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Pressure and Flow Characterisitcs of Restrictive Flow Orifice Devices

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Pressure and Flow Characteristics of Restrictive Flow Orifice Devices

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Abstract

A Restrictive Flow Orifice (RFO) can be used to enhance the safe design of a pressure system in several ways. Pressure systems frequently incorporate a regulator and relief valve to protect the downstream equipment from accidental overpressure caused by regulator failure. Analysis frequently shows that in cases of high-flow regulator failure, the downstream pressure may rise significantly above the set pressure of the relief valve. This is due to limited flow capacity of the relief valve. A different regulator or relief valve may need to be selected. A more economical solution to this problem is to use an RFO to limit the maximum system flow to acceptable limits within the flow capacity of the relief valve, thereby enhancing the overpressure protection of laboratory equipment. An RFO can also be used to limit the uncontrolled release of system fluid (gas or liquid) upon component or line failure. As an example, potential asphyxiation hazards resultant from the release of large volumes of inert gas from a "house" nitrogen system can be controlled by the use of an RFO.

This report describes a versatile new Sandia-designed RFO available from the Swagelok Company and specifies the gas flow characteristics of this device. Two sizes, 0.010 and 0.020 inch diameter RFOs are available. These sizes will allow enhanced safety for many common applications. This new RFO design are now commercially available and provide advantages over existing RFOs: a high pressure rating (6600 psig); flow through the RFO is equal for either forward or reverse directions; they minimize the potential for leakage by incorporating the highest quality threaded connections; and can enhance the safety of pressure systems.

Contents

Figures

Tables

Acknowledgments

The author would like to thank the Swagelok Company for accepting the Sandia design for this new product and providing the proto-type RFOs used in this effort. The completion of this report could not have happened without the contribution of the following individuals: Shane Page of the Industrial Hygiene and Safety Programs Department of Sandia National Laboratories, for assistance in interfacing with the Swagelok Company; Christopher J. Flores of Sandia National Laboratories Primary Physical Standards Laboratory for his expertise and assistance in performing the flow measurements; and Gerald W. Wellman of the Structural Mechanics Engineering Department of Sandia National Laboratories for the important work done in the finite element analysis of this new RFO design.

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Nomenclature

The following acronyms and abbreviations are used throughout this report and are defined here for the reader's convenience.

C_v - flow coefficient. For gases, this is defined as the flow of air in standard cubic feet per minute at standard conditions with a one psi pressure differential across the device

Choked (critical) flow - a flow regime where the inlet pressure to the orifice is two or more times the outlet pressure

High Purity - as related to gas handling systems, implies a piping system incorporating high quality pipe threads or compression type fittings as an accepted practice

MAWP - Maximum Allowable Working Pressure

NPT (SC) - National Pipe Taper or National Pipe Thread (Simultaneous Contact) where the machining process and inspections assure the simultaneous contact of the thread root, crest, and flank dimensions at the wrench-tight position

psig - pounds per square inch, gauge

psia - pounds per square inch, absolute

RFO - Restrictive Flow Orifice

scfm - standard cubic feet per minute

SNL - Sandia National Laboratories

Specific Gravity - (of a gas relative to air) is the ratio of the molecular weight of the gas to the molecular weight of air [2]

UHP - Ultra High Purity as related to gas handling systems, implies a piping system incorporating internally electro-polished components and welded or high integrity face seal type of connections as an accepted practice

Introduction and Objectives

This report describes a new Sandia-designed RFO that is now commercially available from the Swagelok Company. Flow verses pressure measurements for clean, dry nitrogen were recorded in order to establish a matrix of data to be used for the proper selection of RFOs in gas handling systems. These new devices are intended to provide flow limitation for safety purposes. They are not precisely calibrated for use as a primary or secondary gas flow standard.

Background

Flow limitation is useful to address a number of safety related design concerns of gas handling systems. Previous commercially available RFO devices often targeted UHP (Ultra High Purity) piping applications, where all welded construction or the use of face seal fittings and electro-polished components are the accepted construction technique. In these applications, RFO devices are typically installed into the gas cylinder valve itself and therefore can only be provided by the gas supplier. Alternately, an excess flow valve or excess flow switch interfaced to an appropriate microprocessor controller can provide flow limitation.

Some models of previously available RFO devices are "directional" in that the flow data provided only applies to the specified direction of flow. For other RFO designs, the allowable differential pressure rating is directional. This newly designed RFO is more flexible in that it can be installed with flow in either direction, with no effect on the flow vs pressure characteristics or pressure rating. In addition, a leakage concern exists with previously available RFO devices incorporating pipe-threaded connections. It is common to encounter NPT threads produced via a tap and die cutting process. The threads resulting from this process are of minimal acceptable quality and allow a greater potential for leakage, especially when used at high pressures or with gases such as helium or hydrogen.

The new Sandia-designed RFOs described here are available from the Swagelok Company in 316 stainless steel with ¼″ NPT (SC) connections that are suitable for use in high purity gas handling systems where pipe-threaded connections are an acceptable technology. The threads are made to a higher standard, NPT (SC - for Simultaneous Contact) that incorporates inspections of tightly controlled machining and rolling processes to produce threads having simultaneous contact of the thread root, crest, and flank dimensions at the wrench-tight position. These RFOs are based on a modification of a standard Swagelok adapter and are pressure rated for use to a maximum of 6600 psig. These RFO devices can be installed in a system in either a forward (flow direction from female to male) or reverse direction (flow direction from male to female) – flow data is given for both cases and is essentially equal in either direction. Specifically, the RFOs are available in two different sizes (0.010 and 0.020 inch diameters) with connections of ¼″ male NPT to ¼″ female NPT. Actual measured orifice sizes and equivalent C_v values are listed below in Table 2. These RFOs can be ordered directly from Albuquerque Valve & Fitting with the **part number SS-4-A-RFO-010** for the 0.010 inch orifice size (or **-020** for the 0.020 inch orifice size).

The rationale for using an RFO device is derived from previously encountered design concerns on SNL pressure system applications. Examples where RFO devices could enhance the system safety include:

1) Restricting / limiting the maximum potential system flow in order to assure adequate pressure relief valve flow capacity

2) Limiting flow from large volume sources, such as from "house" nitrogen gas.

3) Limiting the accidental release of a hazardous gas (flammable / other hazard) resulting from regulator or other component or tubing failure

Design Features

The RFO device is designed to allow use in either a forward direction (flow from the female to the male side) or in the reverse direction (flow from the male to the female) with minimal effect on gas flow. The RFO design is based on the standard SWAGELOK pipe adapter (part # SS-4-A), with the internal clearance "through hole" being replaced by the orifice design as shown in Figure 1. The RFO design also attempts to minimize the effects of manufacturing tolerances on the flow through the RFO. The length of the RFO is greater than the orifice diameter to allow a consistency of orifice diameter and symmetry. Approach velocity can have considerable effect on flow through an orifice: approach velocity variations are minimized due to the large inside diameter of the fitting (from either side) compared to the small orifice diameter size. [1]

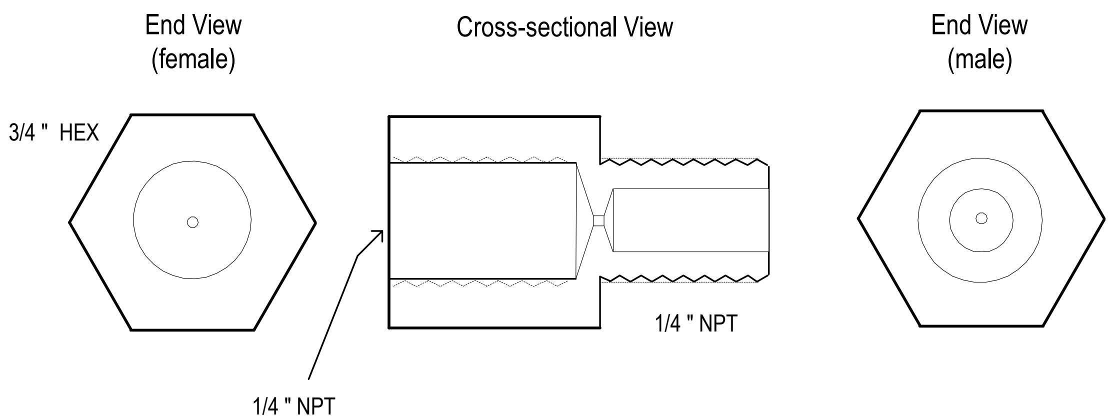


Figure 1 - RFO Design Features

The connections for this device are high quality Swagelok standard ¼ NPT (SC) male and female as included in the SWAGELOK adapter, part # SS-4-A. As with other quality SWAGELOK pipe threaded components, the threads are precisely machined or "rolled" rather than simply cut via tap and die operations. The rolled threads provide a significant improvement to the pressure rating of the component. In addition, the rolled threads also provide a much-improved sealing capability over threads cut in tap and die operations. This is especially important for applications where the RFO is used at high pressures or with gases such as hydrogen or helium.

RFO Design Calculations

The design is based on Swagelok's standard adapter (part # SS-4-A) that has a pressure rating of 6600 psig based on the ¼″ female connection. The modifications to convert the adapter to an RFO do not affect this rating.

Calculations for flat end plate:

The "differential" pressure rating of the new RFO component has also been considered. The orifice design includes a tapered approach to the orifice. A very conservative approach to determining this rating is to consider the rating for a circular flat end plate of 0.28 diameter and a minimum thickness of 0.050 inches thick. Note that this is a conservative approach and that the tapered orifice design would represent a greater wall thickness and therefore a higher pressure rating. The applicable formula for a flat end plate from ASME code Section VIII, Division 1, is: [2]

$$t = d \times \sqrt{\frac{C \times P}{S \times E}}$$ where:

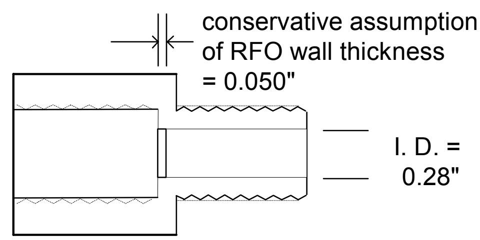


Figure 2

C = a factor dependent on the method of attachment (see ASME UG-34)
(a conservative approach is to use C = 0.10)
d = diameter = 0.28
t = thickness = 0.050
E = joint efficiency (no weld = 1.0)
S = maximum allowable stress = 20,000 psi

Solving for pressure:

$$P = \frac{S \times E \times t^2}{C \times d^2} =$$

$$P = \frac{20{,}000 \times 1.0 \times 0.050^2}{0.10 \times 0.28^2} = \frac{50}{0.00784} = 6377.5 \text{ psid (differential across the orifice wall)}$$

Finite Element Analysis (FEA) Results:

Gerald W. Wellman of the Structural Mechanics Engineering Department of Sandia National Laboratories (and member of the SNL Pressure Safety Committee) performed a finite element analysis for this RFO design. Results are consistent with the acceptance of the Swagelok-supplied rating of 6600 psig for these RFOs. This rating applies to the nominal pressure rating of the component and the differential pressure across the RFO devices.

RFO Design Calculation Summary:

Because of the conservative nature of the above calculations, the use of the RFO component in either a forward or reverse direction up to a maximum pressure of 6600 psig is allowed. Both the differential pressure across the orifice and the pressure rating of the component wall thickness have been addressed. Note that the conservative approach used in the selection of factor C from the ASME Code formula for flat end plates is responsible for the slightly lower calculated pressure rating than the value given by the Swagelok Company.

Testing Methods

The following configuration was used to measure the characteristics of pressure and flow for the two different RFO devices. The measurements were performed by the Primary Physical Standards Department at SNL/NM. Clean, dry nitrogen was passed through the RFOs over an inlet pressure range from approximately 100 psig to 2000 psig. All flow measurements were taken in the choked (or critical) flow regime where the inlet pressure is two or more times the outlet pressure. Data below represents an average from a representative number of measured devices.

The test gas was then collected in a volumetric standard chamber, where measurements produced a rate of flow in standard cubic feet per minute (SCFM) at 21.1 degrees centigrade and at 14.69 psia. The measurement configurations included a ¼″ female NPT inlet to a ¼″ male NPT outlet flow direction – as well as the reverse orientation.

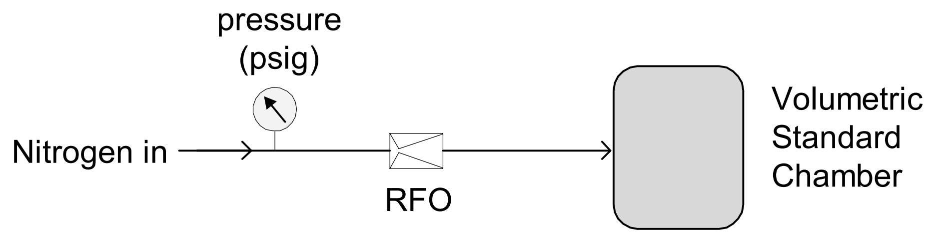


Figure 3 - test measurement configuration

Results

RFO Size (flow direction)	RFO = 0.010 (female to male)	RFO = 0.010 (male to female)	RFO = 0.020 (female to male)	RFO = 0.020 (male to female)
Pressure (psig)	Flow (scfm)	Flow (scfm)	Flow (scfm)	Flow (scfm)
0	0	0	0	0
97	0.12	0.12	0.56	0.565
492	0.555	0.555	2.615	2.575
1002	1.135	1.125	5.28	5.23
1828	2.09	2.055	9.195	9.04

Table 1 - Pressure and Flow (Averaged) Data

RFOs must allow adequate system flow for normal operations as well as provide adequate flow restriction to limit accidental releases. It is therefore important to document the pressure vs flow characteristics of the RFOs, as shown below in the graphs in Figures 4 and 5. A coarse graph (from 0 to 3500 psig), as well as a finer scaled graph (from 0 to 1000 psig) is shown for each RFO size. The highest data point taken is at 1828 psig. In accordance with choked flow theory [3], the flow increases linearly with inlet pressure and it is therefore valid to extrapolate to pressures greater than 1828 psig as shown on the graphs.

The listed sizes of the RFOs (0.010 and 0.020 inches) are nominal values only. The actual orifice sizes of the RFOs were precisely measured using an optical comparator and / or pin gauges. Ten RFOs of each size were measured as a representative sample of the production process. The RFOs were very consistent in their sizes, with the range of diameter values listed below. The calculated equivalent C_v of each RFO is also listed.

Nominal RFO Designation	Measured RFO Size (range)	Calculated Average C_v
0.010 ″	0.0084 to 0.0086	0.0024
0.020 ″	0.0188 to 0.0189	0.0112

Table 2 - Calculated Flow Coefficients

The equivalent C_v numbers were averaged over the entire pressure range and were calculated using the following formula [3]:

$$Q = 0.471 \times N_2 \times C_v \times P_1 \times \sqrt{\frac{1}{S_g \times T_1}}$$

where:

Q = flow rate (scfm)
N_2 = 22.67 (constant to produce flow in units of standard cubic feet per minute)
C_v = flow coefficient
P_1 = inlet pressure in psia - is equal to gauge pressure plus atmospheric pressure (atmospheric pressure at SNL/NM is approximately 12.2 psia)
S_g = specific gravity of the gas relative to air (nitrogen = 0.967 with air = 1.0)
T_1 = absolute upstream temperature (°R)

Solving for C_v : $$C_v = \frac{Q}{0.471 \times N_2 \times P_1 \times \sqrt{\frac{1}{S_g \times T_1}}}$$

For the 0.010 size: $$C_v = \frac{1.13}{0.471 \times 22.67 \times 1014.15 \times \sqrt{\frac{1}{1.0 \times 530}}} = 0.0024$$

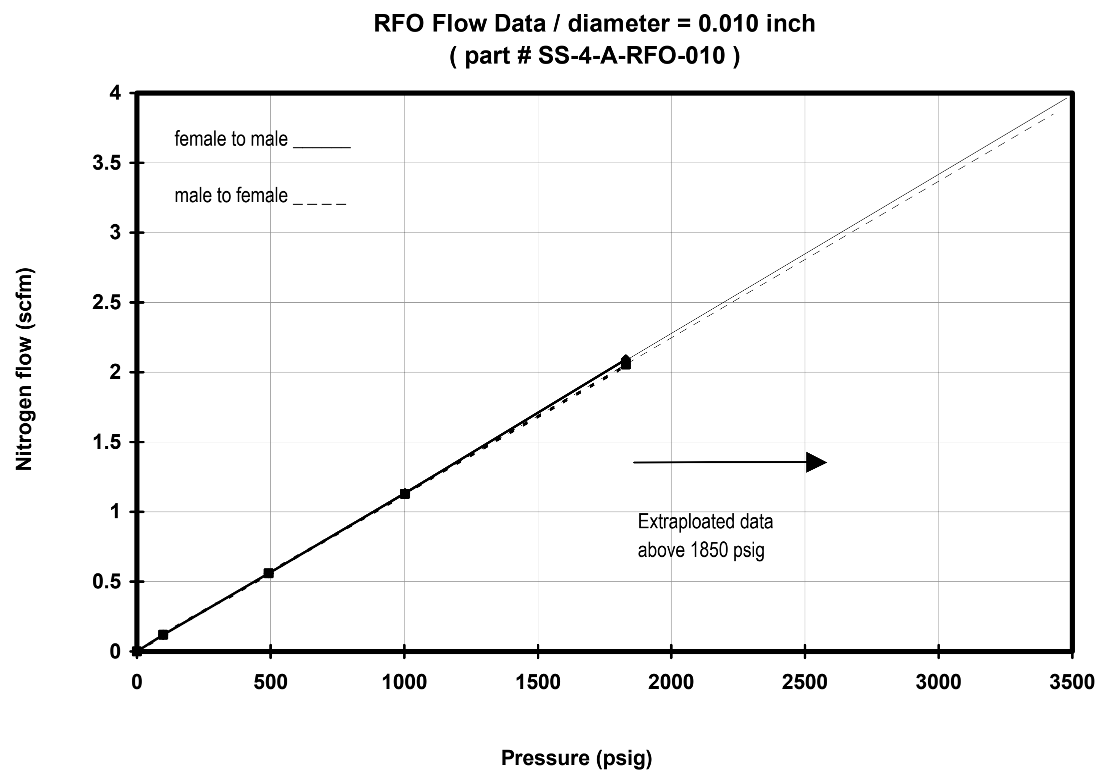
For the 0.020 size: $$C_v = \frac{5.26}{0.471 \times 22.67 \times 1014.15 \times \sqrt{\frac{1}{1.0 \times 530}}} = 0.0112$$

The data table and graphs here are based on clean, dry nitrogen flow through the RFOs. Use the following formula [4] to compensate for a different gas species:

$$Q_g = Q_{air} \times \sqrt{\frac{1}{S_g}}$$

where:

Q_g = flow of the specific gas (scfm)
Q_{air} = flow of air (scfm)
S_g = specific gravity of the gas relative to air



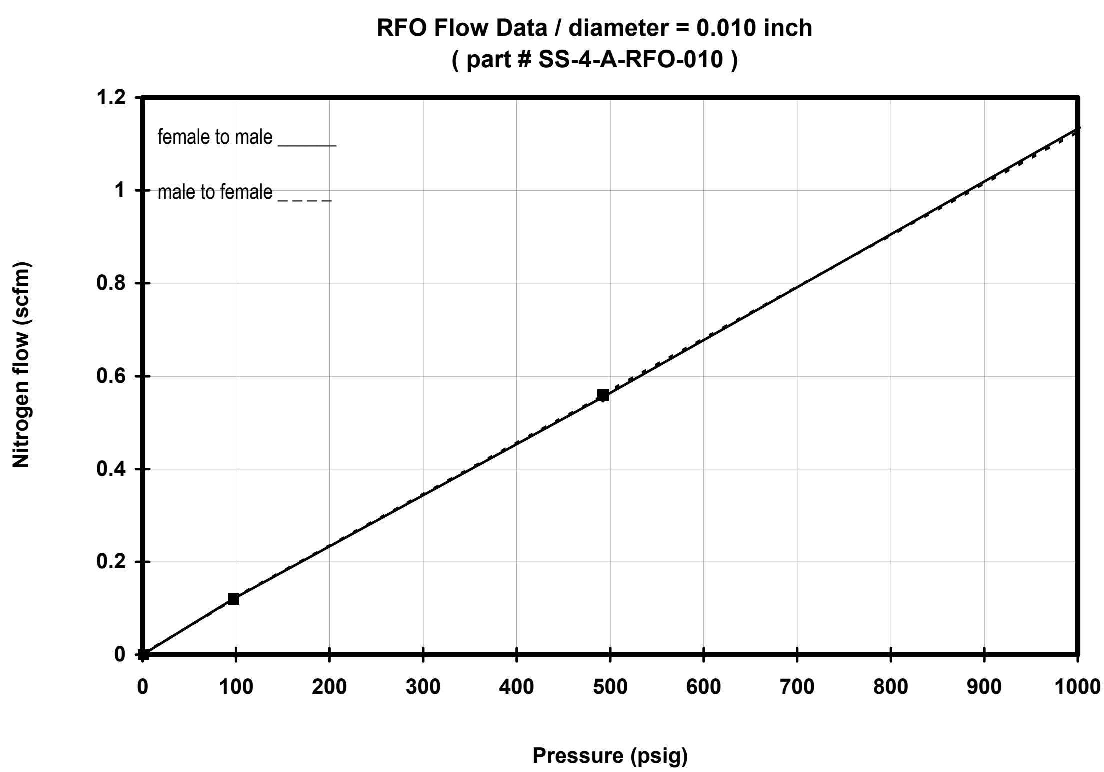
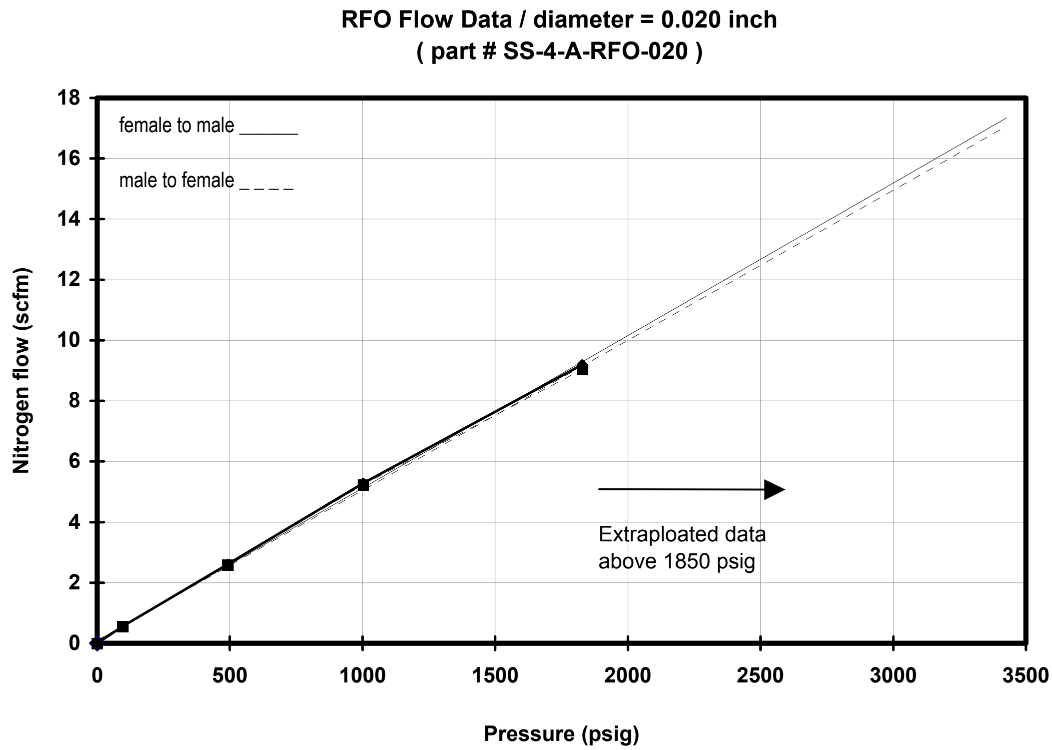


Figure 4 - Flow vs Pressure Data for the 0.010 inch diameter orifice



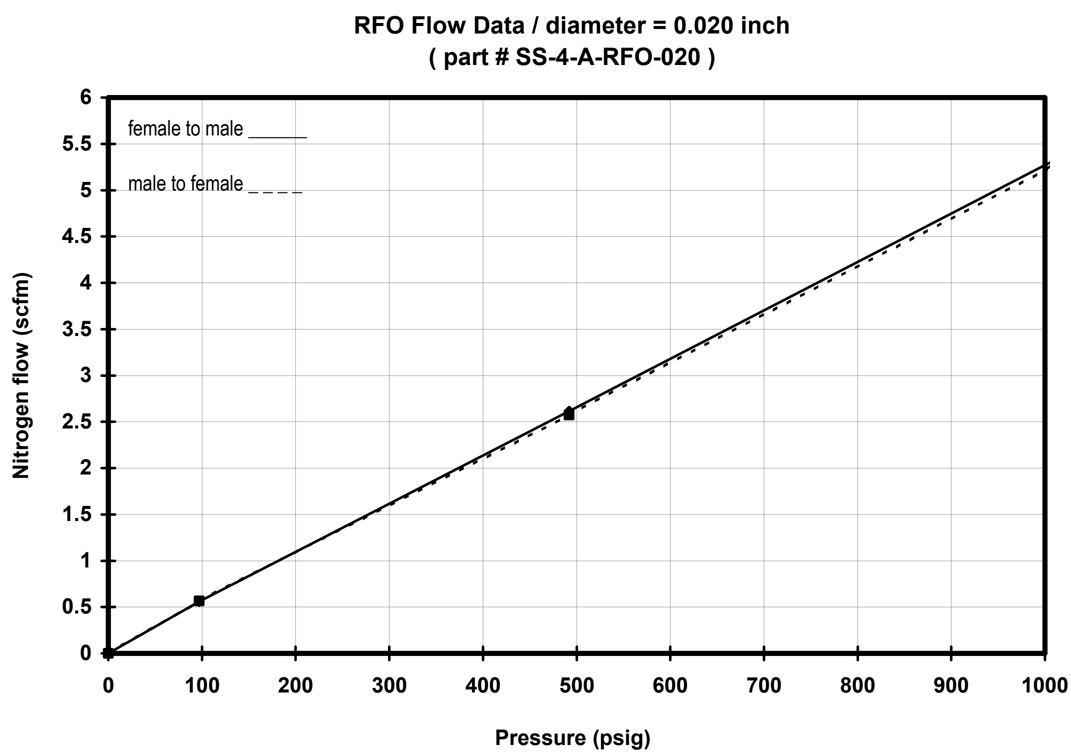


Figure 5 - Flow vs Pressure Data for the 0.020 inch diameter orifice

Analysis

The data confirms a linear response for the pressure and flow ranges tested. The average C_v values can be used to calculate flows for applications requiring flow limitation, or the graphs can be used to interpolate predicted flows. The flow tests were conducted with a straight through ¼″ piping system, the same size as the RFO connections. The use of additional valves, fittings, elbows or tees, size adapters, etc., in a laboratory system may affect the system flow.

One problem that could be encountered (especially when using the 0.010 inch RFO size) is related to the use of Teflon tape when assembling the system components. Care must be taken to prevent even small shreds of Teflon tape from entering the system that could clog the RFO. A good quality Teflon tape (meeting MIL-T-27730A spec), properly applied (no tape on the first thread), will prevent small shreds of Teflon tape from entering the system and blocking the orifice. An inline filter located upstream may also be appropriate for this size RFO.

No attempt was made to characterize the flow of liquids through these devices. The RFO sizes selected, 0.010 and 0.020 inch diameters, may well be too restrictive for many common water or liquid applications.

Applications

The design of a gas handling system frequently incorporates a regulator and a pressure relief valve to protect the downstream equipment from overpressure resultant from potential regulator failure. Analysis frequently shows that in cases of high-flow regulator failure, the calculated downstream pressure may rise significantly above the set pressure of the relief valve. This is due to limited flow capacity of the relief valve. A different regulator or relief valve may then need to be selected. A more economical solution to this problem is to use an RFO to limit the maximum system flow to acceptable limits within the flow capacity of the pressure relief valve, thereby enhancing the overpressure protection of laboratory equipment.

A specific example is depicted below in Figure 6. The regulator selected has a flow coefficient (C_v) = 0.05 and assumed (worst case) to fail in a full open position. Using the previously introduced flow formula [3], the maximum air flow through this regulator (without considering an RFO) at a cylinder pressure of 2000 psig is calculated:

$$Q = 0.471 \times N_2 \times C_v \times P_1 \times \sqrt{\frac{1}{S_g \times T_1}} \;=\; 0.471 \times 22.67 \times 0.05 \times 2012.2 \times \sqrt{\frac{1}{1 \times 532}} \;= 46.5 \text{ scfm}$$

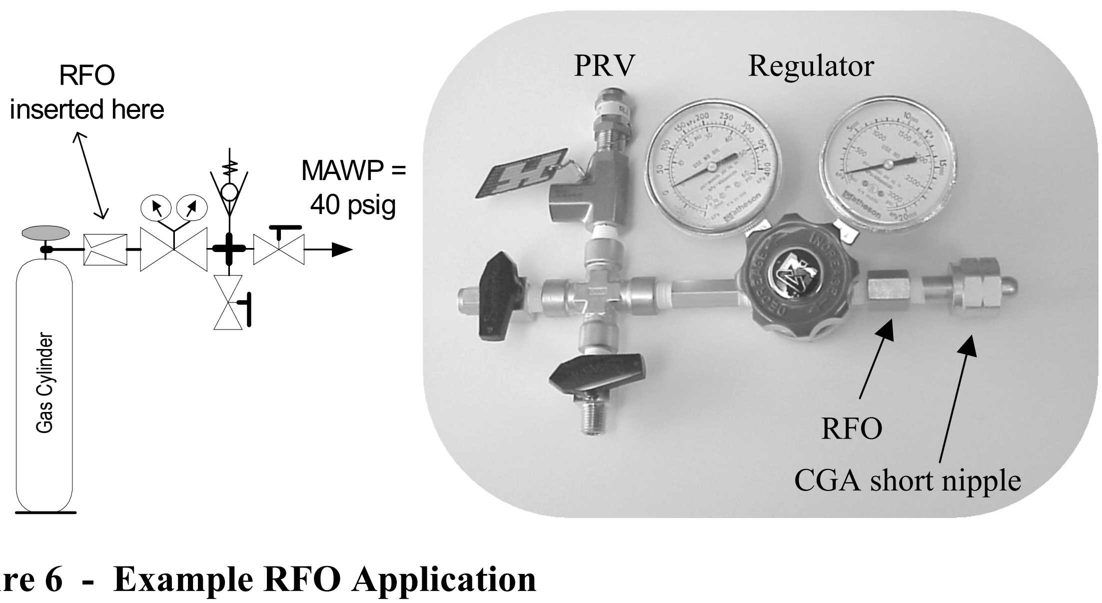


Figure 6 - Example RFO Application

The valve chosen for this example is a Nupro CH4 series valve, and is set at 10 psig cracking pressure. A significant pressure would accumulate across the relief device at such a high flow as described by this failure scenario. The flow curves for this valve (Figure 7 below) show that the pressure at the inlet to the relief valve (and the pressure to the downstream laboratory equipment) could rise to ≈ 118 psig with this regulator failure scenario (as shown by the gray arrows inserted on the graph). This would exceed the 40 psig MAWP of the downstream equipment and is not an acceptable overpressure protection design.

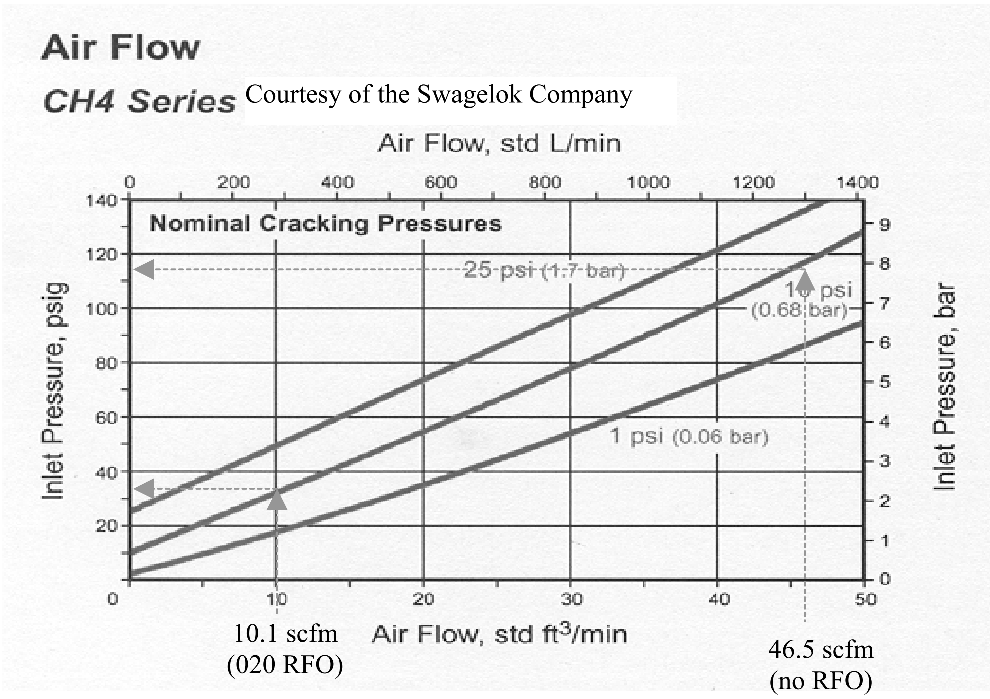


Figure 7 - Pressure Relief Valve Flow Chart [5]

Installing the RFO (0.020 ″ orifice size) as shown would, for the same regulator failure scenario, limit the maximum system flow to ≈ 10.1 scfm (as read from the Figure 5 above). This would limit the system pressure rise to ≈ 33 psig (second set of inserted arrows) and would represent an acceptable overpressure protection design for the downstream equipment. If the 0.010 ″ size RFO were selected, the maximum system flow would be limited to ≈ 2.25 scfm, and the resultant pressure rise would be further minimized to ≈ 18 psig. Note that the small correction for air through the regulator and relief valve and nitrogen flow through the RFO is negligible (less than 2 percent) and ignored for this calculation.

This approach assumes that the installation of a given RFO would allow sufficient gas flow required for normal system operation. The location of an RFO within a system is a function of the system hazards and may vary depending on the design intent for the specific system. In this application, the RFO is located between the regulator and the gas cylinder valve and is intended to limit the gas flow in a worst case regulator failure (i.e., regulator fails in the full open position) to a range that is acceptable according to the pressure relief valve's flow capacity.

Laboratory applications often include the use of large volume inert gas sources, such as "house" nitrogen, for purging sample storage cabinets, backfilling vacuum chambers, clean dusting of optics, etc. Flexible plastic tubing is often used to distribute the nitrogen around the lab in these applications. Failure of this tubing or of the associated connections is a possibility – with the result being a large volume release of inert gas and a potentially oxygen deficient environment in the laboratory. RFOs can be used to limit large volume accidental releases from these gas sources. Similarly, RFOs can also be used to limit the worst-case release rate of other gases presenting concerns, such as hydrogen and the associated concerns of flammability.

Conclusions

The new Sandia-designed RFO devices can enhance system safety by providing a predictable system flow limitation. Commonly encountered problems associated with relief valve flow capacity and the large volume release of inert gases can be economically addressed using these RFOs. Flow parameters are linear over the full allowable pressure range. The inlet and outlet connection styles available for these RFOs will allow the user to easily position this device into gas handling systems commonly used in the laboratory environment wherever quality pipe threaded components are an acceptable technique.

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