INTRODUCTION TO REGULATOR AND RELIEF VALVE SIZING

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Introduction

The following paper was developed using the Fisher Regulator Technical Reference on theory, sizing, selection, and overpressure protection with specific application for natural gas. All figures used in this paper belong to Fisher.

Natural gas regulators provide a means of control over the flow of gas supply to downstream processes or customers. The operating principles of "regulators" and "relief valves" are the same, however, they vary in application. A regulator is used to maintain flow of gas at a constant downstream pressure (P_2), while a relief valve is used to provide overpressure protection through means of sensing and controlling upstream pressure (P_1). There are many different types of regulators that vary in application across all industries involved in the production, transportation, or use of fluids and/or gases. These regulators fall into one of two broad categories: direct-operated (or self-operated), and pilot-operated. Furthermore, within these broad categories, many specific types of regulators exist, including pressure reducing regulators, backpressure regulators, pressure relief valves, pressure switching regulators, and vacuum regulators. For the purpose of this paper, we will focus on the operation, sizing, and selection of pressure reducing regulators, and pressure relief valves, both direct-operated, and pilot-operated.

Regulator Components

There are three essential elements (or components) for direct-operated regulators (Pilot-operated regulators use the same basic elements put together in a slightly different way, which will be addressed in later sections). The essential elements are the restricting element, measuring element, and loading element.

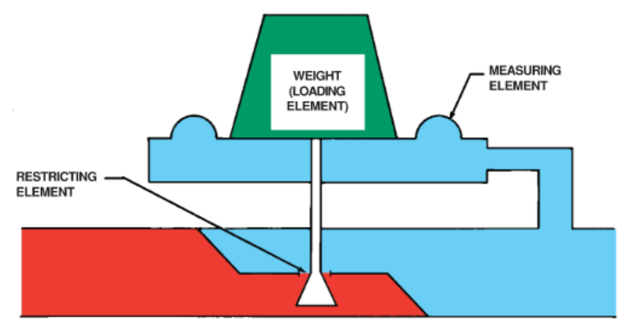

Fig. 1 Essential Regulator Elements

The restricting element is some sort of valve, disk, or plug which is tasked with physically sealing or unsealing to directly control the flow of gas. The measuring element, most commonly a diaphragm, directly senses the downstream pressure (P_2) over it's surface area. As the pressure changes the diaphragm moves, and in turn, the attached restricting element also moves. The loading element, most commonly a spring, counterbalances the downstream pressure (P_2) that is acting on the measuring element. The amount of balance, or rather imbalance, between the loading element, and the measuring element ultimately determines the position of the restricting element and therefore determines and flow of gas through the regulator opening (orifice).

Regulator Operation – Direct-operated Regulators

As previously stated, regulators work by balancing the force of gas over a specific area (diaphragm) with the force of the loading element (spring). To visualize this force balance, consider the example below:

- Upstream Pressure (P_1) = 100 psig
- Downstream Pressure (P_2) = 10 psig
- Pressure Drop Across Reg. (P) = 90 psig
- Diaphragm Area (A) = 10 sq. inch
- Spring Rate = 100 lb/inch

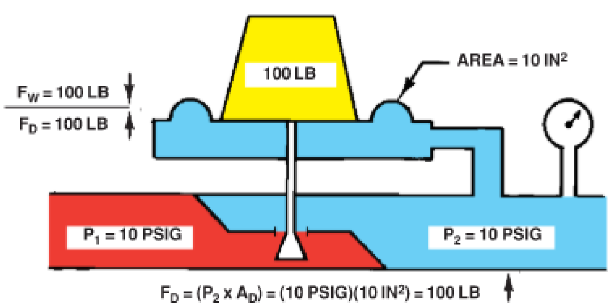

Fig. 2 Direct-operated regulator example at equilibrium

In this example, we want the downstream pressure to remain at 10 psig. To reach this state of equilibrium, the force acting on the diaphragm needs to balance the force exerted by the spring. The force acting on the diaphragm is equal to the downstream pressure (P_2) multiplied by the area of the diaphragm:

10 psig x 10 sq in = 100 lb

The balancing force in the spring must also be equal to 100 lb. Since we have a known spring rate of 100 lb/inch, the spring must be compressed by 1 inch. With these parameters in place, the regulator will continue maintain a 10 psig downstream pressure until downstream demand either rises or falls.

Increase in Downstream Demand

When the downstream demand increases, the downstream pressure (P_2) will drop (as more gas exits the system). When this happens, less force acts upon the diaphragm, which means the force in our spring now exceeds the force across the diaphragm. This causes the restricting element to open wider, allowing more gas to flow to meet the increased downstream demand.

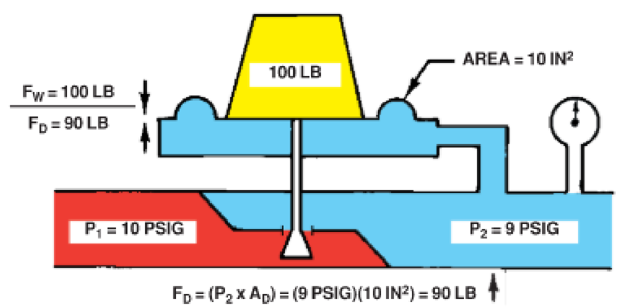

Fig. 3 Direct-operated regulator opening example

In our example, if P_2 drops to 9 psig due to increased demand, the new force acting across the diaphragm becomes:

9 psig x 10 sq in = 90 lb

To balance this new force, the compressed distance in the spring will change. As shown below, the new compressed distance becomes 0.9 inch, which means the spring has actually elongated by 0.1 inch:

$$90 \text{ lb} = 100 \text{ lb/in} \times 0.9 \text{ inch}$$

As you can see from Figure 4, a longer spring length (ie, less compression) leads to an opening in the restricting elements, which leads to an increase in gas flow to meet our new downstream demand.

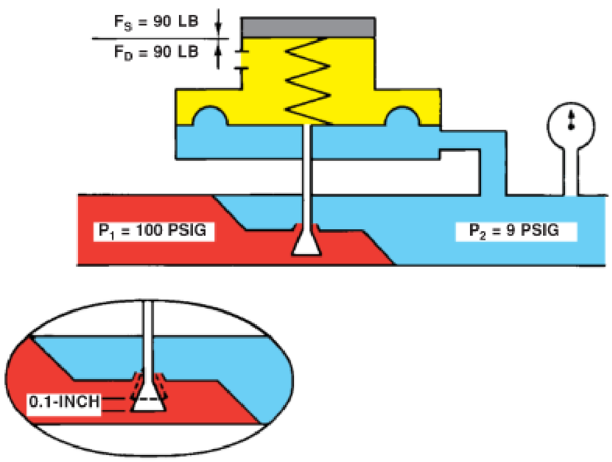

Fig. 4 Spring reaction to increased downstream demand

Decrease in Downstream Demand

When the downstream demand decreases, we have the opposite effect as before. The downstream pressure (P_2) increases (as less gas exits the system), more force acts upon the diaphragm, the spring compresses, the restricting element closes, and less gas flows through the regulator.

Pilot-operated Regulators

Direct-operated regulators are quite robust for certain applications. However, we can improve accuracy, capacity, and sensitivity by taking the principles of the direct-operated regulator and applying them in a slightly different manner to create what is known as a pilot-operated regulator. These regulators are essentially two separate regulators connected together. The smaller regulator is called the pilot, and the larger regulator is referred to as the main regulator.

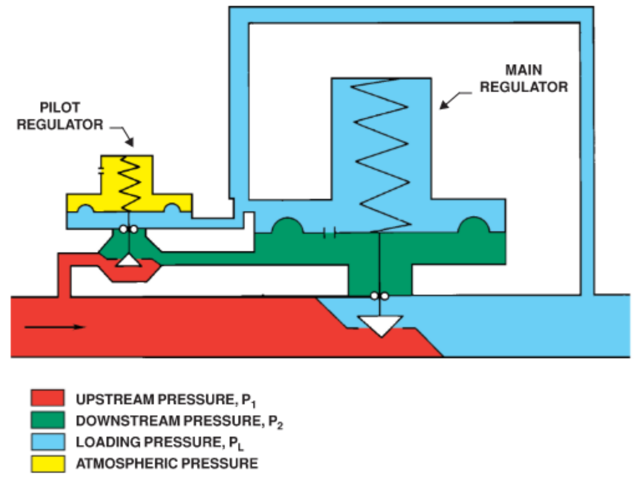

Fig. 5 Pilot-operated regulator basics

The basic advantage of the pilot-operated regulator is the ability to sense P_2 and make a change to the loading pressure, P_L, that is larger than P_2. This is accomplished using a pilot. This increase in sensitivity leads to a reduction in droop and, as a result, has a positive effect on accuracy and capacity.

Pilot-Loading Style

The regulator shown in Figure 5 is a pilot loading regulator. This type of regulator responds to changes in downstream pressure by supplying a loading pressure to move the main valve. During normal operation the pilot acts similar to a direct-operated regulator, in the sense that the pilot spring tends to open the regulator. However, as seen in Figure 5, the spring in the main valve operates in the opposite manner, with the spring tending to close the valve. As downstream demand increases, P_2 decreases, which leads the pilot to open. As the pilot opens, the loading pressure on the main valve increases, compressing the spring, and opening the main valve to increase the flow of gas to meet the downstream demand.

Pilot-Unloading Style

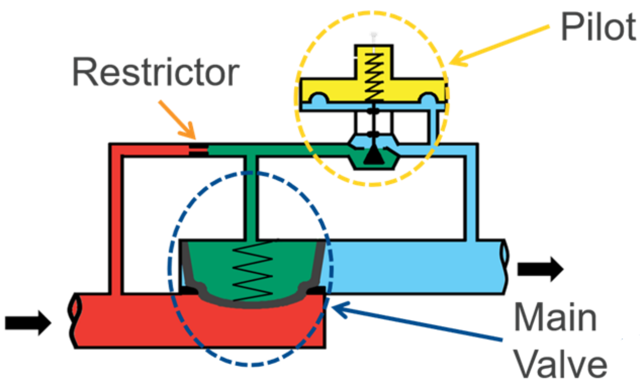

Fig. 6 Pilot-unloading Style Regulator

The regulator shown in Figure 6 is a pilot-unloading style. The basic principles are the same as any other regulator, but the configuration is different. In this style, just like before, when downstream demand increase, P_2 decreases, which leads to the pilot opening. However, in this configuration, the pilot opening leads to a decrease in P_L, which opens the main valve and allows gas to flow to meet the increased downstream demand.

Pilot Gain

Pilot gain is the key to the increased accuracy and stability when compared to a typical direct-operated regulator. Gain is the ratio of the change in loading pressure (P_L) compared to the change in downstream pressure (P_2). For example, a pilot with a gain of 20 will multiply the effects of a 1 psi change on the main diaphragm by 20 – a decrease in P_2 opens the pilot to increase P_L by 20 times as much. The gain allows for a regulator to respond to smaller changes in the downstream pressure. It also allows for a larger main valve restriction and larger main valve spring, which means you can get more flow for the same line size when compared to a direct-operated regulator.

Regulator Performance

An ideal regulator operates in such a way that the downstream demand is met with no change in the downstream pressure (P_2). However, this is not how regulators actually operate. As shown in Figure 7, as downstream demand increases regulating pressure decreases until the desired flow can no longer be met and the regulator has reached its wide-open capacity.

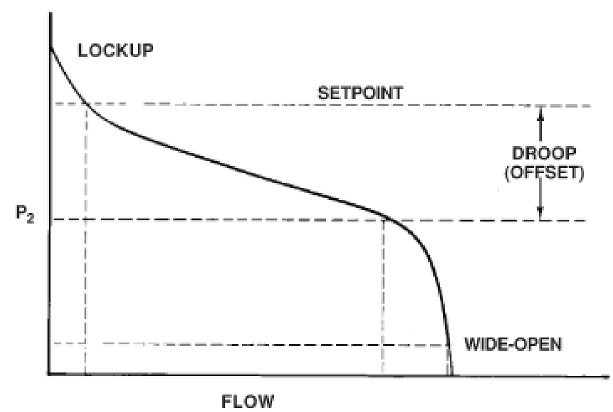

Fig. 7 Typical Performance Curve

We can compare several characteristics of real regulator operation to that of an ideal regulator to help measure it's performance for a given scenario or design criteria. Below is a brief description of some of the properties of regulators and their performance curves.

Setpoint

Setpoint is the downstream pressure (P_2) which we are attempting to maintain. No regulator is ideal, and no two springs are exactly the same. To establish a setpoint, the downstream pressure should be actively monitored, and the spring tension adjusted in real time until the desired output pressure is achieved.

Droop

Droop is a term used to describe how P_2 decreases as downstream demand increases. Droop is the pressure deviation from the setpoint and helps to determine the useful ranges (capacity) for a given regulator. Droop is typically presented as a percentage of the set point.

Lock Up

Lock up describes the pressure above the setpoint required to completely shut off the flow of gas.

Accuracy

The accuracy of a regulator is determined by the amount of flow it can pass for a given amount of droop. The closer the regulator is to the ideal regulator curve (setpoint), the more accurate it is.

Selecting and Sizing Regulators

The two most common methods for sizing regulators are sizing based on the Universal Sizing Equation and sizing following the manufacturer's performance data and sizing criteria.

Universal Sizing Equation

Through experimentation and iteration, we have been able to develop an equation to determine the flow of natural gas through a given orifice. This equation is referred to as the Universal Sizing Equation. It was developed based on Bernoulli's conservation of energy, first with liquids, and then eventually applied to gases. The equation factors in the Specific Gravity, pressure, temperature and characteristics of the valve and orifice to help determine a flow rate.

$$Q_{scfh} = \sqrt{\frac{520}{GT}}\, C_g P_1 \, SIN\left[\left(\frac{59.64}{C_1}\right)\sqrt{\frac{\Delta P}{P_1}}\right] \text{rad.}$$

OR

$$Q_{scfh} = \sqrt{\frac{520}{GT}}\, C_g P_1 \, SIN\left[\left(\frac{3417}{C_1}\right)\sqrt{\frac{\Delta P}{P_1}}\right] \text{Deg.}$$

Fig. 8 Universal Sizing Equation (Radians and Degrees)

The characteristics of the valve needed to accurately size it for gas flow are C_g which is determined by the physical size or flow area of the valve, and C_1, which accounts for differences in valve recovery characteristics. These values are published by the manufacturer. C_1, C_g, and C_v are all related to each other:

$$C_1 = C_g / C_v$$

The only other parameters needed to accurately size the valve would be the minimum inlet pressure (P_1) and the pressure drop across the regulator (ΔP)

Take the following as an example:

- Fisher EZR, 2", 100% capacity
- Line size equals body size
- Without inlet strainer

Fisher Published Coefficients:
$C_g = 1970$
$C_v = 54.6$
$C_1 = 36.1$

Given or Assumed Values:
$T = 520\ °R$
$G = 0.6$
$P_1 = 164$ psia
$P_2 = 74$ psia

Using the Universal Sizing Equation to find the capacity of this regulator:

$$Q = \sqrt{\frac{520}{0.6(520)}}\,(1970)(164)\,\sin\left(\left(\frac{3417}{36.1}\right)\sqrt{\frac{90}{164}}\right)$$

Q = 352 MSCFH

Manufacturer's Performance Data

Regulator manufacturers publish data on the capacities and other characteristics of each model of regulator. This data may be based on actual test data, calculations similar to the ones shown in this paper, and/or interpolation from various test points. For most applications, sizing using the manufacturer's published data is the preferred method since their data accounts for the droop and other characteristics that are specific to the particular performance curve of each individual regulator model. The selection of a regulator starts with a minimum inlet pressure and maximum flow requirements. This information helps us design to "worse-case" conditions. From there, additional requirements can be considered to make a final regulator selection such as maximum pressure, material type, and turn down. Most regulator manufacturers offer various tools to narrow down the list of applicable regulators. These include quick selection guides, product books, and internet applications.

Figure 9 below shows an example of the capacity table for that same Fisher EZR regulator that we sized previously using the Universal Sizing Equation. As you can see, the capacity values are close, but not the same. In this case, I would use the capacity published by Fisher, for the reasons we discussed in the previous paragraph.

Q = 393 MCSFH

INLET PRESSURE		OUTLET PRESSURE		CAPACITIES IN THOUSANDS OF SCFH / Nm³/h OF 0.6 SPECIFIC GRAVITY NATURAL GAS USING 1:1 LINE SIZE TO BODY SIZE PIPING WITHOUT INLET STRAINER											
				NPS 1 / DN 25		NPS 2 / DN 50		NPS 3 / DN 80		NPS 4 / DN 100		NPS 6 / DN 150		NPS 8 / DN 200	
psig	bar	psig	bar	SCFH	Nm³/h	SCFH	Nm³/h	SCFH	Nm³/h	SCFH	Nm³/h	SCFH	Nm³/h	SCFH	Nm³/h
125	8.6	43	3.0	88	2.4	355	9.5	670	18.0	1051	28.2	2076	55.6	3342	89.6
		60	4.1	85	2.3	321	8.6	595	15.9	923	24.7	1969	52.8	3134	84.0
		90	6.2	71	1.9	261	7.0	482	[illegible]	[illegible]	20.0	1609	43.1	2515	67.4
		105	7.2	----	----	208	5.6	382	[illegible]	[illegible]	15.8	1282	34.4	1985	53.2
150	10.3	52	3.6	104	2.8	419	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2453	65.7	3953	106
		60	4.1	103	2.8	393	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2412	64.6	3868	104
		95	6.5	92	2.5	342	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2102	56.3	3308	88.7
		130	9.0	----	----	228	6.1	[illegible]	[illegible]	[illegible]	[illegible]	1406	37.7	2175	58.3
200	13.8	73	5.0	135	3.6	546	14.6	1030	[illegible]	[illegible]	43.3	3194	85.6	5145	138
		110	7.6	127	3.4	479	12.8	887	23.8	1375	36.9	2941	78.8	4662	125
		150	10.3	106	2.8	390	10.5	720	19.3	1112	29.8	2406	64.5	3753	101
		180	12.4	----	----	264	7.1	484	13.0	746	20.0	1628	43.6	2511	67.3

Fig. 9 Fisher EZR capacity table with Type 161EB Pilot

Installation Considerations

Beyond selecting a regulator based on overall capacity, several other factors should be taken into consideration when it comes to actually installing that regulator on a distribution system. Straight pipe on either side of the regulator should be of adequate length to stabilize flow conditions as much as possible through the regulator. Often manufacturers will publish recommendations for what this length should be for a given model of regulator. The same is true for any external sensing lines. These should be connected to a part of the system with minimal turbulence, ideally away from items such as elbows, tees, and spinning meters. The installation instructions for specific models should always be referred to when determining the layout of an installation to confirm that the selected regulator will function as expected.

Regulators also have a vent to atmosphere which allows the diaphragm casing to breath. It is critical to the function of these regulators that these vents stay clear of water, pest intrusion, or other blockages. In some cases, it might be prudent to pipe these vents away from possible sources of combustion and/or enclosed buildings. Vent lines must be adequately sized to allow free flow of gas and to prevent backpressure on the diaphragm.

It is also important to make sure the regulator is not oversized for a given application. Often a reduced size (e.g. 2:1 line size to regulator size) would be preferred to maintain adequate low flow control. Restricted trim that does not reduce the port size of the regulator, or other capacity limiting devices usually do not improve the low flow control of a regulator which may lead to instability. Oversized regulators will also significantly increase the size of required relief valves downstream if they are used for over pressure protection.

Overpressure Protection Overview

Regulators are designed to maintain downstream pressure over a range of possible flow rates. However, in the event of a regulator failure, the downstream system could be subject to pressure which it is not designed for. In order to prevent this, there are several forms of overpressure protection that can and should be installed. Natural gas safety codes and state/federal regulations require overpressure protection whenever a pressure reducing station is installed with the downstream system having a lower MAOP (Maximum Allowable Operating Pressure) than the upstream system.

The most common types of overpressure protection are relief valves, monitors, series regulation, and shutoff. For the purpose of this paper we will focus on relief valves and their associated sizing requirements.

Relief Valves

A relief valve is a device the vents gas to the atmosphere to maintain downstream pressure at or below the MAOP (or other set pressure). Relief valves operate using similar principles as regulators, which is why the selection and sizing for both can be covered under one topic.

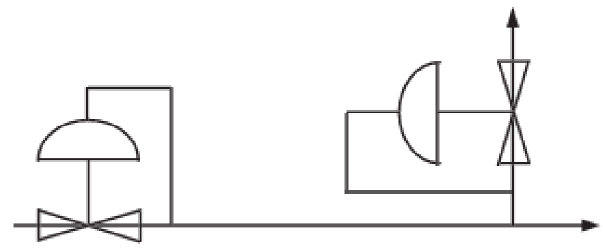

Fig. 10 Relief Valve Schematic

Relief valves are considered to be the most reliable type of overpressure protection since they are not subject to blockage by objects in the line during normal operations. They also have no effect on the capacity of the regulator they are protecting. In addition to overpressure protection, the sound and smell that a relief valve produces when it goes off acts as an alarm to aid in alerting those nearby of a potential issue.

There are a few disadvantages of relief valves when compared to other forms of overpressure protection. Relief valves, by their very nature, vent gas to atmosphere which can be a hazard, or at least a nuisance to the surrounding area. Relief valves must also be sized carefully in order to relieve enough gas to protect the downstream from overpressure.

The basic types of relief valves are pop type, direct-operated, pilot-operated, and internal relief.

The pop style relief valve is the simplest and “pops” wide open when the pressure has exceeded the set point of the valve. The pop style valve can be unstable, opening and closing repeatedly as pressure fluctuates, making it less ideal for most natural gas distribution applications.

Direct-operated relief valves offer a step up in accuracy and can throttle better than the pop style relief. They are relatively simple, with the underlying principles being very similar to the direct-operated regulators discussed in previous sections. The main drawback of this style of relief is the large amount of build up typically required to obtain a required capacity.

Like regulators, pilot-operated relief valves offer the most accuracy. They require significantly less build-up than direct-operated reliefs and typically have large capacities and are available in larger sizes than other relief valve styles. Of course, with improved accuracy and capacity comes increased costs, so it may not always be prudent or necessary to install a pilot-operated relief.

Internal Relief (IRV), as its name indicates, is a relief valve built directly into the regulator. Just like our other reliefs, it vents gas to atmosphere when the pressure exceeds a certain value. IRVs typically have a smaller capacity than the other relief valve styles but offer an economical solution in small applications such as residential service regulators.

Fig. 11 Types of Fisher Relief Valves

Selecting and Sizing Relief Valves

There are several criteria that should be taken into account when selecting and sizing and relief valves. Chief among them include the maximum pressure conditions, the wide-open flow capacity, and the downstream demand. Since relief valves are just a special type of regulator, the same variables are taken into account for sizing and determining wide-open flow rate.

Just like regulators, relief valves can be sized using manufacturer's published data, and/or using a basic relief capacity calculation. The basic sizing requirement being that the relief valve has a higher capacity than the wide-open capacity of whatever regulator is upstream.

You can calculate the wide-open capacity of a regulator (Q_{max}) with the following data. Maximum P_1 upstream of the regulator you are assuming failed, the maximum allowable P_2 of that regulator, and the wide open C_g of the regulator you are assuming failed. The wide-open C_g is published by the manufacturer and can be higher than the regulating C_v. The formula for Q_{max} is:

$$Q_{max} = (P_{1\,max})(C_{g\,wo})(1.29)$$

This flow rate can then be compared to published flow data tables to select the appropriate relief valves. These tables will be published with a build-up value that shows the pressure above setpoint required to achieve that flow rate.

Other factors to consider when making a final selection on relief style and size include sensitivity, throttling capabilities, installation cost, maintenance cost, and space requirements.

Let’s continue our example before and size an appropriate relief valve for the 2” EZR regulator that we selected in our previous example.

Fisher Published Coefficients:
C_g (wide-open) = 1950

Given Values:
P_1 = 164 psia

$$Q = (164)(1950)(1.29)$$

Q_{max} = 413 MSCFH

In order to protect the downstream system, we would need to select a relief valve capable of relieving at least 413 MSCFH at the given pressure.

To simplify the selection for the purpose of this paper we will only consider the Fisher EZR Relief valve for sizing. As shown in Figure 12 below, to meet this wide-open flow of the 2” EZR regulator, we will need to select a 3” EZR Relief Valve (2:1) which has a capacity of 771 MSCFH.

SET PRESSURE RANGE, SPRING PART NUMBER AND COLOR	SET PRESSURE(1)		CAPACITIES IN THOUSANDS OF SCFH / Nm³/h OF 0.6 SPECIFIC GRAVITY NATURAL GAS WITH 2:1 LINE SIZE TO BODY SIZE PIPING WITHOUT INLET STRAIN											
	psig	bar	NPS 1 / DN 25		NPS 2 / DN 50		NPS 3 / DN 80		NPS 4 / DN 100		NPS 6 / DN 150		NPS 8 / DN 200	
			SCFH	Nm³/h	SCFH	Nm³/h	SCFH	Nm³/h	SCFH	Nm³/h	SCFH	Nm³/h	SCFH	Nm³/h
20 to 40 psig / 1.4 to 2.8 bar 1E392527022, Yellow	20	1.4	24	0.6	87	2.3	166	4.4	267	7.2	496	13.3	864	23.2
	25	1.7	27	0.7	99	2.7	189	5.1	303	8.1	576	15.4	1000	26.8
	30	2.1	31	0.8	111	3.0	211	5.7	340	9.1	563	15.0	1133	30.4
	40	2.8	38	1.0	135	3.6	257	6.9	413	11.1	806	21.6	1396	37.4
35 to 125 psig / 2.4 to 8.6 bar 1K748527202, Red	40	2.8	38	1.0	140	3.8	267	7.2	429	11.5	806	21.6	1409	37.8
	60	4.1	52	1.4	183	4.9	350	9.4	562	15.1	1102	29.5	1926	51.7
	80	5.5	67	1.8	231	6.2	441	11.8	709	[illegible]	[illegible]	37.3	2447	65.6
	100	6.9	81	2.2	279	7.5	533	14.3	856	[illegible]	[illegible]	44.9	2964	79.5
	125	8.6	99	2.7	339	9.1	646	17.3	[illegible]	[illegible]	[illegible]	[illegible]	3602	96.6
75 to 140 psig / 5.2 to 9.7 bar 17B1261X012, Green	75	5.2	63	1.7	220	5.9	420	10.3	[illegible]	[illegible]	[illegible]	[illegible]	2324	62.3
	100	6.9	81	2.2	279	7.5	533	14.3	[illegible]	[illegible]	[illegible]	[illegible]	2964	79.5
	125	8.6	99	2.7	340	9.1	648	17.4	[illegible]	[illegible]	[illegible]	[illegible]	3615	96.9
	140	9.7	110	2.9	377	10.1	719	[illegible]	[illegible]	[illegible]	[illegible]	60.0	4010	107.5
130 to 200 psig / 9.0 to 13.8 bar 17B1263X012, Blue	140	9.7	110	2.9	379	10.2	723	[illegible]	[illegible]	[illegible]	2237	60.0	4035	108.2
	150	10.3	117	3.1	404	10.8	771	20.7	1238	33.2	2375	63.6	4303	115.4
	175	12.1	136	3.6	466	12.5	888	23.8	1427	38.2	2716	72.8	4965	133.1
	200	13.8	154	4.1	527	14.2	1006	27.0	1617	43.3	3052	81.8	5627	150.9

Fig. 12 Fisher EZR Relief Capacity Table

Conclusion

There are a vast number of regulator manufacturers, each with an expansive product line. This can make it feel overwhelming when attempting to select and size regulators and relief valves. However, through a basic understanding of regulators, access to tools and training, developing relationships with vendors, and some practice, the art of selecting and sizing regulators will become second nature. When in doubt, it’s best to reach out directly to vendors and product engineers if you have questions about a specific application. This paper is meant to be an introduction to regulators and relief valves, and many design considerations weren’t described in full depth. However, through a basic understanding of their operations, you should be equipped to ask the necessary questions or seek out further training to continue building your knowledge on these important devices.

References

Fisher Regulator Technical Reference

Introduction to Regulator and Relief Valve Sizing, Mark Dykoff, 2019