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Superseding AIR1922A

(R) Aerospace - System Integration Factors
That Affect Hydraulic Pump Life

RATIONALE

Revision B of this document reflects various technical and editorial corrections and improvements that were identified during its 5-year review.

AIR1922B has been reaffirmed to comply with the SAE Five-Year Review policy.

FOREWORD

The information provided in this Aerospace Information Report (AIR) is compiled from various sources and is based on the experience and judgment of engineering and operating personnel of aircraft hydraulic components and systems.

This document is intended to be informative when considering hydraulic pump life and performance since there are no hard and fast rules for determining the optimum combination or arrangement of all the components in each hydraulic system.

However, the criteria to be followed and the operating parameters to be utilized when designing a hydraulic system remains with the designer.

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1. SCOPE

This SAE Aerospace Information Report presents the following factors that affect hydraulic pump life and performance:

- a. The need to supply hydraulic fluid at the correct pressure and quality to the pump inlet port
- b. Considerations for the pump output
- c. Factors to be considered for the pump case drain lines
- d. The mounting of the hydraulic pump
- e. Hydraulic fluid properties, including cleanliness

1.1 Field of Application

This document applies to pumps operating constantly or for long periods at quasi-constant speed such as engine driven pumps or within narrow speed ranges such as electric motor driven pumps.

Wide speed range and intermittent duty cycle pumps, such as those used in Electrohydrostatic Actuators, are not covered by this document.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

NOTE: Appendix A provides a list of documents that provide additional hydraulic system design information. It should be noted that some documents may be difficult to obtain.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AS595	Aerospace – Civil Type Variable Delivery, Pressure Compensated, Hydraulic Pump
AIR810	Degradation Limits of Hydrocarbon-Based Hydraulic Fluids, MIL-PRF-5606, MIL-PRF-83282, MIL-PRF-87257 Used in Hydraulic Test Stands
AS1241	Fire Resistant Phosphate Ester Hydraulic Fluid for Aircraft
AIR1362	Aerospace Hydraulic Fluids Physical Properties
AS4059	Aerospace Fluid Power – Contamination Classification for Hydraulic Fluids
ARP4205	Aerospace Fluid Power - Hydraulic Filter Elements - Method for Evaluating Dynamic Efficiency with Cyclic Flow
AIR4543	Aerospace Hydraulics and Actuation Lessons Learned
AIR5277	Aerospace Fluid Power - Waste Reduction Practices for Used Phosphate Ester Aviation Hydraulic Fluid

ARP5376 Methods, Locations and Criteria for System Sampling and Measuring the Solid Particle Contamination of Hydraulic Fluids

AIR5829 Air in Aircraft Hydraulic Systems

AS19692 Pumps, Hydraulic, Variable Flow, General Specification For

2.1.2 ISO Publications

Available from American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, Tel: 212-642-4900, www.ansi.org.

or if using the Switzerland address:

Available from International Organization for Standardization, ISO Central Secretariat, 1, ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, Tel: +41 22 749 01 11, www.iso.org.

ISO16889 Hydraulic Fluid Power - Filters - Multi-Pass Method For Evaluating Filtration Performance of a Filter Element

2.1.3 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

RTCA/DO-160 Environmental Conditions and Test Procedures for Airborne Equipment

2.1.4 U.S. Government Publications

Copies of these documents are available online at <http://quicksearch.dla.mil>.

MIL-STD-810 Environmental Test Methods and Engineering Guidelines

MIL-F-8815 Filter and Filter Elements, Fluid Pressure, Hydraulic Line, 15 Micron Absolute and 5 Micron Absolute, Type II Systems, General Specification For

MIL-PRF-83282 Hydraulic Fluid, Fire Resistant Synthetic Hydrocarbon Base, Aircraft

MIL-PRF-87257 Hydraulic Fluid, Fire Resistant Synthetic Hydrocarbon Base, Aircraft

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Aerospace document.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP4752 Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems

ARP4925 Aerospace - Design and Installation of Commercial Transport Helicopter Hydraulic System

AS5440 Hydraulic Systems, Military Aircraft, Design and Installation Requirements for

2.3 Definitions

DISSOLVED AIR: This is air that is physically in solution in the hydraulic fluid.

ENTRAINED AIR: This is air in the form of bubbles that are typically less than 0.04 inch (1 mm) in diameter that are dispersed in the hydraulic fluid.

FREE AIR: This is a pocket of air that is trapped in part of a hydraulic system.

NOTE: Refer to AIR5829 for more information on these different forms of air in hydraulic systems.

HYDRAULIC PUMP STABILITY: This is the freedom from persistent or quasi-persistent oscillation of the delivery control mechanism.

OUTGASSING PRESSURE: This is the pressure below which dissolved gas begins to separate from the fluid and becomes free or entrained.

RESPONSE TIME: This is the time required for the change of displacement of the pump when subjected to a specific discharge circuit transient.

NOTE: On most pump models it is not possible to measure the pump displacement. Instead, a test can be carefully designed wherein it is possible to deduce the change in displacement of the pump by the inspection of the pump discharge pressure. This measurement is called "Response Time" as it is a dynamic characteristic of a pump operating in a specified discharge circuit. It is not strictly an attribute of the pump. In such a test, the response time is the time interval between the instant when an increase (or decrease) in discharge pressure change initiates; and the subsequent instant when the discharge pressure reaches its first maximum (or minimum) value.

SATURATION PRESSURE: This is the static pressure below which there occurs a net migration of molecules (normally atmospheric) to the gaseous state (outgassing).

NOTE: The steady-state saturation pressure of hydraulic fluid at rest in an open container is the local atmospheric pressure. The saturation pressure in a system may not be homogeneous and may change over time.

VAPOR PRESSURE: This is the pressure below which the fluid changes phase and forms vapor bubbles.

3. PUMP INLET LINE

3.1 General

Any positive displacement pump designed to flow a liquid requires some minimum pressure at its inlet port to produce satisfactory performance. The magnitude of this minimum pressure (expressed in terms of absolute pressure such as psia (kPa abs)) is a function of the pump's design, shaft speed, duty cycle, and the viscosity of the liquid being pumped.

If the pump is mounted inside an open reservoir of liquid, the inlet pressure will be atmospheric pressure plus the "head" of liquid above the pump. If such an installation does not provide the necessary inlet pressure, the reservoir could be closed and pressurized by means to the pressure required by the pump for the particular set of operating conditions.

NOTE: If hydraulic fluid is supplied to the pump by a suction line in the reservoir, then there should be an analysis of the pressure drop (see 3.6.4) and fluid acceleration (see 3.6.2) to check that there is sufficient pressure available to avoid cavitation of the pump.

For numerous reasons, it is often impractical to mount the pump inside a reservoir, thus the need for an inlet line to connect the source of liquid with the pump inlet port. Furthermore, in practice the medium is not a pure liquid but a mixture of fluids, as there is always some air mixed in it. To the extent that the inlet line affects the net inlet pressure and quality of the fluid available at the pump, it has a significant effect on the pump's performance and life. (The term "quality" here refers to the form of air mixed in the liquid.)

The primary factors to be considered so as to ensure that the inlet line is optimized for supplying fluid to the pump are:

- its cross-section;
- length, routing;
- restrictions;
- air tightness.

3.2 Inlet Pressure

Despite the many improvements made to hydraulic fluids (e.g., lubricity, shear strength, viscosity stability, etc.), one physical characteristic cannot be changed, and that is the complete lack of tensile strength of the fluid. It is, therefore, impossible to move a quantity of liquid, larger than a drop, by pulling on it and to move a fluid it has to be pushed, that is, propelled by pressure behind it – even to the inlet of a pump.

In order to obtain a satisfactory performance and life from a positive displacement pump, its internal pumping elements should remain filled with fluid, ideally as close as possible to a pure liquid. To achieve this, not only should free air be avoided, but also the fluid environment has to remain above the fluid's outgassing pressure and especially above its vapor pressure. For the fluids of interest, even at their maximum system operating temperature, the vapor pressure is typically below 1.0 psia (6.9 kPa abs), which may sound too low to be of practical concern. However, this low pressure can easily occur at the valving surfaces inside a pump operating at high speeds or during flow transients in long inlet lines.

NOTE: Airframe inertial accelerations can also act on the fluid mass and that the momentum of flowing fluid are also factors.

Between the pump inlet port and the actual internal pumping elements, there are, of necessity, fluid passages of discrete dimensions. In addition, there is a valving mechanism to separate the inlet area from the high pressure discharge area. These generate a restriction to fluid flow, hence a pressure drop. Consequently, to maintain close to saturation pressure in the pumping elements, the pressure at the inlet port should be higher. The resulting pressure for practical purposes is designated as the "Critical Inlet Pressure of the Pump."

The magnitude of the critical inlet pressure will vary as a function of pump design, operating conditions and fluid characteristics. It should be noted that at low temperatures (typically between 32 to 64 °F (0 to 16 °C)), the fluid flow tends to become laminar, thus increasing the critical inlet pressure due to fluid viscosity effects within the pump.

Typical critical inlet pressure (P_{crit}) requirements are shown in Figure 1 for various pump sizes. The critical inlet pressure for a specific pump should be readily available from the pump manufacturers.

Any operation below this critical inlet pressure will cause pump cavitation with the subsequent reduction in outlet flow, increased pressure ripple, and will result in severe damage to the pump. The amount of damage depends on how much the inlet pressure was below the critical value, and for how long. While periods of only a few milliseconds will cause only limited damage, the destructiveness is cumulative and can manifest itself as serious damage in less than a hundred hours.

It is also important to remember that the measured pressure at the pump inlet may appear adequate even though the fluid contains substantial amounts of undissolved air. In such cases, pump damage will still occur.

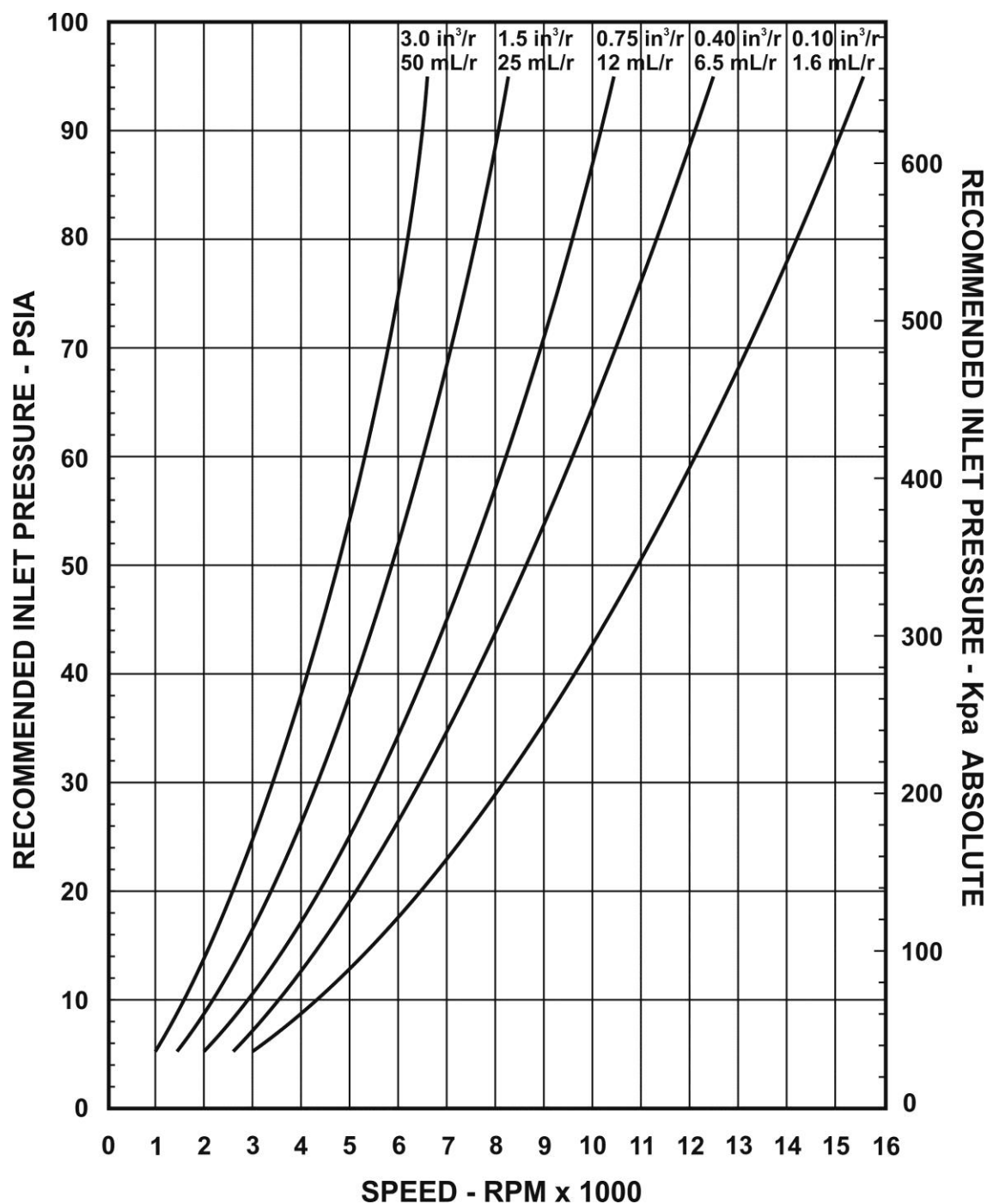


Figure 1 - Typical critical inlet pressure values for inline pumps

NOTES:

1. Consult the hydraulic pump supplier for the definitive critical inlet pressure for a specific pump application.
2. The inlet pressures shown in Figure 1 are for pumps operating with MIL-PRF-83282, and MIL-PRF-87257 hydraulic fluids at nominal fluid temperatures. An increase of 30% is recommended for operation with AS1241 hydraulic fluids to allow for their increased density compared to the MIL-PRF fluids.

3.3 Cavitation

If the inlet fluid contains entrained (undissolved) gas, typically air, or if the inlet pressure of the fluid is allowed to drop below its outgassing pressure so that dissolved air comes out of solution or worse yet, below its vapor pressure, there will be bubbles. After these enter the pumping elements and are then compressed to pump discharge pressure, they will collapse violently and generate a shockwave. In the case of piston pumps, this violent release of localized energy will manifest itself as cavitation erosion in such areas as:

- cylinder blocks/cylinder barrels;
- valving plates/port plates;
- shoes/slippers;
- shoe bearing/wear plates.

The occurrence of cavitation is clearly noticeable by its characteristic noise and line vibration. However, in the case of pressure transients, the noise and vibration may be masked by other factors. Damage to the pumping elements as a result of cavitation consists of small particles of material being removed from their surfaces and subsequently carried by the fluid through the discharge and case drain ports into the system. Since there is material removed, the damage is cumulative.

The material removal can cause changes to pump timing and hydrostatic balance, which in turn can cause premature wear of the sliding surfaces. Additionally, the wear debris in suspension may score other hydrodynamic sliding surfaces thereby creating more debris. Most of the contaminants will then circulate through the pump bearings precipitating their premature failure.

It is therefore important that pump cavitation is avoided at all times, including during transient conditions. The design of the system and components should ensure that the required inlet pressure on the fluid at the pump is always maintained.

3.4 Air in Hydraulic Fluids

The hydraulic system can contain air in three forms:

- a. dissolved air;
- b. entrained air;
- c. free air.

The first two were commented on as they affect cavitation, and will be cited again in relation to inlet line configuration.

Extensive documents including AIR5829 have been written on air in hydraulic fluids, including experience with quantitative amounts of dissolved and entrained air.

Free air in a hydraulic system can also cause extensive damage to pumps as well as to other components. It does so primarily by interrupting the lubricating fluid film in critical areas, thereby allowing metal-to-metal contact.

Aside from pump damage, free air (often manifested as foam) can have serious operational effects such as:

- system instability;
- increased pressure ripple;
- the loss of pump prime;
- the inability of the pump to maintain flow and pressure;
- damaging the hydraulic fluid over time because when free air is compressed to design operating pressure, will also create a very tiny, but extremely hot, pocket of gas.

The presence of free air is often due to inadequate bleeding of the system; however, poorly thought-out design details can make adequate bleeding next to impossible.

System design details that will help avoid serious air problems include:

- a. Ensure that the pump case drain port is located in the upward direction.
- b. Avoid non-uniformity in line size and sharp bends in the pump inlet line.
- c. As hoses generally cause a larger pressure drop than tubing, they should be used with caution.
- d. Design tubing routes to prevent air, water, and particulate entrapment and avoid vertical loops in the inlet line as this increases the risk of having air traps which make pump priming and system bleeding very difficult and sometimes impossible during adverse conditions.
- e. Ensure that hydraulic controls elevated above the reservoir can be adequately bled during ground maintenance activities.
- f. Install bleed valves at high points in the hydraulic system to remove entrapped air.

NOTE: Bleed valves are normally installed where there is an air trap combined with low pressures and low flow rates.

- g. Minimize the number of fittings in pump inlet lines. While these may not leak hydraulic fluid, they can ingest air.
- h. With bootstrap reservoirs:
 1. Provide low piston friction to reduce the vacuum effect in the inlet line as the hydraulic system cools down.
 2. Provide sufficient auxiliary force (i.e., spring, gas pressure, etc.) to retain the reservoir piston against the fluid when the hydraulic system is depressurized.
 3. Provide automatic bleed valves permanently mounted at the highest point of the reservoir to bleed free air.
 4. Provide an in-system air eliminator to reduce dissolved air to below saturation conditions to further reduce the potential of free air.
 5. Assure components do not include restrictors that cause air formation as discussed in AIR4543 and AIR5829.

i. With air-pressurized reservoirs:

1. Use an air to oil separator in the reservoir in order to minimize the amount of air in the hydraulic system.

NOTE: If a separator is used, then the bootstrap reservoir requirements (h), 3, 4, and 5 apply.

2. The use of unseparated, air-pressurized reservoirs can significantly increase the dissolved air content of the system which can lead to out-gassing in the pump suction line. In this arrangement, it may be advantageous to include an integral inlet boost stage in the pump (see 3.5.1).

3.5 Boost Pumps

3.5.1 Integral Inlet Boost Stage in the Pump

When the inlet line is compromised, or reservoir pressure too low, the resulting inlet pressure may be too low for the positive displacement pump. In that case, the pump manufacturer may incorporate an integral inlet boost section, typically an impeller, into the pump.

The pressure boost capabilities of typical, well designed centrifugal impellers are in the 20 to 40 psi (138 to 276 kPa) range, depending on their size and operating speed, as well as the flow rate, fluid and temperature. When all these parameters are in their optimal combination, the critical inlet pressure of the pump combination can be reduced to the 5 to 10 psia (34.5 to 69 kPa abs) range. Effective performance without cavitation below approximately 5 psia (34.5 kPa abs) inlet pressure may require the addition of inducers or injectors, in addition to an impeller.

Integral boost mechanisms in the pump can be very effective and have the advantage of dissolving some of the entrained air, but they will add size, weight, and cost to the pump. Their design is very critical and maximum effectiveness is in a relatively narrow performance band in terms of speed and temperature, as compared to that of the positive displacement pump. In many situations, the total system would be better served by improving the inlet line (reducing its pressure drop) than by tolerating an inferior inlet line with the more complex two-stage or even three-stage pump combinations.

3.5.2 Alternatives

The following should be considered if it is not feasible or desirable to introduce an integral inlet boost section into the pump:

- a. Incorporate a centrifugal boost pump near the reservoir produces one of the best inlet conditions for the main pump as it minimizes the side effects of the air in the fluid.
- b. Install a charged accumulator in close proximity to the pump inlet port if a poor inlet condition occurs only during transients.
- c. To allow or specify a slower pump response when high flows are required from large displacement pumps with marginal inlet pressure.
- d. Fittings and quick disconnects installed close to or in the pump inlet port are to have a minimal pressure drop. (This is to prevent air coming out of solution at the pump inlet).

3.6 Inlet Line - Sizing and Configuration

The design of the pump inlet line, reservoir location, and reservoir pressurization are major system elements affecting hydraulic pump life. Once the basic needs of pump inlet pressure and the inevitable consequences of air and cavitation are understood, attention to the components in the pump inlet line becomes more meaningful.

At the reservoir end, sufficient pressure should be available to push the fluid through the inlet line such that, at the pump inlet port, the fluid pressure is still above the pump's critical inlet pressure under the worst commonly encountered conditions.

To put these conditions in perspective, it should be remembered that the response requirements of many hydraulic systems demand that a variable volume pump responds from its zero flow "dead headed" condition to full flow output in 50 to 200 ms. While most pumps have little difficulty in providing such response, it should be remembered that "you cannot get out what you do not put in". Therefore, the inlet pressurization should be such that the entire mass of fluid in the inlet line will also be accelerated in 50 to 200 ms and still remain above the critical inlet pressure at the pump inlet port.

It follows then that reservoir pressure should be determined by the following elements:

$$P_{\text{resv}} = P_{\text{crit}} + \Delta P_{\text{acc}} + \Delta P_{\text{com}} + \Delta P_{\text{lin}} + \Delta P_{\text{sta}} \quad (\text{Eq. 1})$$

where:

P_{resv} = reservoir pressure

P_{crit} = pump critical inlet pressure

ΔP_{acc} = pressure to accelerate fluid mass in pump response time

ΔP_{com} = pressure loss of inlet line components at maximum flow

ΔP_{lin} = frictional pressure loss in inlet line and hose assembly at maximum flow

ΔP_{sta} = static pressure head

NOTE: Appendix B provides an example of calculating a required reservoir pressure that incorporates all the elements listed above.

3.6.1 Pump Critical Inlet Pressure

This is discussed in 3.2.

3.6.2 Transient or Acceleration Pressure

The transient or acceleration pressure (ΔP_{acc}) is that pressure necessary to accelerate the fluid mass in the inlet line to the maximum required flow within the response time of the pump. The pressure can be determined from the basic equation for acceleration force ($F = ma$) as follows:

$$m = \rho AL \text{ (fluid density x volume)} \quad (\text{Eq. 2})$$

$$a = \frac{dv}{dt} \text{ (time rate of change of velocity)} \quad (\text{Eq. 3})$$

$$F = \rho AL \times \frac{dv}{dt} = \rho AL \times \frac{\frac{dQ}{A}}{dt} = \rho L \times \frac{dQ}{dt} \quad (\text{Eq. 4})$$

The acceleration pressure needed to produce this force is:

$$\Delta P_{\text{acc}} = \frac{F}{A} = \frac{\rho L}{\pi / 4 \times D^2} \times \frac{dQ}{dt} \quad (\text{Eq. 5})$$

When converted to a form that utilizes the commonly used engineering units, and assuming a linear pump response, the foregoing formula appears as follows:

$$\Delta P_{\text{acc}} = 88.1 \times 10^{-6} \frac{\rho L}{D^2} \times \frac{dQ}{dt} \quad (\text{English units}) \quad (\text{Eq. 6})$$

$$\Delta P_{\text{acc}} = 21.2 \frac{\rho L}{D^2} \times \frac{dQ}{dt} \quad (\text{metric units})$$

where:

ΔP_{acc} = pressure required to accelerate, psi (kPa)

dQ = maximum flow change, gpm (L/min)

dt = pump response (seconds), s

L = length of tubing, feet (m)

D = tube inside diameter, inch (mm)

ρ = mass density of the fluid, lb_m/ft³ (kg/L)

A = tube inside cross-section area, in² (mm²)

3.6.2.1 Allowance for Fluid Acceleration Non-Uniformity

If the non-uniformity of the fluid acceleration due to wave effects is taken into account, then the transient pressure term ΔP_{acc} , is oscillatory, with its average value given by Equation 5, but with its maximum value given by:

$$\Delta P_{\text{acc}} = ((\rho \ c) \times (\Delta Q/A)) \quad (\text{Eq. 7})$$

If dQ/dt is constant over the time $2\Delta t$, then ΔQ is equal to $2\Delta t \cdot dQ/dt$ or $2 (L/c) dQ/dt$, so that substituting its value in Equation 7, one gets:

$$\text{The maximum value of } \Delta P_{\text{acc}} = 2 \rho L (dQ/dt)/A \quad (\text{Eq. 8})$$

When converted to a form that utilizes the commonly used engineering units, and assuming a linear pump response, the foregoing formula appears as follows:

$$\Delta P_{\text{acc}} = 176.2 \times 10^{-6} \frac{\rho L}{D^2} \frac{dQ}{dt} \quad (\text{English units}) \quad (\text{Eq. 9})$$

$$\Delta P_{\text{acc}} = 42.4 \frac{\rho L}{D^2} \times \frac{dQ}{dt} \quad (\text{metric units})$$