reader is encouraged to consult any good text on basic hydraulic design. For additional information on transient pressure drops, refer to *Appendix D*, page 39.

Introducing additional flow from external sources into these return lines can also result in transient pressure pulses that may exceed the drain, or case pressure limits of these products. Sauer-Danfoss recommends that the bearing drain and case drain lines return directly to the reservoir and remain dedicated to their intended function without connecting them to additional flow sources.

FILTRATION

To prevent premature wear, it is imperative that only clean fluid enters the pump and hydraulic circuit. A filter capable of controlling the fluid cleanliness to class 22/18/13 (per ISO 4406-1999) or better, under normal operating conditions, is recommended. Since the filter must be changed at regular intervals, the filter housing should be located in an accessible area. Appropriate filter change intervals may be determined by test or by gages indicating excessive pressure drop across the filter element. For additional technical information on hydraulic fluids and filtration refer to **520L0463** *Hydraulic Fluids and Lubricants, Technical Information Bulletin*.

OPERATING TEMPERATURES

With Buna seals and normal operating conditions, the system temperature should not exceed 82 °C [180 °F] except for short periods to 93 °C [200 °F]. With optional Viton elastomer, the system may be operated at continuous temperatures up to 107°C [225°F] without damage to the pump.

⚠ Caution

Operation in excess of 107 °C [225 °F] may cause external leakage or premature unit failure.

FLUIDS

A mineral based fluid is recommended that includes additives to resist corrosion, oxidation and foaming. The oil should have a maximum viscosity commensurate with system pressure drop and pump suction pressures. Since the fluid serves as a system lubricant, as well as transmitting power, careful selection of the fluid is important for proper operation and satisfactory life of the hydraulic components. Hydraulic fluids should be changed at appropriate intervals determined by test, supplier, or by change in color, or odor, of the fluid. For additional technical information on hydraulic fluids refer to **520L0463**, *Hydraulic Fluids and Lubricants, Technical Information Bulletin* and specific product technical bulletins.

Every 10°C [18°F] rise in continuous reservoir temperature over 80°C [176 °F] decreases the life of the oil by ½.

MOUNTING

The pump mount/drive should be designed to minimize axial and radial loads on the shaft. When using an indirect (chain, belt, or gear) drive, contact Sauer-Danfoss to determine permissible load limits and orientation of the installation.

The motor mount should be designed to position the motor/fan assembly within the shroud for optimum fan performance and to locate the leading edge of the fan blades relative to the adjacent surface of the heat exchanger. The support structure should be constructed so that it will be robust against forces and deflections due to shock and vibration as well as the loads applied to it by the fan and the hydraulic plumbing that will be connected to the motor.

AXIAL THRUST MOTORS

When a fan is directly mounted onto the drive shaft of a hydraulic motor, it imparts both a radial and an axial thrust load onto the shaft. In general, the weight of the fan is insignificant when compared to the radial load capacity of the bearings in the motor. But, the axial thrust load must be considered carefully. Under normal operating conditions, Sauer-Danfoss gear motors have adequate axial thrust capacity for most fans that are applied in the industry, but they do have limitations. It is recommended that the system designer determine the axial thrust force that will be produced by the fan and compare it to the values listed below:

Axial thrust load capacities

| Group | Motor product family | Thrust load capacity |
|---------|----------------------|----------------------|
| Group 1 | (SNM1) | 230N [52 lbf] |
| Group 2 | (SNM2, SNM2Y, SGM2Y) | 500N [112 lbf] |
| Group 3 | (SNM3, SNM3Y, SGM3Y) | 1050N [236 lbf] |

Refer to page 26 and 27 for equations that will assist in calculating the axial thrust loads from the fan, but these loads should be confirmed by test.

PIPING

The choice of piping size and installation should always be consistent with minimizing maximum fluid velocity. This will reduce system noise, pressure drops and overheating, thereby adding to cost savings for the operation of the system. Inlet piping should be designed to prevent continuous pump inlet pressures below 0.8 bar abs. [6 in. Hg vac.] or 0.6 bar abs. [12 in. Hg vac.] during start-up. When selecting pipe sizing, recognize pressure drops are related to flow velocity. Sauer-Danfoss recommends limiting the maximum average mean flow velocity to 5 m/sec [15 ft/sec.] in pressure lines, and 2.5 m/sec [7 ft/sec.] in suction lines.

In addition to limiting maximum flow velocity, it is recommended that the designer select the hoses, fittings and integral valve elements to be compatible with the desired working pressure of the hydraulic system. The following documents may be used to determine the working pressure ratings for the respective system elements:

- SAE J514: for working pressure ratings and fitting installation torques for - O-ring boss fittings/ports and JIC 37° flared tubing connections
- SAE J518: for working pressure ratings and bolt installation torques for SAE code 61 4-Bolt flange fittings/ports,
- SAE J517: for working pressure ratings for SAE hydraulic hose
- SAE J1453: for working pressure ratings for flat face O-ring fittings.

RESERVOIR

The reservoir should be designed to accommodate expected maximum volume exchange during all system operating modes and to prevent aeration of the fluid as it passes through the reservoir. Return and inlet lines should be positioned below the reservoir low oil level and be located as far as possible from each other. A diffuser and a baffle plate located between the pump inlet and return line is desirable to reduce turbulence and to allow the oil to de-aerate before it re-enters the pump.

Reservoirs must be sized to ensure de-aeration of the oil before it re-enters the pump. For dwell times of less than 90 seconds, the system designer is encouraged to verify that entrained air (bubbles) are not included in the oil that is being transmitted from the reservoir to the pump. This may be accomplished by placing a sight gage into the inlet line between the reservoir and the pump. Placing a variable frequency strobe light source behind the sight gage will improve the observer's ability to see air bubbles present in the fluid as it passes through the inlet line.

Sauer-Danfoss encourages system designers to locate the reservoir so that the oil level in the reservoir will remain above the level of the inlet port of the pump under all conditions. By doing this, a positive head is produced that can offset the effects of line losses and altitude on the inlet pressure available at the pump.

Sauer-Danfoss also encourages system designers to consider the potential for air to be introduced into the inlet line within the reservoir via the introduction of a vortex or whirlpool, between the surface of the oil and the inlet port. One way to discourage a vortex is to locate a baffle between the inlet passage, or suction strainer, and the surface of the oil. The system designer should consider the design parameters of size and position for the baffle to ensure that a vortex cannot form if the reservoir attitude is at its extremes, the oil level is at or below the minimum recommended capacity, or if sloshing occurs due to operation of the machine.

CAVITATION AND AERATION DAMAGE

Hydraulic oil used in the majority of systems contains about 10% dissolved air by volume. This air, under certain conditions of vacuum within the system, is released from the oil causing air bubbles. These entrained air bubbles collapse if subjected to pressure, and this collapse creates erosion of the adjacent metal and degradation of the oil. Because of this, it becomes obvious that the greater the air content within the oil, or the greater the vacuum in the inlet line, the more severe will be the resultant damage. The main causes of over-aeration of the oil are air leaks, particularly on the inlet side of the pump, and flow line restrictions such as inadequate pipe sizes, elbow fittings and sudden changes in flow passage cross-sectional area. Provided that defects in plumbing and construction are avoided, pump inlet pressure and rated speed requirements are maintained, and reservoir size and location are adequate: no cavitation problems should occur with Sauer-Danfoss pumps and motors.

When entrained air entering the pump is pressurized at the pump outlet, it is forced into solution in the oil as the bubbles collapse. This super-saturated solution of dissolved air and oil will release its air when the pressure is released. Symptoms of this condition can be observed by oil / foam escaping from the fill port of the reservoir when the system is shut down.

COOLING

Depending on duty cycle and reservoir/line construction, an oil-cooler may be required. The oil-cooler size is based on typical power losses in the hydraulic circuit. The oil cooler is usually placed in the return line.

PRESSURE PROTECTION AND RATINGS

The pump, as well as other system components, has pressure limitations. Thus a relief valve, or pressure limiting device, must be installed in the system, and its setting must be consistent with the product ratings. Refer to the relevant Sauer-Danfoss technical bulletins for this information.

Caution

Failure to install a relief valve or over-pressure protection may result in premature unit failure.

BEARING LIFE EXPECTANCY

All Sauer-Danfoss piston pumps and motors utilize anti-friction, rolling element bearings. All Sauer-Danfoss gear pumps and motors utilize pressure-balanced journal bearings, which have an oil film maintained at all times between the gear/shaft and bearing surfaces. If this oil film is sufficiently sustained through proper system maintenance and the product's operating limits are adhered to, a long bearing life can be expected.

A B-10 type life expectancy number is generally associated with rolling element bearings and does not exist for journal bearings. Journal bearing life is a function of speed, system pressure, and other system parameters such as oil viscosity and oil cleanliness.

TERMINOLOGY

Trim speed is the maximum fan speed required at the full-on condition. This is equal to, or greater than, the fan speed required to meet the maximum cooling needs of the cooling system.

Engine set point is the engine speed at which trim speed should occur, and is provided by the cooling system designer. This is equal to, or less than, the engine speed at which maximum system cooling is required.

Fan power at trim is the power that needs to be generated at the motor shaft to drive the fan at trim speed.

Fan rating is the value by which different types of fans can be compared. Usually designated as X power @ Y rpm and equates back to an air volume (mass flow rate) that can be moved per minute at the Y rpm.

To assist with the sizing exercise, Sauer-Danfoss has developed a sizing tool to perform the necessary calculations. Within the sizing tool, worksheets are provided for both fixed displacement pump/fixed displacement motor, and variable displacement pump/fixed displacement motor hydraulic systems. The sizing tool has been provided to your Sauer-Danfoss representative.

Refer to the data sheets on [pages 14, 15 and 16](#). When the data on these sheets is complete, calculations can be made to determine the most suitable pump/motor/controller combination for the application based on:

- Pump drive available (torque, shaft, mounting flange, overall space envelope)
- System pressure required
- Additional flow/pressure required from the pump, (for example: steering flow)
- Control type requested by the customer
- Limiting operating parameters of the fan drive family products
- Fit (space envelope)

Contact your Sauer-Danfoss representative for a report of the performance prediction generated by the fan drive sizing tool.

FANS

Fans are generally divided into two classifications:

- Centrifugal or radial flow - in which the air flows radially thru the impeller within a scroll type of housing
- Axial flow - in which the air flows axially thru the impeller within a cylinder or ring.

The typical axial flow fan is commonly referred to as a propeller fan, and is customarily used for free delivery, or against low resistance. They are usually mounted within a circular ring or shroud with a circular opening.

FAN PERFORMANCE

Fan performance is a measure of volume, total pressure, static pressure, speed, power input, mechanical efficiency, and static efficiency, at a stated density. Some useful definitions are:

- **Volume** delivered by a fan is the number of cubic feet of air per minute (or, cubic meters per second), expressed at fan inlet conditions.
- **Total pressure** is the rise of pressure from fan inlet to fan outlet.
- **Velocity pressure** is the pressure corresponding to the average velocity, determined from the volume of airflow at the fan outlet area.
- **Static pressure** is the total pressure diminished by the fan's velocity pressure. Static pressure is a measure of the fan's performance and is reported by the fan manufacturer in their technical literature. Static pressure is also a measure of the resistance to the flow of air thru the heat exchanger.
- **Power output** is expressed in horsepower (or, kilowatts) and is based on fan volume and fan total pressure.
- **Power input** is expressed in horsepower (or, kilowatts) and is the measured power delivered to the fan shaft.
- **Mechanical efficiency** of a fan is the ratio of power output to power input.
- **Static efficiency** of a fan is the mechanical efficiency multiplied by the ratio of static pressure to the total pressure.

The theoretical power required to move a quantity of air may be determined by the following formula:

SI system

$$\text{Theoretical power} = \frac{\left(\frac{\text{m}^3}{\text{sec}} \right) \cdot (\text{Total pressure, [Pa]}, \left[\frac{\text{N}}{\text{m}^2} \right])}{(1.0)} \quad [\text{watts}]$$

English system

$$\text{Theoretical hp} = \frac{\left(\frac{\text{ft}^3}{\text{min}} \right) \cdot (\text{Total pressure, [in H}_2\text{O]})}{(6356)} \quad [\text{hp}]$$

Pressure and power both vary with air density.

FAN PERFORMANCE
 (continued)

Fan efficiencies may be determined by the following formulae:

SI system

$$\text{Mechanical (total) efficiency} = \frac{\left(\frac{\text{m}^3}{\text{sec}}\right) \cdot (\text{Total pressure, [Pa]}, \left[\frac{\text{N}}{\text{m}^2}\right])}{(\text{Power input, [watts]})}$$

English system

$$\text{Mechanical (total) efficiency} = \frac{\left[\left(\frac{\text{ft}^3}{\text{min}}\right) \cdot (\text{Total pressure, [in H}_2\text{O]})\right]}{(6356.0)} \div (\text{Horsepower input})$$

Mechanical efficiency, based on total pressure is applicable for fans operating with high outlet velocity pressure relative to the static pressure, typical of centrifugal fans.

SI system

$$\text{Static efficiency} = \frac{\left(\frac{\text{m}^3}{\text{sec}}\right) \cdot (\text{Static pressure, [Pa]}, \left[\frac{\text{N}}{\text{m}^2}\right])}{(\text{Power input, [watts]})}$$

English system

$$\text{Static efficiency} = \frac{\left[\left(\frac{\text{ft}^3}{\text{min}}\right) \cdot (\text{Static pressure, [in H}_2\text{O]})\right]}{(6356.0)} \div (\text{Horsepower input})$$

Static efficiency, based on static pressure is applicable to fans with high static pressure relative to the velocity pressure. Static pressure and static efficiency are used more often than mechanical efficiency and total pressure. When a fan operates against no resistance, the static efficiency becomes zero and is meaningless.

AXIAL THRUST

Total pressure = static pressure + velocity pressure

Velocity pressure is proportional to air velocity.

$$\text{Air velocity, } V = \frac{\text{Average flow rate}}{\text{Cross sectional area}}$$

SI system

$$\text{Velocity pressure} = \frac{V^2 \cdot \rho}{2}, \left[\text{Pa}, \frac{\text{N}}{\text{m}^2} \right]$$

$$V = \left[\frac{\text{m}}{\text{sec}} \right]$$

$$\rho = \text{Density of air, } \left[\frac{\text{Kg}}{\text{m}^3} \right]$$

AXIAL THRUST
(continued)

English system

$$\text{Velocity pressure} = \left(\frac{V}{4005}\right)^2, [\text{in H}_2\text{O}]$$

$$V = \left[\frac{\text{ft}}{\text{min}}\right]$$

SI system

$$\text{Axial thrust} = \left[\frac{\pi \cdot \text{Total pressure} \cdot (\text{Fan diameter})^2}{4}\right], [\text{N}]$$

$$\text{Total pressure}, \left[\text{Pa}, \frac{\text{N}}{\text{m}^2}\right]$$

Fan diameter, [m]

English system

$$\text{Axial thrust} = \left[\frac{\pi \cdot 5.193 \cdot \text{Total pressure} \cdot (\text{Fan diameter})^2}{4}\right], [\text{lbf}]$$

Total pressure, [in H₂O]

Fan diameter, [ft]

FAN LAWS

The performance characteristics of fans of all types follow certain laws, which are useful in predicting the effect upon performance of certain changes in the conditions of operation, or the size of the equipment due to limitations of space, power, and/or speed. In the following categories, Q = air flow, and Pres. = static, velocity, or total pressure. The categories pertaining to fan size apply only to fans, which are geometrically similar, i.e., those in which all of the dimensions are proportional to some linear dimension identified as **size**.

1) Variation in fan speed::

Constant air density – Constant system

- (a) Q: Varies as fan speed
- (b) Pres: Varies as square of fan speed
- (c) Power: Varies as cube of fan speed

2) Variation in fan size:

Constant tip speed – Constant air density

Constant fan proportions – Fixed point of rating

- (a) Q: Varies as square of fan diameter
- (b) Pres: Remains constant
- (c) rpm: Varies inversely as fan diameter
- (d) Power: Varies as square of fan diameter

FAN LAWS (continued)

- 3) Variation in fan size:
At constant rpm – Constant air density
Constant fan proportions – fixed Point of rating
(a) Q: Varies as cube of fan diameter
(b) Pres: Varies as square of fan diameter
(c) Tip speed: Varies as fan diameter
(d) Power Varies as fifth power of diameter
- 4) Variation in air density: (Refer to *Appendix F* page 45)
Constant volume – Constant system
Fixed fan size – Constant fan speed
(a) Q: Constant
(b) Pres: Varies as density (SI), specific weight (English)
(c) Power: Varies as density (SI), specific weight (English)
- 5) Variation in air density: (Refer to *Appendix F* page 45)
Constant pressure – Constant system
Fixed fan size – Variable fan speed
(a) Q: Varies inversely as square root of density (SI), specific weight (English)
(b) Pres: Constant
(c) rpm: Varies inversely as square root of density (SI), specific weight (English)
(d) Power: Varies inversely as square root of density (SI), specific weight (English)
- 6) Variation in air density: (Refer to *Appendix F* page 45)
Constant weight of air – Constant system
Fixed fan size – Variable fan speed
(a) Q: Varies inversely as density (SI), specific weight (English)
(b) Pres: Varies inversely as density (SI), specific weight (English)
(c) rpm: Varies inversely as density (SI), specific weight (English)
(d) Power: Varies inversely as square of density (SI), specific weight (English)

FAN LAWS (continued)

Fan laws at a glance

| | Variation in fan speed | Variation in fan size | | | Variation in air density | | |
|-----------------------------------|--|--|--|--------------------------------------|--|---|--|
| Fan laws | Fan law #1 | Fan law #2 | Fan law #3 | Fan law #4 | Fan law #5 | Fan law #6 | |
| Parameters | Constant air density & constant system | Constant tip speed & constant air density | Constant rpm & constant air density | Constant volume & constant system | Constant pressure & constant system | Constant weight of air & constant system | |
| | | Constant tip proportions & fixed point of rating | Constant fan proportions & fixed point of rating | Fixed fan size & constant fan speed | Fixed fan size & variable fan speed | Fixed fan size & variable fan speed | |
| Q, Air volume, (flow rate) | Varies as fan speed | Varies as square of fan diameter | Varies as cube of fan diameter | Constant | Varies inversely as square root of density or specific weight | Varies inversely as density or specific weight | |
| Pressure | Varies as square of fan speed | Remains constant | Varies as square of fan diameter | Varies as density or specific weight | Constant | Varies inversely as density or specific weight | |
| rpm | Constant | Varies inversely as fan diameter | Constant | Constant | Varies inversely as square root of density or specific weight | Varies inversely as density or specific weight | |
| Power | Varies as cube of fan speed | Varies square of fan diameter | Varies as 5th power of diameter | Varies as density or specific weight | Varies as inversely as square root of density or specific weight | Varies as inversely as square of density or specific weight | |
| Tip Speed | N/A | N/A | Varies as fan diameter | N/A | | | |

Example 1

A fan delivers 12,000 cfm at a static pressure of 1 in. H₂O when operating at a speed of 400 rpm and requires an input of 4 hp. If in the same installation, 15,000 cfm are required, what will be the speed, static pressure, and power?

Using fan law 1:

$$\text{Speed} = 400 * \{15,000/12,000\} = 500 \text{ rpm}$$

$$\text{Static pressure} = 1 * \{500/400\}^2 = 4.56 \text{ in. H}_2\text{O}$$

$$\text{Power} = 4 * \{500/400\}^3 = 7.81 \text{ hp}$$

FAN LAWS (continued)

Example 2

A fan delivers 12,000 cfm at 70 °F and normal barometric pressure (density = 0.075 lb per cubic foot) at a static pressure of 1 in. H₂O when operating at 400 rpm, and requires 4 hp. If the air temperature is increased to 200 °F (density = 0.0602 lb per cubic foot) and the speed of the fan remains the same, what will be the static pressure and power?

Using fan law 4:

$$\text{Static pressure} = 1 * \{0.0602/0.075\} = 0.80 \text{ in. H}_2\text{O}$$

$$\text{Power} = 4 * \{0.0602/0.075\} = 3.20 \text{ hp}$$

Example 3

If the speed of the fan in example 2 is increased to produce a static pressure of 1 in. H₂O at 200 °F, as at 70 °F, what will be the speed, capacity, and static power?

Using fan law 5:

$$\text{Speed} = 400 * \text{SQRT} \{0.0705/0.0602\} = 446 \text{ rpm}$$

$$\text{Capacity} = 12,000 * \text{SQRT} \{0.075/0.0602\} = 13,392 \text{ cfm (measured at 200°F)}$$

$$\text{Power} = 4 * \text{SQRT} \{0.075/0.0602\} = 4.46 \text{ hp}$$

Example 4

If the speed of the fan in the previous examples is increased to deliver the same weight of air (same cooling capacity) at 200°F as at 70°F, what will be the speed, capacity, static pressure, and power?

Heat transfer is determined by the mass, or weight, of the air presented to the heat exchanger, or radiator.

Using fan law 6:

$$\text{Speed} = 400 * \{0.075/0.0602\} = 498 \text{ rpm}$$

$$\text{Capacity} = 12,000 * \{0.075/0.0602\} = 14,945 \text{ cfm (measured at 200 F)}$$

$$\text{Static Pressure} = 1 * \{0.075/0.0602\} = 1.25 \text{ in. H}_2\text{O}$$

$$\text{Power} = 4 * \{0.075/0.0602\}^2 = 6.20 \text{ hp}$$

The fan laws may be combined to give other overall values. One useful combination is the product of Laws 1 and 3, which gives the following relationships:

- Capacity (flow rate of air) varies as the ratio of size cubed, times the ratio of the rpm.
- Pressure varies as the ratio of size squared, times the ratio of the rpm squared.
- Power varies as the ratio of the size to the fifth power, times the ratio of the rpm cubed.

FAN LAWS (continued)

Centrifugal fans produce pressure from two independent sources: from the centrifugal force created by rotating the enclosed air column, and from the kinetic energy imparted to the air by virtue of its velocity leaving the impeller. The energy imparted to the air depends on the velocities and is dependent on the curvature of the fan blades. Therefore, for fans with forward curved blades, the energy per pound of air rises rapidly with an increase of air delivery. For fans with backward curved blades, the energy per pound of air may decrease with air delivery (flow rate). For fans with straight blades, the energy per pound of air is roughly constant, regardless of air delivery (flow rate). A unique characteristic of centrifugal fans is that the maximum power required by the fan is found at maximum delivery. Or, otherwise stated, the minimum power required by the fan is found at zero delivery, or under stall conditions.

Axial-flow fans develop none of their static pressure by centrifugal force; all of the static pressure is derived from the change in velocity in passing thru the impeller and its conversion into static pressure. They are inherently high velocity fans and are very dependent on the shape of the blade. Since any particular shape of blade can only be correct for a narrow range of capacity at constant speed, the performance curves for individual fan blade shapes are unique and vary significantly from manufacturer, to manufacturer. To absorb energy, the air must be given a tangential motion in passing thru the impeller; as with the centrifugal fan, the pressure rises generally from free delivery to no delivery, but may drop significantly when the capacity decreases below a certain volume. The drop in pressure is indicative that a stall condition occurs and the blades cease to function in the normal manner.

Fan manufacturers generally agree that the tip clearance around the fan's blades is significant and will contribute to the performance, delivery, and operating efficiency of the fan. Likewise, the type of shroud that surrounds the fan, the axial position of the fan within the shroud, and the clearance between the leading edge of the fan and the cooler can contribute significantly to the performance, operating efficiency, and noise of operation of the fan. The system designer is advised to consult with both the fan and cooler manufacturer for these specific design elements for the system under consideration.

FAN DRIVE SIZING EQUATIONS AND DERIVATIONS

Fan drive sizing equations - SI system

Pf = Rated fan power, [kW]

Nr = Rated fan speed, [rpm]

Nfr = Fan speed, [rpm]

Cf = Fan power coefficient, $[\frac{kW}{rpm^3}]$

$$1. Pf \equiv Cf \cdot Nfr^3 \equiv \frac{Tfr \cdot Nfr}{9549}, [kW]$$

Tfr = Rated fan torque, [N·m]

$$2. Tfr = \frac{\Delta P \cdot Dm \cdot n_{tm}}{20\pi}, [N \cdot m]$$

ΔP = Pressure drop across hydraulic motor, [bar]

Dm \equiv Motor displacement, $[\frac{cm^3}{rev}]$

$$Dm = (\text{Motor displacement, } ([\frac{in^3}{rev}] \cdot (2.54 \frac{cm}{in})^3)), [\frac{cm^3}{rev}]$$

n_{tm} = Motor mechanical efficiency, no dimension

n_{vm} = Motor volumetric efficiency, no dimension

n_{vp} = Pump volumetric Efficiency, no dimension

$$3. Pf = \frac{(\Delta P \cdot Nf \cdot Dm \cdot \eta_{tm})}{(20\pi \cdot 9549)}, [kW]$$

$$4. Qm = \frac{Nf \cdot Dm}{(1000.0 \cdot \eta_{vm})}, [\frac{L}{min}]$$

$$5. Nf \cdot Dm = (Cf \cdot Nf^3) \cdot \frac{(20\pi \cdot 9549.0)}{(\Delta P \cdot \eta_{tm})}, [\frac{cm^3}{min}]$$

$$6. Qm = (Cf \cdot Nf^3) \cdot \frac{(20\pi \cdot 9549.0)}{(\Delta P \cdot \eta_{tm} \cdot 1000 \cdot \eta_{vm})}, [\frac{L}{min}]$$

Re-arranging #5. above,

$$7. Nf = \sqrt{\frac{\Delta P \cdot Dm \cdot \eta_{tm}}{(600,000 \cdot Cf)}}, [rpm]$$

And also,

$$8. Qm = \left[\frac{\sqrt{\frac{\Delta P \cdot Dm^3 \cdot \eta_{tm}}{(600,000 \cdot Cf)}}}{(1,000 \cdot \eta_{vm})} \right], [\frac{L}{min}]$$

Likewise,

$$9. Dm = \left[\frac{Nf^2 \cdot 600,000 \cdot Cf}{\Delta P \cdot n_{tm}} \right], [\frac{cm^3}{rev}]$$

and,

$$10. \Delta P = \left[\frac{Cf \cdot Nf^2 \cdot 600,000}{Dm \cdot \eta_{tm}} \right], [bar]$$

**FAN DRIVE SIZING
EQUATIONS AND
DERIVATIONS (continued)**

Fan drive sizing equations - English system

Pf = Rated fan power, [hp]
Nfr = Rated fan speed, [rpm]
Nf = Fan speed, [rpm]
Cf = Fan power coefficient, $\left[\frac{\text{hp}}{\text{rpm}^3}\right]$

$$1. Pf \equiv Cf \cdot Nfr^3 \equiv \frac{Tfr \cdot Nfr}{63,025}, [\text{hp}]$$

Tfr = Rated fan torque, [lbf · in]

$$2. Tfr = \frac{\Delta P \cdot Dm \cdot \eta_{tm}}{2\pi}, [\text{lbf} \cdot \text{in}]$$

ΔP = Pressure drop across hydraulic motor, [psid]

Dm = Motor displacement, $\left[\frac{\text{in}^3}{\text{rev}}\right]$

$$Dm \equiv \frac{(\text{Motor Displacement, } \left[\frac{\text{cm}^3}{\text{rev}}\right])}{(2.54 \left[\frac{\text{cm}}{\text{in}}\right])^3}, \left[\frac{\text{in}^3}{\text{rev}}\right]$$

η_{tm} = Motor mechanical efficiency, no dimension

η_{vm} = Motor volumetric efficiency, no dimension

η_{vp} = Pump volumetric efficiency, no dimension

$$3. Pf = \frac{(\Delta P \cdot Nf \cdot Dm \cdot \eta_{tm})}{(2\pi \cdot 63025)}, [\text{hp}]$$

$$4. Qm = \frac{Nf \cdot Dm}{(231 \cdot \eta_{vm})}, [\text{US gal/min}]$$

$$5. Nf \cdot Dm = (Cf \cdot Nf^3) \cdot \frac{(2\pi \cdot 63,025)}{(\Delta P \cdot \eta_{tm})}, \left[\frac{\text{in}^3}{\text{min}}\right]$$

$$6. Qm = (Cf \cdot Nf^3) \cdot \frac{(2\pi \cdot 63,025)}{(\Delta P \cdot \eta_{tm} \cdot 231 \cdot \eta_{vm})}, [\text{US gal/min}]$$

Re-arranging #5. above,

$$7. Nf = \sqrt{\frac{\Delta P \cdot Dm \cdot \eta_{tm}}{(396,000 \cdot Cf)}}, [\text{rpm}]$$

And also,

$$8. Qm = \left[\frac{\sqrt{\frac{\Delta P \cdot Dm^3 \cdot \eta_{tm}}{(396,000 \cdot Cf)}}}{(231 \cdot \eta_{vm})} \right], [\text{US gal/min}]$$

Likewise,

$$9. Dm = \left[\frac{Nf^2 \cdot 396,000 \cdot Cf}{\Delta P \cdot \eta_{tm}} \right], \left[\frac{\text{in}^3}{\text{rev}}\right]$$

and,

$$10. \Delta P = \left[\frac{Cf \cdot Nf^2 \cdot 396,000}{Dm \cdot \eta_{tm}} \right], [\text{psid}]$$

FAN DRIVE SIZING EQUATIONS AND DERIVATIONS (continued)

Therefore, comparing equations 7 thru 10 on the previous pages, for any given combination of fan configuration and motor displacement, there is a unique relationship between system pressure, motor flow, and motor speed.

HYDRAULIC SYSTEM COMPARISONS

One application of the sizing equations is to use them to relate the fan speed/pressure relationship from one condition to another.

SI system

From equation 7,

$$Nf^2 = \left[\frac{\Delta P \cdot Dm \cdot \eta_{tm}}{(600,000 \cdot Cf)} \right]$$

Therefore at condition 1:

$$Nf_1^2 = \left[\frac{\Delta P_1 \cdot Dm \cdot \eta_{tm}}{(600,000 \cdot Cf)} \right]$$

and at condition 2:

$$Nf_2^2 = \left[\frac{\Delta P_2 \cdot Dm \cdot \eta_{tm}}{(600,000 \cdot Cf)} \right]$$

Then,

$$\frac{Nf_1^2}{Nf_2^2} = \frac{\Delta P_1}{\Delta P_2}$$

$$Nf_2 = Nf_1 \cdot \sqrt{\frac{\Delta P_2}{\Delta P_1}}$$

English system

From equation 7,

$$Nf^2 = \left[\frac{\Delta P \cdot Dm \cdot \eta_{tm}}{(396,000 \cdot Cf)} \right]$$

Therefore at condition 1:

$$Nf_1^2 = \left[\frac{\Delta P_1 \cdot Dm \cdot \eta_{tm}}{(396,000 \cdot Cf)} \right]$$

and at condition 2:

$$Nf_2^2 = \left[\frac{\Delta P_2 \cdot Dm \cdot \eta_{tm}}{(396,000 \cdot Cf)} \right]$$

Then,

$$\frac{Nf_1^2}{Nf_2^2} = \frac{\Delta P_1}{\Delta P_2}$$

$$Nf_2 = Nf_1 \cdot \sqrt{\frac{\Delta P_2}{\Delta P_1}}$$

**HYDRAULIC SYSTEM
 COMPARISONS
 (continued)**

If the theoretical trim pressure is 2822 psid at a fan speed of 2000 rpm, what is the fan speed at a minimum standby pressure of 310 psid?

$$Nf_2 = Nf_1 \cdot \sqrt{\frac{\Delta P_2}{\Delta P_1}}$$

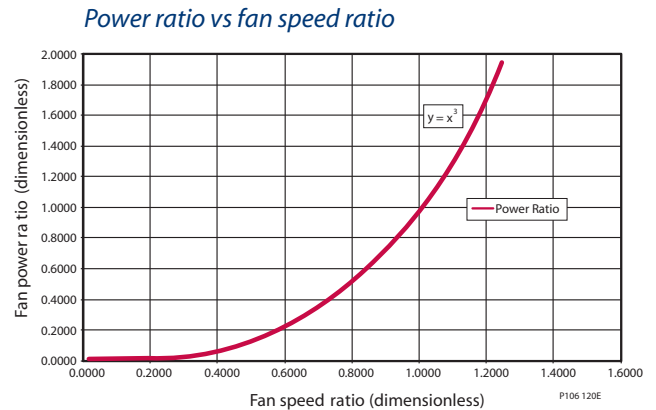
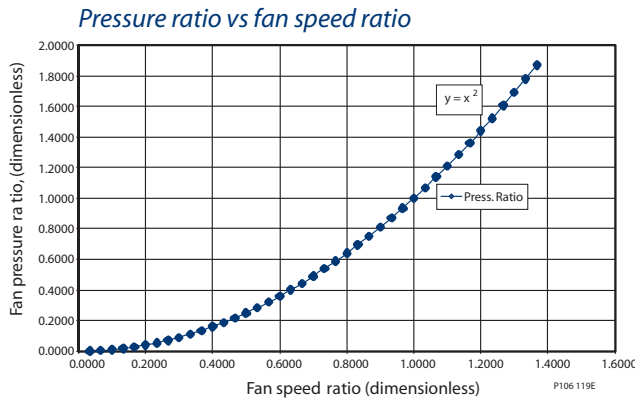
$$Nf_2 = 2000 \cdot \sqrt{\frac{310}{2822}} = 663 \text{ rpm}$$

If the minimum standby pressure suddenly changes from 310 psid, to 400 psid, due to the external circuit, what is the resulting fan speed?

$$Nf_2 = Nf_1 \cdot \sqrt{\frac{\Delta P_2}{\Delta P_1}}$$

$$Nf_2 = 663 \cdot \sqrt{\frac{400}{310}} = 753 \text{ rpm}$$

The graph below illustrates this quadratic relationship between fan system delta pressure and fan speed. The graph is normalized by dividing the individual operating parameters of pressure and speed by the trim pressure and trim speed of the fan so that the curve is representative of all fan systems. Consequently, the curve converges on the coordinates of (1.000, 1.000) for both the fan pressure ratio and the fan speed ratio.



On examination of the curve, one can see:

- To increase fan speed 10% above the trim speed we would need to increase the delta pressure across the motor by 21%
- To reduce fan speed below 32% of the trim speed we would need to reduce the delta pressure across the motor by more than 90%.

HYDRAULIC SYSTEMS WITH 2 POSITION, VARIABLE DISPLACEMENT MOTORS, EQUATIONS AND DERIVATIONS

Some systems may require additional cooling when the engine is at the low idle speed. A system with a fixed displacement motor may require additional pump flow to accomplish this. If the pump flow is limited, there is the possibility of providing additional cooling by utilizing a variable displacement motor in the hydraulic circuit. For normal operation, the variable displacement motor is held in the maximum displacement position in order to minimize the operating pressure for any given cooling requirement. But, when the engine is at the low idle speed, the control system can command the motor to its minimum displacement position to take full advantage of the flow that is available from the pump. In both conditions, the fan speed is modulated in response to the temperature of the coolant to satisfy the cooling needs of the system.

If you would like to determine the optimum minimum displacement for a variable motor, which would provide the maximum fan speed when, the engine speed is at low idle and the system pressure is at the trim pressure setting:

The following analysis assumes that the bypass flow around the motor is zero.

SI system

Assume $Q_m = Q_p$,

$$\frac{N_f \cdot D_m}{\eta_{vm}} = N_p \cdot D_p \cdot \eta_{vp}$$

Therefore:

$$11. N_f = \frac{N_p \cdot D_p \cdot \eta_{vp} \cdot \eta_{vm}}{D_m} = \left[\frac{(N_e \cdot R) \cdot D_p \cdot \eta_{vp} \cdot \eta_{vm}}{D_m} \right]$$

N_e = Engine speed, rpm (In this case, N_e = engine low idle speed.)

R = Engine-pump gear ratio, no dimension.

Combining eq. 1. and eq. 11.,

$$12. P_f = C_f \cdot N_f^3 = \frac{\Delta P \cdot D_m \cdot \eta_{tm}}{600,000} \cdot \frac{N_e \cdot R \cdot D_p \cdot \eta_{vp} \cdot \eta_{vm}}{D_m}, [kW]$$

$$13. N_f = \left[\frac{\Delta P \cdot N_e \cdot R \cdot D_p \cdot \eta_{tm} \cdot \eta_{vp} \cdot \eta_{vm}}{600,000 \cdot C_f} \right]^{1/3}, [rpm]$$

Combining eq. 11. and eq. 13.,

$$14. \left[\frac{N_e \cdot R \cdot D_p \cdot \eta_{vp} \cdot \eta_{vm}}{D_m} \right]^3 = \left[\frac{\Delta P \cdot N_e \cdot R \cdot D_p \cdot \eta_{tm} \cdot \eta_{vp} \cdot \eta_{vm}}{600,000 \cdot C_f} \right]$$

Solving for D_m ,

$$15. D_m = \left[\frac{600,000 \cdot C_f}{\Delta P \cdot \eta_{tm}} \cdot (N_e \cdot R \cdot D_p \cdot \eta_{vp} \cdot \eta_{vm})^2 \right]^{1/3}, \left[\frac{cm^3}{rev} \right]$$

HYDRAULIC SYSTEMS WITH 2 POSITION, VARIABLE DISPLACEMENT MOTORS, EQUATIONS AND DERIVATIONS (continued)

English system

Assume $Q_m = Q_p$,

$$\frac{N_f \cdot D_m}{\eta_{vm}} = N_p \cdot D_p \cdot \eta_{vp}$$

Therefore:

$$11. N_f = \left[\frac{N_f \cdot D_p \cdot \eta_{vp} \cdot \eta_{vm}}{D_m} \right] = \left[\frac{(N_e \cdot R) \cdot D_p \cdot \eta_{vp} \cdot \eta_{vm}}{D_m} \right]$$

N_e = Engine speed, rpm (In this case, N_e = engine low idle speed.)

R = Engine/pump gear ratio, no dimension.

Combining eq. 1. and eq. 11.,

$$12. P_f = C_f \cdot N_f^3 = \frac{\Delta P \cdot D_m \cdot \eta_{tm}}{396,000} \cdot \frac{N_e \cdot R \cdot D_p \cdot \eta_{vp} \cdot \eta_{vm}}{D_m}, [\text{hp}]$$

$$13. N_f = \left[\frac{\Delta P \cdot N_e \cdot R \cdot D_p \cdot \eta_{tm} \cdot \eta_{vp} \cdot \eta_{vm}}{396,000 \cdot C_f} \right]^{1/3}, [\text{rpm}]$$

Combining eq. 11. and eq. 13.,

$$14. \left[\frac{N_e \cdot R \cdot D_p \cdot \eta_{vp} \cdot \eta_{vm}}{D_m} \right]^3 = \left[\frac{\Delta P \cdot N_e \cdot R \cdot D_p \cdot \eta_{tm} \cdot \eta_{vp} \cdot \eta_{vm}}{396,000 \cdot C_f} \right]$$

Solving for D_m ,

$$15. D_m = \left[\frac{396,000 \cdot C_f}{\Delta P \cdot \eta_{tm}} \cdot (N_e \cdot R \cdot D_p \cdot \eta_{vp} \cdot \eta_{vm})^2 \right]^{1/3}, \left[\frac{\text{cm}^3}{\text{rev}} \right]$$

This is the optimum minimum motor displacement at which the fan speed will be maximum for the given pump flow at engine idle and at the system's trim pressure. An Excel™ spreadsheet has been developed to calculate the optimum minimum displacement for the variable displacement motor. Consult your Sauer-Danfoss representative for assistance.

SPREADSHEET TO CALCULATE OPTIMUM MINIMUM DISPLACEMENT FOR TWO POSITION VARIABLE MOTOR

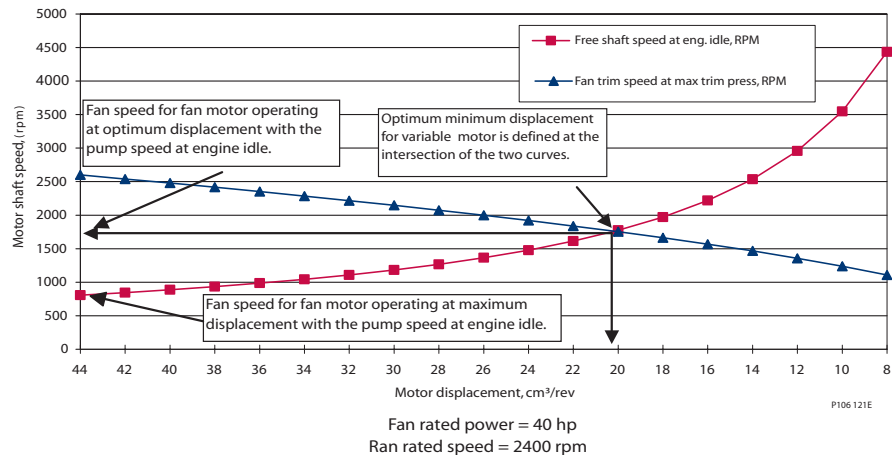
Spreadsheet calculator tool (example)

| | | | | |
|---------------------------------------|----------|---|----------------------------|--------------|
| Rated fan power, hp | 40 | Input data only in cells with blue font: | | |
| Rated fan speed, rpm | 2400 | Optimum displ. Dm = | ln ³ /rev 1.230 | cc/rev 20.15 |
| Desired fan trim speed, rpm | 2600 | | | |
| Trim pressure, Psig | 3205 | | | |
| Motor displ., cc/rev | 44 | | | |
| Motor torque eff | 90% | | | |
| Cf = hp_fan/Nf³ | 2.89E-09 | | | |
| Engine idle speed, rpm | 700 | | | |
| Engine: pump ratio, :1 | 1 | | | |
| Pump displ, cc/rev | 55 | | | |
| Pump displ, ln³/rev | 3.36 | | | |
| Motor vol eff | 96% | | | |
| Pump vol eff | 96% | | | |

This relationship is illustrated in the graph below.

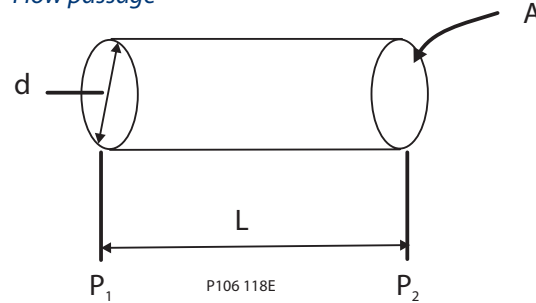
- The curve described by the square data points represents the speed of the motor shaft as a function of motor displacement when the pump's displacement is constant, and the pump's input speed is at the engine idle speed.
- The curve described by the triangular data points represents the speed of the motor shaft as a function of the fan power coefficient, the trim pressure and the motor's displacement.
- For the system parameters that have been chosen, the optimum minimum motor displacement for the variable motor will be found at the intersection of these two curves.

Variable motor shaft speed vs. displacement



PRESSURE CHANGE DUE TO TRANSIENT FLOW IN A PASSAGE, EQUATIONS AND DERIVATIONS

Flow passage



Definitions

| | |
|---|---|
| $\Delta P = (P_1 - P_2)$, psid | Required pressure to achieve fluid acceleration, a |
| a , in/sec ² | Fluid acceleration in L length of conduit |
| $L = 1$ ft | Length of conduit |
| A , in ² | Area of conduit |
| m , lbf-sec ² /in ⁴ | Fluid mass within the L length of conduit |
| S.G. = 0.861 | Specific gravity of the fluid |
| $Q = V \cdot A$ | Flow rate |
| V , ft/sec | Velocity of fluid in conduit |
| D , in | Diameter of the conduit |
| F , lbf | Force |
| ρ | Mass density of the fluid |
| g | Acceleration of gravity |
| γ | Weight density of the fluid |
| $\gamma/g = \rho$ | Weight density of fluid/acceleration of gravity = mass density of the fluid |
| t | Time interval, seconds |
| D | Pump displacement |

$$F = \Delta P \cdot A, \text{ lbf} = m \cdot a = \rho_f \cdot Q \cdot V,$$

$$\Delta P \cdot A = \rho_f \cdot Q \cdot V = \rho \cdot \left(\frac{L \cdot A}{t} \right) \cdot V$$

$$\Delta P \cdot A = \rho_f \cdot \left(\frac{L \cdot A}{t} \right) \cdot \frac{Q}{A}$$

$$\Delta P = \rho_f \cdot \left(\frac{L \cdot Q}{t \cdot A} \right)$$

$$\text{and, } \rho_f = \text{S.G.} \cdot \rho_{H20}$$

PRESSURE CHANGE DUE TO TRANSIENT FLOW IN A PASSAGE, EQUATIONS AND DERIVATIONS (continued)

therefore:

SI system

$$\frac{\Delta P}{L} = (2.122E - 7) \cdot \left(\frac{S.G. \cdot Q}{t \cdot d^2} \right), \left[\frac{\text{bar}}{\text{meter}} \right]$$

$$Q = \text{flow}, \left[\frac{\text{L}}{\text{min}} \right]$$

$$L = \text{length}, [\text{m}]$$

$$d = \text{diameter}, [\text{m}]$$

and,

$$\frac{\Delta P}{L} = (0.2122) \cdot \left(\frac{S.G. \cdot Q}{t \cdot d^2} \right), \left[\frac{\text{bar}}{\text{meter}} \right]$$

when:

$$d = \text{diameter}, [\text{mm}]$$

also,

$$\frac{\Delta P}{L} = (2.122E - 4) \cdot \left(\frac{S.G. \cdot N \cdot D}{t \cdot d^2} \right), \left[\frac{\text{bar}}{\text{meter}} \right]$$

when:

$$d = \text{diameter}, [\text{mm}]$$

$$D = \text{displacement}, \left[\frac{\text{cm}^3}{\text{Rev}} \right]$$

$$N = \text{speed}, [\text{rpm}]$$

and,

$$\frac{\Delta P}{L} = (2.122E - 4) \cdot \left(\frac{S.G. \cdot D \cdot a}{d^2} \right), \left[\frac{\text{bar}}{\text{meter}} \right]$$

when:

$$d = \text{diameter}, [\text{mm}]$$

$$D = \text{displacement}, \left[\frac{\text{cm}^3}{\text{Rev}} \right]$$

$$a = \frac{\Delta N}{t}, \text{average acceleration}, \left[\frac{\text{rpm}}{\text{sec}} \right]$$

English system

$$\frac{\Delta P}{L} = (5.4996E - 3) \cdot \left(\frac{S.G. \cdot Q}{t \cdot d^2} \right), \left[\frac{\text{psid}}{\text{ft}} \right]$$

$$Q = \text{flow}, [\text{GPM}]$$

$$L = \text{length}, [\text{ft}]$$

$$d = \text{diameter}, [\text{in}]$$

$$\frac{\Delta P}{L} = (3.7189E - 3) \cdot \left(\frac{Q}{t} \right), \left[\frac{\text{psid}}{\text{ft}} \right]$$

when:

$$S.G. = 0.861$$

$$A = 1 \text{ in}^2$$

$$\frac{\Delta P}{L} = (2.3808E - 3) \cdot \left(\frac{S.G. \cdot D}{d^2} \right) \cdot a, \left[\frac{\text{psid}}{\text{meter}} \right]$$

when:

$$a = \frac{\Delta N}{t} = \text{average acceleration}, \left[\frac{\text{rpm}}{\text{sec}} \right]$$

$$D = \text{displacement}, \left[\frac{\text{in}^3}{\text{rev}} \right]$$

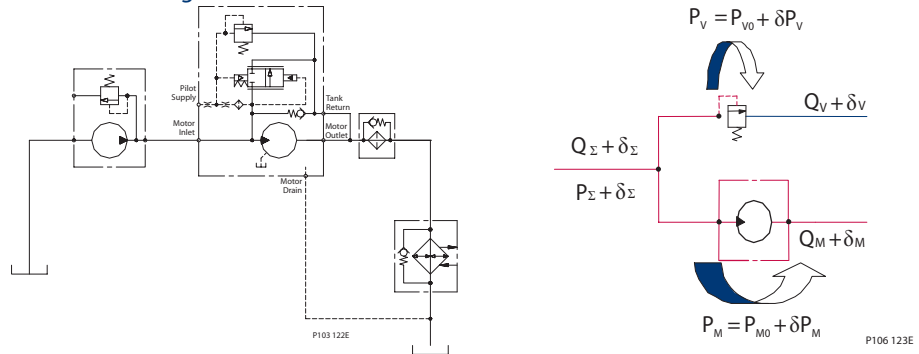
INFLUENCE OF BYPASS VALVE PRESSURE DROP ON FAN TRIM SPEED, IN APPLICATIONS USING FIXED DISPLACEMENT PUMPS, EQUATIONS AND DERIVATIONS

In applications where the system is sized close to the maximum limits of fan speed, motor speed, or component pressure ratings, it may be necessary to determine the influence of the bypass valve's pressure-flow characteristics on the system. In a typical circuit, there will be a rise in pressure across a component with an increase in flow. This is normal, and the system's designer is encouraged to check whether this characteristic will have an adverse effect on the system and its components.

In this section, we will determine the effect of the *pressure rise with flow* characteristic of the bypass valve on the change in trim speed of the fan and the trim pressure across the hydraulic motor. In most pressure regulating valves there is a range of flows where the pressure rise is either linear, or nearly linear, with increases in flow. This is illustrated below for the electro-hydraulic proportional pressure control that is integrated into the rear covers of the S-D SNM2Y, SNM3Y, SGM2Y and SGM3Y fan drive motors. Adjacent to each of the characteristic curves is a coefficient, which is the nominal slope of each curve. With this coefficient and other system parameters that is described below: the system designer can determine the change in trim speed and trim pressure with increases in engine speed above the *engine set point* that we have selected.

For the purposes of this derivation, the basic modulating fan drive circuit may be simplified as shown below:

Basic modulating fan drive circuit



As can be seen in the simplified schematic, all of the pump flow, Q_{Σ} goes thru either the bypass valve, Q_V , or the fan motor, Q_M . At the initial condition for our derivation, the flow thru the bypass valve is zero and all of the pump flow is passing thru the motor. This is the **trim point**, when the engine is at the engine set point. Above this point, a portion of the flow will pass thru the motor and the remaining flow will pass thru the bypass valve. The proportion of the flow going thru each will be determined by the pressure-flow characteristics of the valve and the pressure-flow relationship of the motor-fan that is determined by the fan laws.

INFLUENCE OF BYPASS VALVE PRESSURE DROP, EQUATIONS AND DERIVATIONS (continued)

This is described in the derivation, below:

$$Q_{\Sigma 0} = Q_{V0} + Q_{M0}$$

$$Q_{\Sigma 0} + \delta Q_{\Sigma} = Q_{V0} + \delta Q_V + Q_{M0} + \delta Q_M$$

$$@t = 0, Q_{V0} = 0.0$$

$$\therefore Q_{\Sigma 0} = Q_{M0}$$

$$\therefore \delta Q_{\Sigma} = \delta Q_V + \delta Q_M$$

From the graph of ΔP_V vs ΔQ_V ,

$$P_V = P_0 + K_p \cdot \delta Q_V$$

$$K_p \equiv \left(\frac{\Delta P_V}{\Delta Q_V} \right),$$

$$\text{From the fan laws, } \left(\frac{P_2}{P_1} \right) = \left(\frac{Q_2}{Q_1} \right)^2,$$

$$\text{Therefore, } \delta P_m = \left[P_0 \left(\frac{Q_{M0} + \delta Q_M}{Q_{M0}} \right)^2 - P_0 \right],$$

$$\delta P_m \equiv \delta P_V, \text{ therefore:}$$

$$\delta P_V = P_0 \cdot \left[\left(\frac{Q_{M0} + \delta Q_M}{Q_{M0}} \right)^2 - 1 \right],$$

$$\frac{\delta P_V}{P_0} = \left[\left(\frac{Q_{M0} + \delta Q_M}{Q_{M0}} \right)^2 - 1 \right],$$

Expanding the right side of the equation,

$$\frac{\delta P_V}{P_0} = \left[\left(1 + 2 \left(\frac{\delta Q_M}{Q_{M0}} \right) + \left(\frac{\delta Q_M}{Q_{M0}} \right)^2 \right) - 1 \right],$$

$$\text{If } \left(\frac{\delta Q_M}{Q_{M0}} \right)^2 \ll \left[2 \left(\frac{\delta Q_M}{Q_{M0}} \right) \right],$$

This is valid for $\delta Q_M \leq 0.5 \cdot \delta Q_{M0}$

$$\text{Then, } \frac{\delta P_V}{P_0} = 2 \left(\frac{\delta Q_M}{Q_{M0}} \right),$$

$$\text{Since, } \delta P_V = K_p \cdot \delta Q_V = K_p \cdot (\delta Q_{\Sigma} - \delta Q_M),$$

Therefore,

$$\frac{K_p}{P_0} (\delta Q_{\Sigma} - \delta Q_M) = 2 \left(\frac{\delta Q_M}{Q_{M0}} \right),$$

Expanding,

$$K_p \cdot \delta Q_{\Sigma} = P_0 \cdot \left[2 \left(\frac{\delta Q_M}{Q_{M0}} \right) \right] + K_p \cdot \delta Q_M,$$

$$K_p \cdot \delta Q_{\Sigma} = \frac{\delta Q_M}{Q_{M0}} \cdot \{ 2P_0 + K_p \cdot Q_{M0} \},$$

$$\text{Then, } \delta Q_M = \left\{ \frac{K_p \cdot \delta Q_{\Sigma} \cdot Q_{M0}}{(2P_0 + K_p \cdot Q_{M0})} \right\},$$

$$\text{Therefore, } \delta N_M = \frac{\delta Q_M}{D_M},$$

Likewise;

$$(\delta Q_V) = (\delta Q_{\Sigma} - \delta Q_M),$$

$$\delta Q_V = \delta Q_{\Sigma} \cdot \left\{ 1 - \left[\frac{K_p \cdot Q_{M0}}{(2P_0 + K_p \cdot Q_{M0})} \right] \right\},$$

Then,

$$\delta P_V = K_p \cdot \delta Q_{\Sigma} \cdot \left\{ 1 - \left[\frac{K_p \cdot Q_{M0}}{(2P_0 + K_p \cdot Q_{M0})} \right] \right\}$$

Summarizing then:

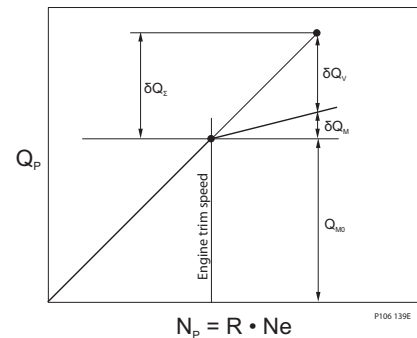
If we know the increase in pump flow, δQ_{Σ} above the engine set point, the flow thru the motor at the engine set point, Q_{M0} , the motor displacement, D_M , the initial trim pressure, P_0 , and the bypass valve's flow-pressure coefficient, K_p ; then we can determine the increase in fan speed, δN_{Mf} above the theoretical trim speed, N_{M0} .

$$\delta N_M = \left\{ \frac{K_p \cdot \delta Q_{\Sigma} \cdot Q_{M0}}{D_M \cdot (2P_0 + K_p \cdot Q_{M0})} \right\}$$

Likewise, we can determine the change in pressure across the fan motor, δP_V , as shown.

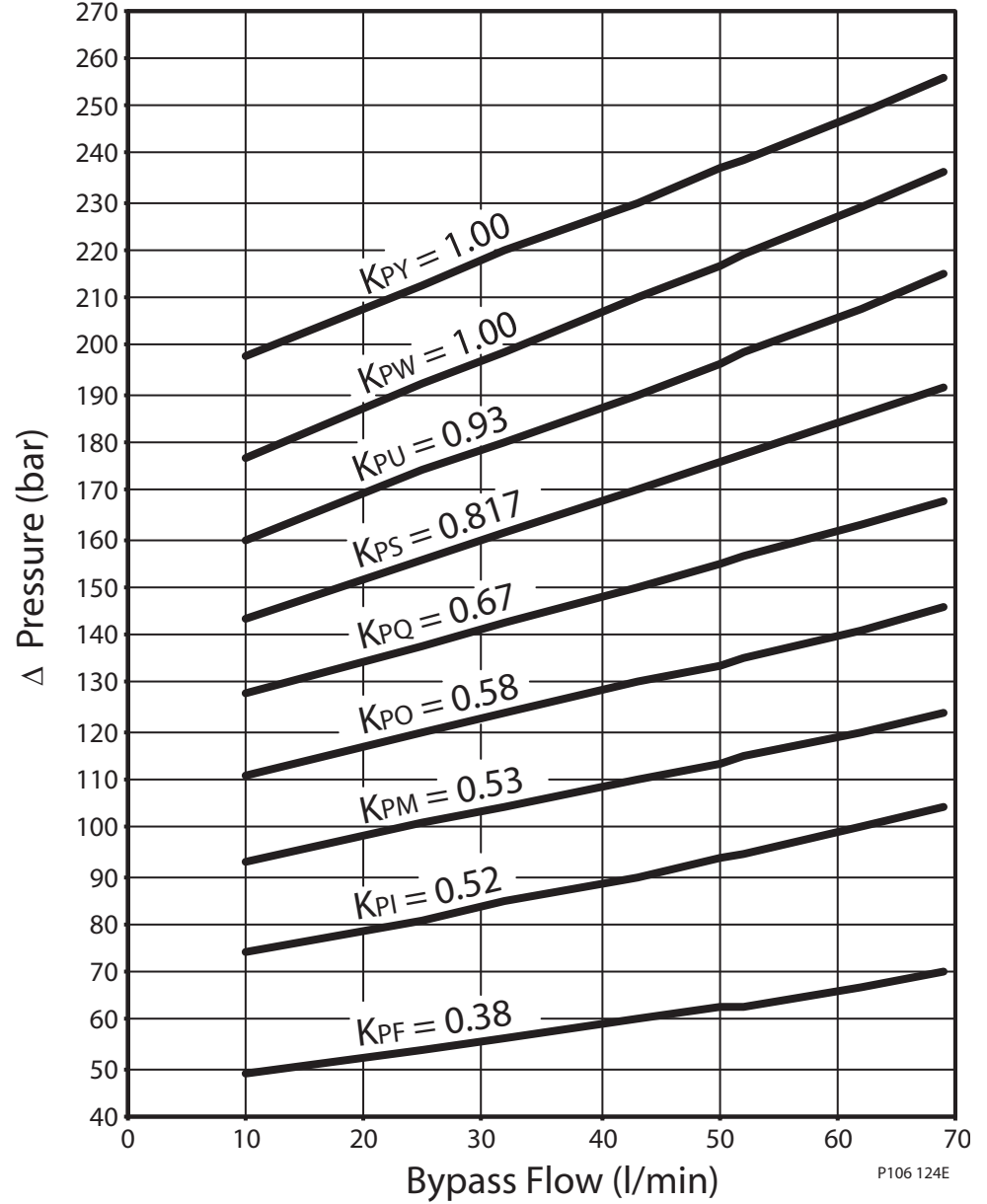
$$\delta P_V = K_p \cdot \delta Q_{\Sigma} \cdot \left\{ 1 - \left[\frac{K_p \cdot Q_{M0}}{(2P_0 + K_p \cdot Q_{M0})} \right] \right\}$$

Bypass valve and fan motor flow vs. pump flow



**INFLUENCE OF BYPASS
VALVE PRESSURE
DROP, EQUATIONS
AND DERIVATIONS
(continued)**

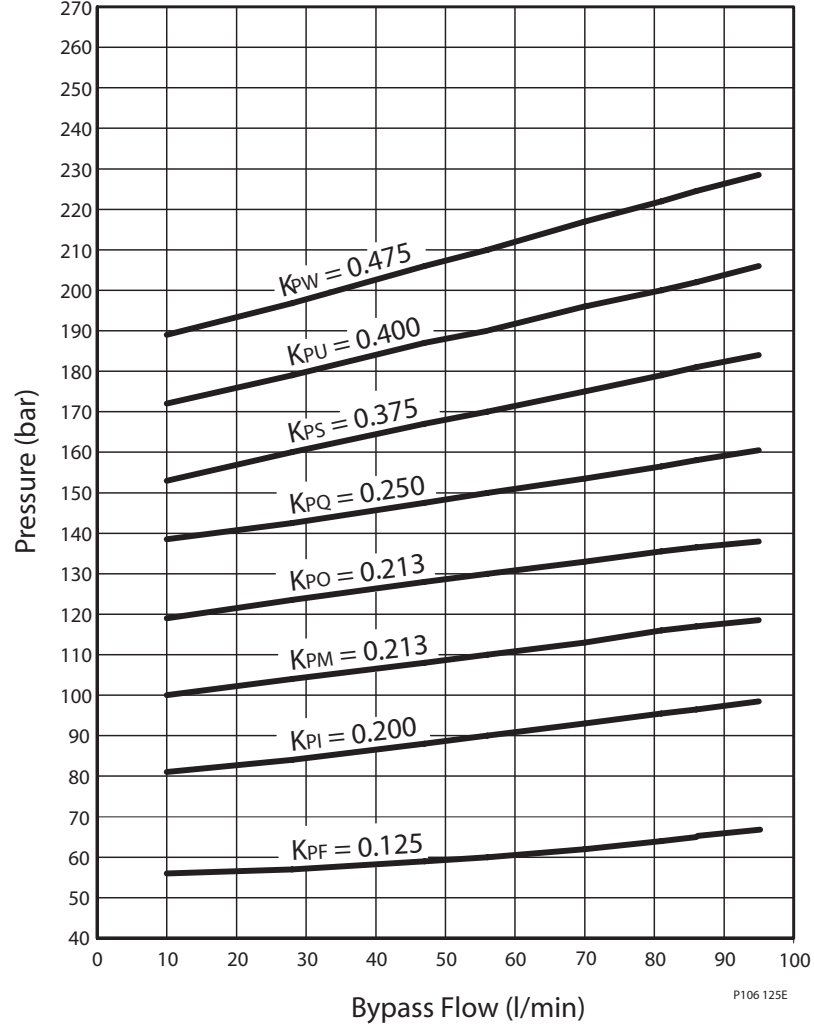
Pressure vs. flow diagram Group 2 motors for valve identification



Y, W, U, etc. - Refer to electro-hydraulic proportional valve nomenclature code in **520L0824 Hydraulic Fan Drive Systems Technical Information**.

**INFLUENCE OF BYPASS
VALVE PRESSURE
DROP, EQUATIONS
AND DERIVATIONS
(continued)**

Pressure vs. flow diagram Group 3 motors for valve identification



Y, W, U, etc. - Refer to electro-hydraulic proportional valve nomenclature code in **520L0824 Hydraulic Fan Drive Systems Technical Information.**

Appendix F1-Influence of temperature, pressure and relative humidity on specific weight of air

INFLUENCE OF TEMPERATURE, PRESSURE AND RELATIVE HUMIDITY ON SPECIFIC WEIGHT OF AIR

$$v = 0.0749 \cdot \left[\frac{530}{460 + T} \right] \cdot \left[\frac{P - 0.3786 \cdot RH \cdot Pvs}{29.92} \right]$$

Where:

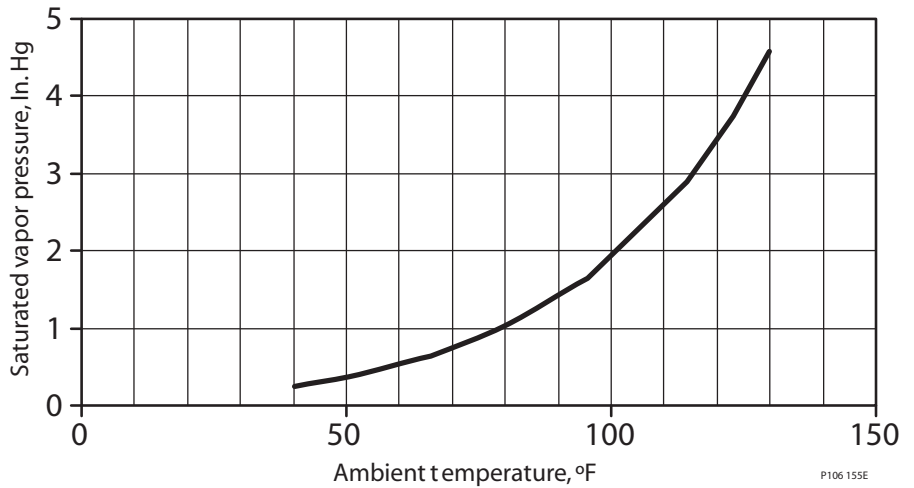
- v = Specific Weight of Air, lbf/ft³
- P = Standard Barometric Pressure, in Hg
- RH = Relative Humidity, (%/100)
- Pvs = Saturation Water-Vapor Pressure, in Hg
- T = Temperature, °F
- H = Altitude, ft.

Standard barometric pressure varies with altitude

$$P = (1.34955E-8)H^2 - (1.07145E-9)H + 29.92, \text{ in. Hg}$$

Accurate within +/- 0.01 in. Hg from - 1000 to 15000 ft

Saturated water vapor pressure vs ambient temperature, °F



$$y = 4E-06x^3 - 0.0005x^2 + 0.0343x - 0.5782$$

$$R^2 = 1$$

Temperature, vs pressure (in. Hg)

| Temp., °F | Pvs, in. Hg |
|-----------|-------------|
| 40 | 0.2478 |
| 42 | 0.2671 |
| 44 | 0.2891 |
| 46 | .03119 |
| 48 | 0.3363 |
| 50 | 0.3624 |
| 52 | 0.3905 |
| 54 | 0.42 |
| 56 | 0.4518 |
| 58 | 0.4854 |

| Temp., °F | Pvs, in. Hg |
|-----------|-------------|
| 60 | 0.5214 |
| 62 | 0.5597 |
| 64 | 0.6004 |
| 66 | 0.6438 |
| 68 | 0.6898 |
| 70 | 0.7387 |
| 72 | 0.7906 |
| 74 | 0.8456 |
| 76 | 0.904 |
| 78 | 0.9657 |

| Temp., °F | Pvs, in. Hg |
|-----------|-------------|
| 80 | 1.032 |
| 82 | 1.101 |
| 84 | 1.175 |
| 86 | 1.253 |
| 88 | 1.335 |
| 90 | 1.421 |
| 92 | 1.513 |
| 94 | 1.609 |
| 96 | 1.711 |
| 98 | 1.818 |

| Temp., °F | Pvs, in. Hg |
|-----------|-------------|
| 100 | 1.932 |
| 102 | 2.0528 |
| 104 | 2.1786 |
| 106 | 2.3109 |
| 108 | 2.4502 |
| 110 | 2.5966 |
| 112 | 2.7505 |
| 114 | 2.9123 |
| 116 | 3.0821 |
| 118 | 3.3606 |

| Temp., °F | Pvs, in. Hg |
|-----------|-------------|
| 120 | 3.4474 |
| 122 | 3.6436 |
| 124 | 3.8492 |
| 126 | 4.0649 |
| 128 | 4.2907 |
| 130 | 4.5272 |

**INFLUENCE OF ALTITUDE
ON ATMOSPHERIC
PRESSURE**

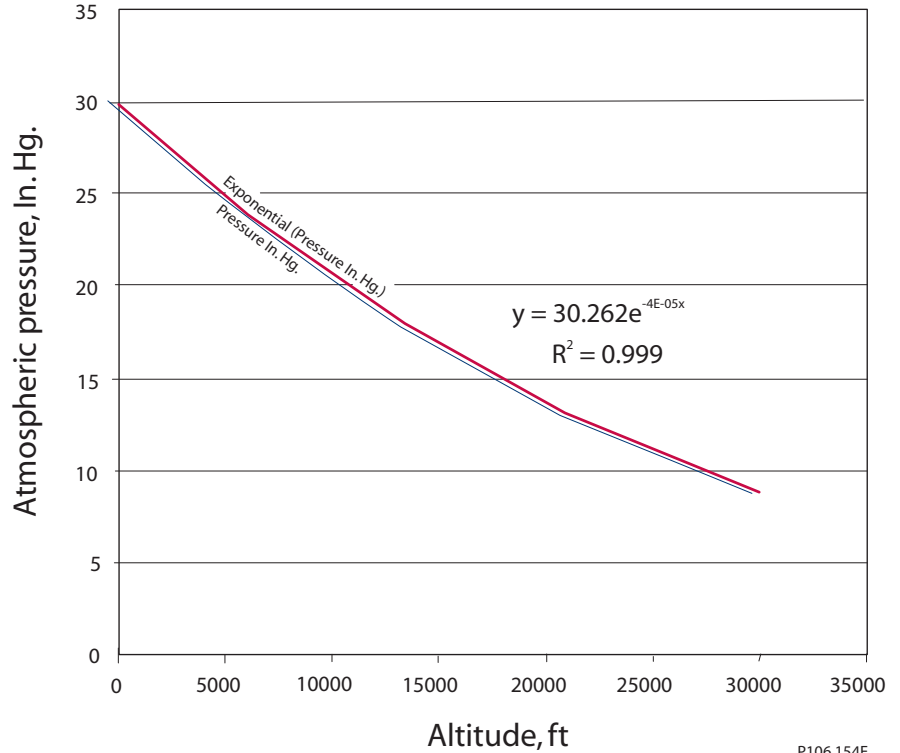
Atmospheric Properties:

| Altitude | | Atmospheric pressure, Psia @ 32 deg F | Absolute pressure Inches Mercury | Absolute pressure millimeters Mercury |
|----------|-------|---------------------------------------|----------------------------------|---------------------------------------|
| Meters | Feet | | | |
| 0 | 0 | 14.696 | 29.92 | 760 |
| 30 | 98 | 14.64 | 29.80 | 757 |
| 60 | 197 | 14.58 | 29.69 | 754 |
| 90 | 295 | 14.52 | 29.57 | 751 |
| 120 | 394 | 14.47 | 28.45 | 748 |
| 150 | 492 | 14.41 | 29.34 | 745 |
| 180 | 591 | 14.35 | 29.22 | 742 |
| 210 | 689 | 14.30 | 29.11 | 739 |
| 240 | 787 | 14.24 | 28.99 | 736 |
| 270 | 886 | 14.18 | 28.88 | 734 |
| 300 | 984 | 14.13 | 28.76 | 731 |
| 330 | 1083 | 14.07 | 28.65 | 728 |
| 360 | 1181 | 14.02 | 28.54 | 725 |
| 390 | 1280 | 13.96 | 28.43 | 722 |
| 420 | 1378 | 13.91 | 28.32 | 719 |
| 450 | 1476 | 13.85 | 28.20 | 716 |
| 480 | 1575 | 13.80 | 28.09 | 714 |
| 510 | 1673 | 13.74 | 27.98 | 711 |
| 540 | 1772 | 13.69 | 27.87 | 708 |
| 570 | 1870 | 13.64 | 27.76 | 705 |
| 600 | 1969 | 13.58 | 27.65 | 702 |
| 900 | 2953 | 13.06 | 26.59 | 675 |
| 1200 | 3937 | 12.55 | 25.56 | 649 |
| 1500 | 4921 | 12.07 | 24.57 | 624 |
| 1800 | 5906 | 11.60 | 23.63 | 600 |
| 2100 | 6890 | 11.16 | 22.71 | 577 |
| 2400 | 7874 | 10.73 | 21.84 | 555 |
| 2700 | 8858 | 10.31 | 20.99 | 533 |
| 3000 | 9843 | 9.91 | 20.18 | 513 |
| 3300 | 10827 | 9.53 | 19.40 | 493 |
| 3600 | 11811 | 9.16 | 18.65 | 474 |
| 3900 | 12795 | 8.81 | 17.93 | 456 |
| 4200 | 13780 | 8.47 | 17.24 | 438 |
| 4500 | 14764 | 8.14 | 16.58 | 421 |
| 6000 | 19685 | 6.69 | 13.61 | 346 |

Appendix F3-Influence of generic altitude on atmospheric pressure pressure

**INFLUENCE OF
GENERIC ALTITUDE ON
ATMOSPHERIC PRESSURE**

Atmospheric pressure vs altitude



P106 154E

Data showing atmospheric pressure vs altitude

| Data from ASHRAE Guide: | | Calculated pressure in. Hg | Error = calculated - given pressure in. Hg |
|-------------------------|-----------------|----------------------------|--|
| Altitude, ft. | Pressure in. Hg | | |
| -1000 | 31.02 | 31.50 | 0.48 |
| -500 | 30.47 | 30.87 | 0.40 |
| 0 | 29.921 | 30.26 | 0.34 |
| 500 | 29.38 | 29.66 | 0.28 |
| 1000 | 28.86 | 29.08 | 0.22 |
| 5000 | 24.89 | 24.78 | -0.11 |
| 10000 | 20.58 | 20.29 | -0.29 |
| 15000 | 16.88 | 16.61 | -0.27 |
| 20000 | 13.75 | 13.60 | -0.15 |
| 25000 | 11.1 | 11.13 | 0.03 |
| 30000 | 8.88 | 9.11 | 0.23 |
| 35000 | 7.04 | 7.46 | 0.42 |
| 40000 | 5.54 | 6.11 | 0.57 |
| 45000 | 4.36 | 5.00 | 0.64 |
| 50000 | 3.436 | 4.10 | 0.66 |

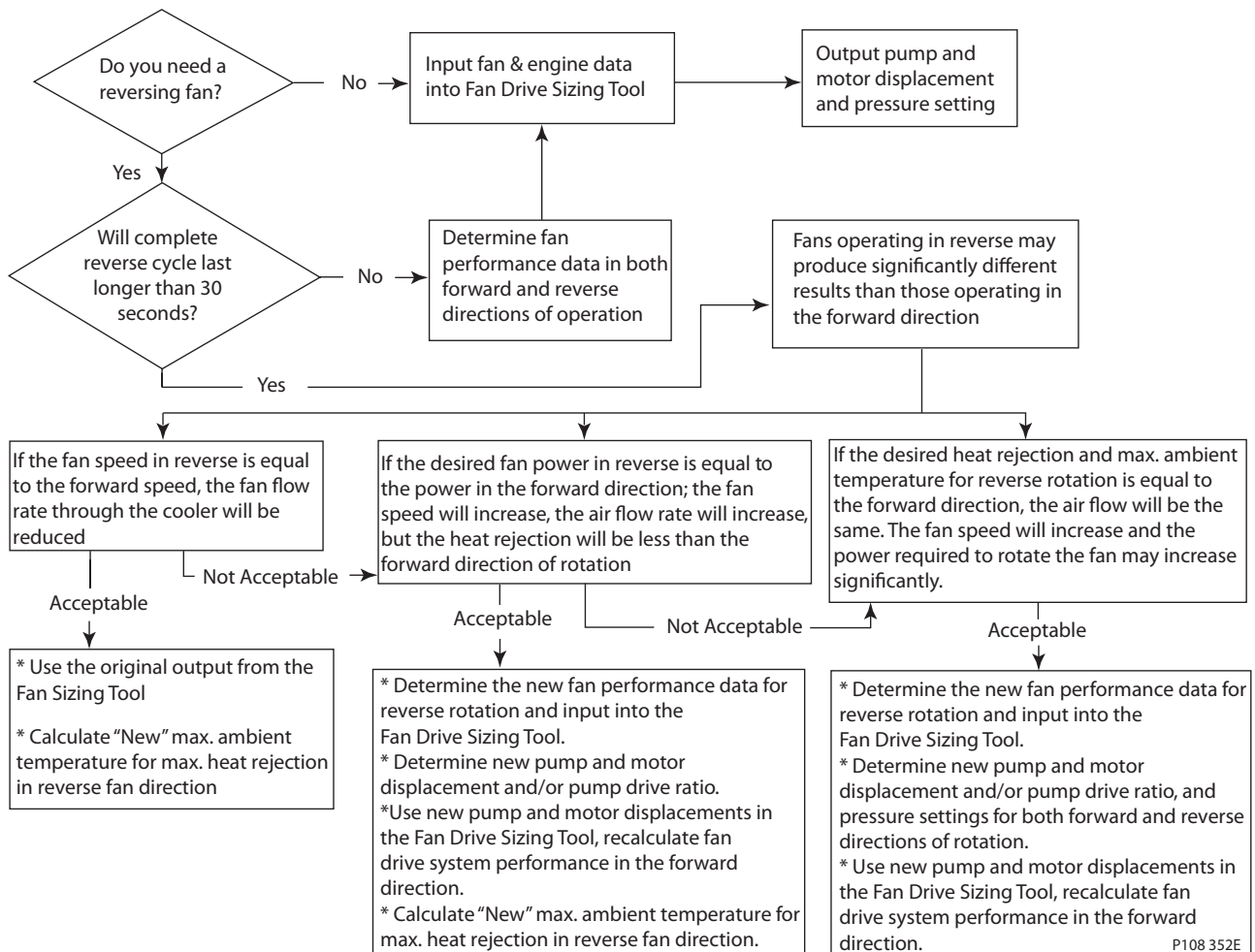
Appendix G-Influence of reversed fan rotation on system performance

INFLUENCE OF REVERSED FAN ROTATION ON SYSTEM PERFORMANCE

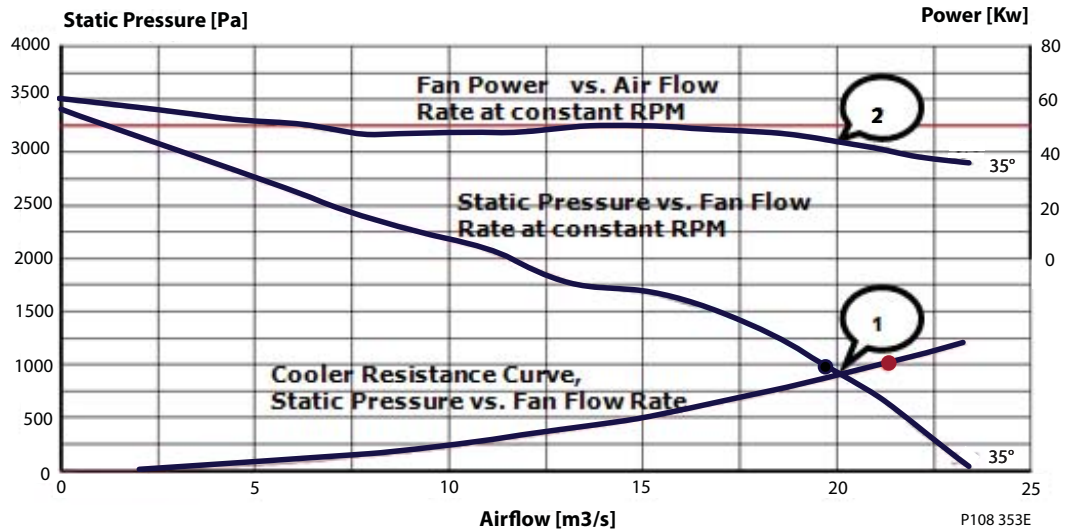
In applications where it is necessary to change the direction of fan rotation, most fans will have reduced performance. Some fans are designed for equal, or similar, performance in the reverse direction, but this is not typical of many axial flow fans that are installed in vehicles today. Some fan blade designs have significantly different efficiencies depending on their direction of rotation and pitch angle (angle of attack). In this instance, we're using the term "efficiency" to indicate that the fan does not produce the same amount of air flow at the same speed; and/or it requires more power to produce the same amount of air flow as in the forward direction of rotation.

The cooling system designer is encouraged to consult with their fan supplier for performance characteristics specific to their fan; based on the speed of operation, static pressure drop, and direction of rotation. Using this information, it is possible to validate whether the fan will meet the specific needs of the cooling system. Given this information, the system designer can investigate the effect of these changes and determine if corrective actions need to be introduced.

The following is a guide to some of the characteristics that one could encounter when reversing the direction of a fan. For these purposes, the fan is assumed to be operating at its design "trim" speed and at the desired maximum "static" operating pressure across the cooler when in the forward direction.



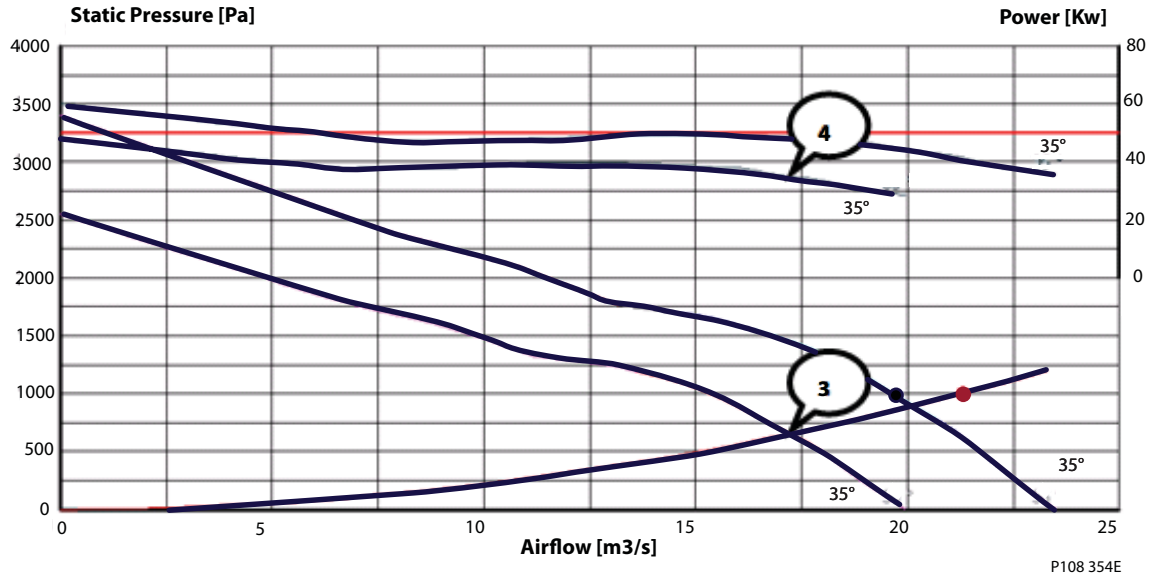
Baseline: Fan operating in Forward Direction at 2600 RPM



1. The Flow Rate for a given fan speed is determined by the intersection of the Fan's Flow/Static-Pressure Curve for that speed and the Cooler's Resistance Pressure vs Airflow characteristic curve.
2. The power required to turn the fan at that speed (airflow & static pressure) is located directly above this intersection point on the Fan Flow Rate vs Fan Power Curve at constant RPM. The magnitude of the fan power is determined by the secondary Y-Axis in the upper right hand corner of the graph.

Appendix G-Influence of reversed fan rotation on system performance

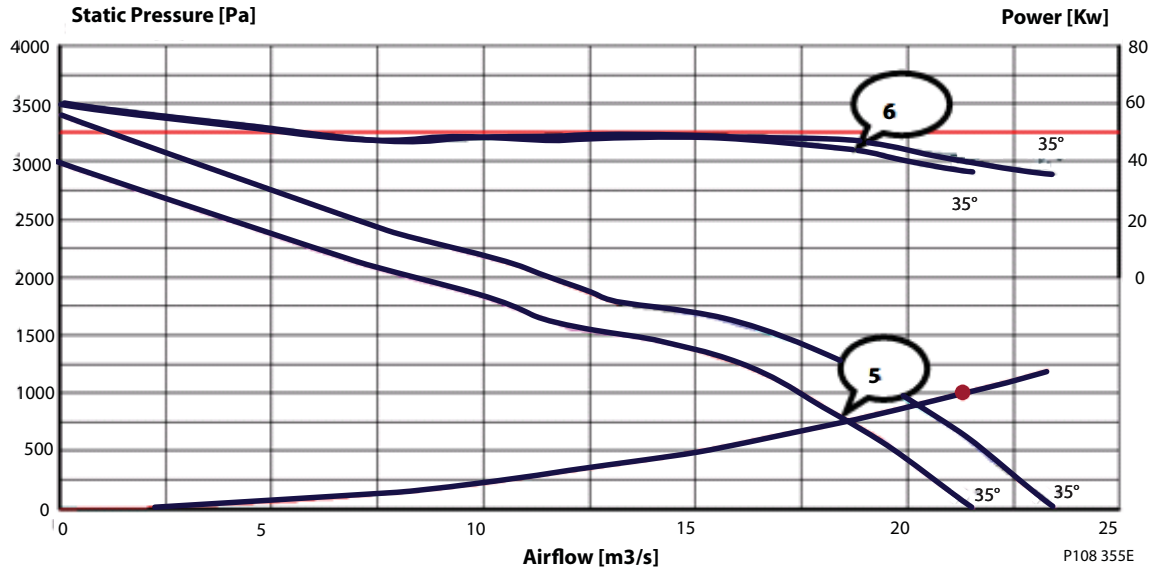
Condition 1: Fan operating in Reverse Direction at 2600 RPM



3. The Flow Rate for 2600 RPM in the reverse direction is less than that produced by the fan at 2600 RPM in the forward direction of rotation. Since the air flow rate is less, the static pressure across the cooler is also reduced.
4. The power required to turn the fan at the same speed, but in reverse direction, is less than that required in the forward direction of rotation. The fan is producing less flow at a lower static pressure; thus a lower power requirement.

Appendix G-Influence of reversed fan rotation on system performance

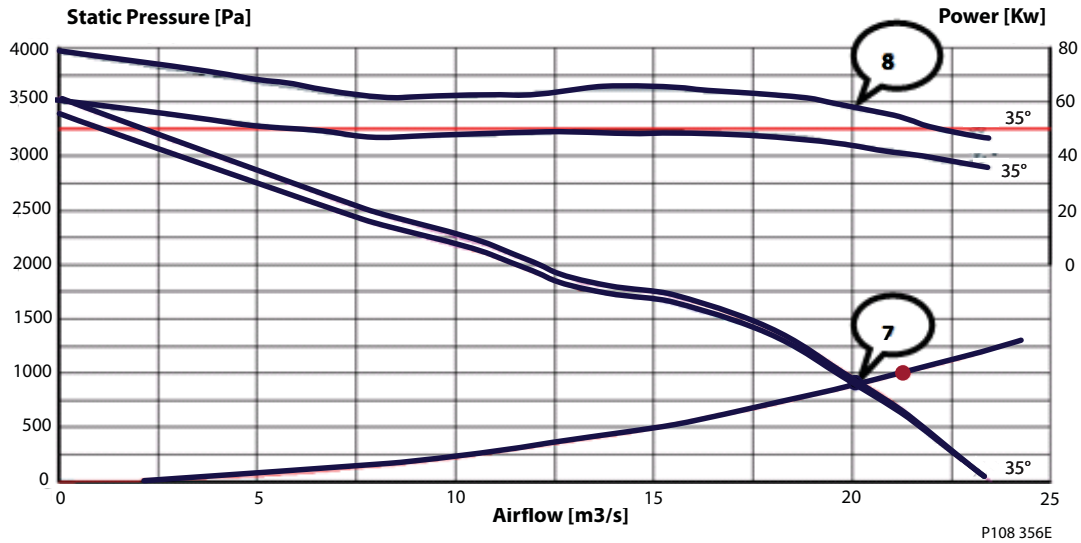
Condition 2: Fan operating in Reverse Direction at approximately the same input power level (by increasing the fan speed in reverse)



5. The fan is producing less flow, even though the fan speed is now 2810 RPM in the reverse direction of rotation.
6. The power required to turn the fan at 2810 RPM, in reverse direction, is approximately the same as that required to turn the fan at 2600 RPM in the forward direction of rotation. The fan is still producing less flow at a lower static pressure. (Fan efficiency is reduced in the reverse direction.)

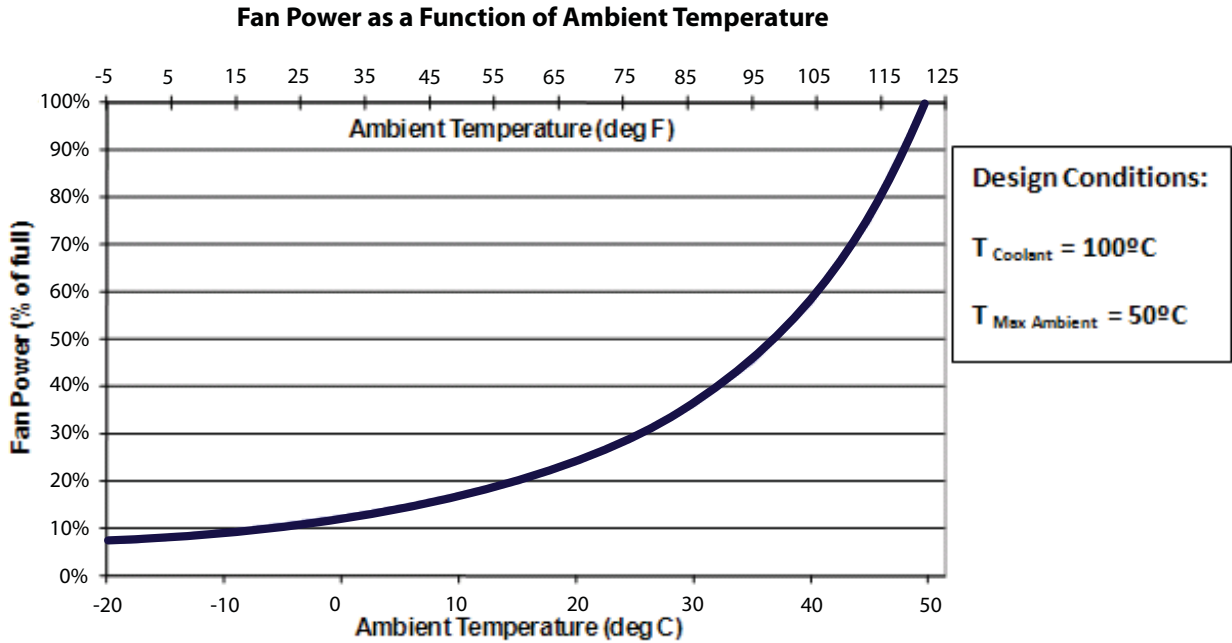
Appendix G-Influence of reversed fan rotation on system performance

Condition 3: Fan operating in Reverse Direction at approximately the same flow rate (by increasing the fan speed in reverse)



7. The fan is producing approximately the same flow rate, even though the fan speed is now 3060 RPM in the reverse direction of rotation.
8. The fan requires more power at the same flow rate and static pressure, because the fan is less efficient in the reverse direction of rotation.

System Response to Reversed Fan Rotation:



$$\frac{T_{Coolant} - T_{ActualAmb}}{T_{Coolant} - T_{MaxAmbient}} = \text{Cooling Effectiveness}$$

P108 357E

- “Cooling Effectiveness” is proportional to the cooling capacity of the cooler; i.e., the ratio is greater than one when the actual Ambient Temperature is less than the original design Maximum Ambient Temperature (System Design Temperature). When the ratio is greater than 1.0, the cooler will not require as much air flow to satisfy the cooling needs of the system. Therefore, the Fan Power requirement will be less than at the “design” maximum ambient temperature.
- At the “design” Maximum Ambient Temperature, reducing the air flow rate thru the cooler has an equivalent effect of reducing the “Cooling Effectiveness” of the cooler; as such, the two concepts may be equated.
- Therefore, as the air flow rate thru the cooler is reduced (Cooling Effectiveness ≤ 1.0); a new “ $T_{ActualAmb}$ ” can be calculated, which will define a new upper limit of ambient temperature where the cooler will still satisfy the maximum heat load.

The new “ $T_{ActualAmb}$ ” temperature will be lower than the original Design Maximum Ambient Temperature.

Derivation:

$$\text{Heat Rejection}_{\text{Actual}} = \dot{m}_{\text{Actual}} * C_p * (T_{\text{Coolant}} - T_{\text{Actual Amb}})$$

and

$$\text{Heat Rejection}_{\text{Maximum}} = \dot{m}_{\text{Maximum}} * C_p * (T_{\text{Coolant}} - T_{\text{Maximum Actual Ambient}})$$

$$\left(\frac{\text{Heat Rejection}_{\text{Actual}}}{\text{Heat Rejection}_{\text{Maximum}}} \right) = \left(\frac{Q_{\text{Actual}} * (T_{\text{Coolant}} - T_{\text{Actual Amb}})}{Q_{\text{Maximum}} * (T_{\text{Coolant}} - T_{\text{Maximum Actual Ambient}})} \right)$$

IF

$$\left(\frac{\text{Heat Rejection}_{\text{Actual}}}{\text{Heat Rejection}_{\text{Maximum}}} \right) \equiv 1.0, \text{ and } Q_{\text{Actual}} \leq Q_{\text{Maximum}}$$

then

$$\left(\frac{Q_{\text{Actual}}}{Q_{\text{Maximum}}} \right) \leq 1.0, \text{ and}$$

$$\left(\frac{T_{\text{Coolant}} - T_{\text{Actual Amb}}}{T_{\text{Coolant}} - T_{\text{Max Ambient}}} \right) \text{ must be } \geq 1.0, \text{ therefore the new } T_{\text{Actual Amb in Rev}} \text{ must be } \leq T_{\text{Max Ambient}}$$

Let :

$$\left(\frac{Q_{\text{Actual}}}{Q_{\text{Maximum}}} \right) = 0.8424 = \left(\frac{\text{Flow at 2600 RPM Reverse}}{\text{Flow at 2600 RPM Forward}} \right)$$

And Let :

$$\left(\frac{\text{Heat Rejection}_{\text{Actual}}}{\text{Heat Rejection}_{\text{Maximum}}} \right) \equiv 1.0,$$

$$T_{\text{Coolant}} = 100^{\circ} C$$

$$T_{\text{Max Ambient}} = 50^{\circ} C$$

Therefore,

$$(T_{\text{Coolant}} - T_{\text{Maximum Actual Ambient}}) * \left(\frac{Q_{\text{Maximum}}}{Q_{\text{Actual}}} \right) = (T_{\text{Coolant}} - T_{\text{New Actual Amb in Rev}})$$

$$T_{\text{New Actual Amb in Rev}} = \left(\frac{1}{0.8424} \right) * 100^{\circ} C - \left(\frac{1}{0.8424} - 1 \right) (100^{\circ} C - 50^{\circ} C) = 40.65^{\circ} C$$

Suggested Guidelines for Reversing Fan Drive Systems:

IF the desire is to keep the **fan speed** in the reverse direction the same as in the forward direction:

This will occur automatically, IF the fan drive system is flow limited by pump speed, or displacement; but not IF the system is pressure limited.

- The heat rejected by the cooling system will be less than in the forward direction of rotation,
- The power to drive the fan in reverse will be less than in the forward direction,
- The Torque to turn the fan, and therefore the delta pressure across the hydraulic motor, will be proportional to the power ratio, since the fan speed is the same.

IF the desire is to keep the **fan power** in the reverse direction the same as in the forward direction:

- The Heat Rejection by the system will still be less than in the forward direction, but better than when maintaining constant fan speed, (HR Speed Ratio)
- The fan speed in reverse will be greater than in the forward direction. The Torque to turn the fan (and hydraulic delta pressure) will be less than in the forward direction, (Power to turn the fan is the same, but the speed is greater.)
- This condition may define the maximum pump displacement or speed required to satisfy the flow requirements of the fan system, since the flow required to rotate the fan will be larger in the reverse direction than in the forward direction.
- Be sure to validate these conditions with the fan supplier. The new speed requirement may exceed the maximum speed limit.

Tip speed is proportional to the fan rotational speed and internal stresses in the fan are proportional to the square of the fan speed.

IF the desire is to keep the **fan flow rate** in the reverse direction the same as in the forward direction:

- The Heat Rejection by the system will be the same as in the forward direction,
- The Power required to rotate the fan in the reverse direction will be greater than in the forward direction of rotation, because the fan is less efficient in the reverse direction of rotation,
- The fan speed in reverse will be greater than in the forward direction. The Torque to turn the fan (and hydraulic delta pressure) may be greater than in the forward direction, (Power to turn the fan is greater, and the speed is greater.)
- This condition may define the maximum pump displacement required to satisfy the flow requirements of the fan system, since the flow required to rotate the fan will be larger in the reverse direction than in the forward direction.
- Be sure to validate these conditions with the fan supplier. The new speed requirement may exceed the maximum speed limit.

Tip speed is proportional to the fan rotational speed and internal stresses in the fan are proportional to the square of the fan speed.

Appendix G-Influence of reversed fan rotation on system performance

Performance Summary: (For Reference Only)



Refer to performance curves in previous graphs

| Direction of Rotation | Forward | | Reverse | | |
|----------------------------------|-------------------|--|-------------------|-------------------|-------------------|
| Fan Speed, RPM | 2600 | | 2600 | 2810 | 3060 |
| Air Flow Rate, m ³ /s | 20.1 ¹ | | 17.2 ³ | 18.6 ⁵ | 20.3 ⁷ |
| Static Pressure, Pa | 894 | | 653 | 763 | 904 |
| Total Pressure, Pa | 1450 | | 1060 | 1240 | 1460 |
| Fan Power, kW | 43.7 ² | | 34.8 ⁴ | 43.9 ⁶ | 56.8 ⁸ |
| Total Efficiency, % | 67% | | 52% | 52% | 52% |

P108 359E

Appendix H-System considerations for H1 Fan Drives with reversed fan rotation

As was said in Appendix G, in applications where it is necessary to change the direction of fan rotation, most fans will have reduced performance. For fan systems using H1 pumps with the H1 Fan Drive Control Valve, the control valve receives a command from the PLUS+1 Controller to regulate fan speed by changing pump displacement. When the pump speed is at the design "set point," fan speed required for the desired cooling capacity is determined by the pump's displacement.

In many systems, the fan's speed at this condition may be close to its maximum design speed. If the pump speed increases beyond the "set point" and the pump is commanded to maximum displacement; then the fan speed will increase in proportion to the pump speed ratio and the delta pressure across the fan motor will increase in proportion to the square of the pump speed ratio.

To prevent this from happening, the system designer is encouraged to limit the maximum fan speed in each direction of rotation by adjusting the set pressure of the Pressure Limiters for both directions of rotation.

For the forward direction of rotation, determine the delta pressure across the fan motor when it's at maximum desired fan speed and power. Adjust the pressure limiter setting to be equal to "the forward design pressure + 20 bar" for the forward direction of rotation.

For the reverse direction of rotation, determine the delta pressure across the fan motor when it's at maximum desired fan speed and power (consult with the fan and cooler manufacturer to determine the desired fan speed and power for the fan when rotating in the reverse direction, reference Appendix G). Adjust the pressure limiter setting to be equal to "the reverse design pressure + 20 bar" for the reverse direction of rotation.

Verify that the pressure limiter settings will not cause the fan speed to exceed the manufacturer's maximum speed limitation. Make adjustments accordingly.



Hydraulic Fan Drive Systems
Design Guidelines
Notes



Hydraulic Fan Drive Systems
Design Guidelines
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