PRELIMINARY PERFORMANCE STUDY OF SHERWOOD REGULATOR

By

Osvaldo Augusto Barrera Valero

A Project Thesis Submitted in Partial Fulfillment of the requirements for the degree of

MASTER IN MECHANICAL ENGINEERING

UNIVERSITY OF PUERTO RICO
MAYAGÜEZ CAMPUS
2006

Approved by:

Yi Jia, PhD President, Graduate Committee	Date
Frederick A. Just Agosto, PhD Member, Graduate Committee	Date
David B. Dooner, PhD Member, Graduate Committee	Date
Jayanta Banerjee, PhD Member, Graduate Committee	Date
Paul Sundaram, PhD Chairperson of the Department	Date

ABSTRACT

This is a Project of practical application directed to the liquefied petroleum gas industry at the University of Puerto Rico and the objectives of this project are to study the 800 JBC Sherwood Regulator performances and its operation system and to design the calibration system. Through several tests developed in Colombia, the result shows a comparative analysis of the spring compression effect on the outlet pressure and allows the using of the same spring for the handling of natural gas. In a graph that compares the result by using the two fuels can be appreciate the phenomenon of proportional band that is a pressure drop of 4.37 "W.C. Lastly the orifices and flow rate are calculated, which are essentials to prepare the calibration.

RESUMEN

El presente trabajo es un proyecto de aplicación práctica dirigido a la industria del gas licuado del petróleo para la Universidad de Puerto Rico. Los objetivos de este proyecto son estudiar el desempeño del Regulador Sherwood 800 JBC y su sistema de operación, y diseñar el sistema de calibración. A través de varias pruebas realizadas en Colombia, los resultados muestran un análisis comparativo del efecto de la compresión de un resorte helicoidal sobre la presión de salida; y se comprueba que es posible utilizar el mismo resorte para emplear como combustible gas natural. En la gráfica que compara los resultados para el uso de los dos combustibles se puede apreciar el fenómeno de banda proporcional, que es una caída de presión de 4.37 "C.A, finálmente se calculan los orificios y el caudal los cuales son esenciales para poder efectuar la calibración.

DEDICATORY

To all my family, for their unconditional support at every moment

ACKNOWLEDGMENT

I really thank the valuable help and support from Dr. Yi Jia. I would also like to thank Dr. Jay Banerjee, Dr. Fred A. Just Agosto, and Dr. David Dooner for their helpful comments. Similar to Dr. Paul Sundaram and whole Department of Mechanical Engineering of the University of Puerto Rico, Mayagüez Campus.

Table of Contents

List of tables

Tables **Page**

List of Figures

Figures **Page**

NOMENCLATURE

A	Area
Ad	Diaphragm area
Ao	Orifice area
A_T	Orifice area by table
Av	Relief valve area
A227	wire stretched hard A227
BTU	British thermal units
c1	Elbow ½"
C	spring index
Cf	Flow controller
Cn	Coefficient of nozzle (0.9)
d	diameter of the wire
D	mean diameter of the spring
Do	external diameter of the spring
DMS	Code
F	Force
Fa	stress amplitude
Fc	Correction factor
Fd	Descending force applied by the spring over the diaphragm
Fi	Inlet force
Fm	Mean stress
Fo	Outlet force
Fr	spring required force
Fs	Control force applied by the spring
F_{Sd}	Force on seat disc
F_t	Total effective force
Fu	Upward force applied in the diaphragm by the gas
Fx	Horizontal component
Fy	Vertical component
G	Initial spring compression
G_A	Specific gravity of the air
G_{LP-G}	Specific gravity of the LP-Gas
G_{NG}	Specific gravity of the natural gas
h	test pressure
JBC	Inlet and outlet, right angle, high capacity vents

K	Spring elasticity constant
Kb	Factor of Bergstrasser
Ks	factor of correction by shear stress
Lbf	pound-force
L_f	Free longitude
LP-Gas	Liquefied petroleum gas
m	Exponent
Mg1	hose number 1
Mg2	hose number 2
m.o.s.l	Meters over the sea level
M_A	Moment in A
MB1	Bourdon tube manometer number 1
MB2	Bourdon tube manometer number 2
MB3	Bourdon tube manometer number 3
M_C	Clockwise moment
MU1	U manometer number 1
MU2	U manometer number 2
n	safety factor
N_a	Number of active spires
N_t	Total number of spires
NFPA	National Fire Protection Association
NG	Natural gas
NTC	Normas Técnicas Colombianas
OK	Okay
P	Pressure
pa	Pascal
PB	Proportional band
Pi	Inlet pressure
Po	Outlet pressure
Psig	Pounds per square inch
P1	Outlet pressure at 0.25 in. displacement (no change in diaphragm area)
P2	Outlet pressure at 0.25 in. displacement (change in diaphragm area)
Q_A	Flow rate
RP1	Pilot-operated regulator
s.c.f.h	Standard cubic foot per hour
Ssy	Fluence resistance to the torsion
Sut	Minimun stress resistance
T	Valve displacement of 0.25 in
T4	Tea ½" number 4
T5	Tea ½" number 5
τ	Shearing stress

τ_a	Shear stress amplitude
τ_m	Mean shear stress
Va1	Needle valve number 1
Va2	Needle valve number 2
Va3	Needle valve number 3
Va4	Needle valve number 4
Va5	Needle valve number 5
vb1	Fast closure valve
vb2	Ball valve number 2
vb3	Ball valve number 3
"W.C	Inches of water column
"C.A	Pulgadas columna de agua
X	Distance compressed by the spring
X_S	Distance from position A to B
X_L	Distance from position O to A
%Pd	percentage in pressure drop

1 INTRODUCTION

This is a project of practical application directed to the industry of propane gas at the University of Puerto Rico and it has as purpose to develop a preliminary study of performance characteristics of 800 JBC Sherwood Regulator (Fig 1.1). It makes emphasis on the regulator because it is the central part in a distribution line of gas in a system, and because its correct calibration within the ranges of operation is given by the manufacturer to allow safety at the point of consumption by users.

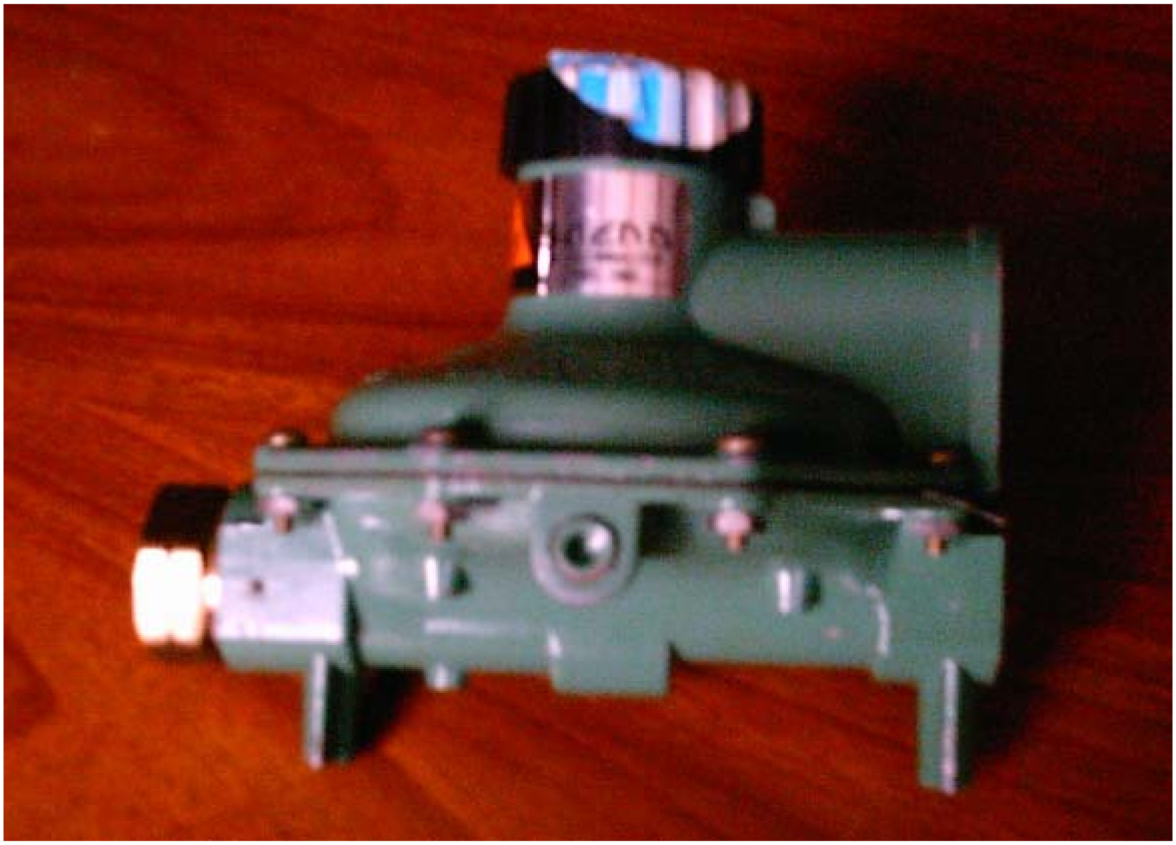

Figure 1.1 800 JBC Sherwood Regulator

1.1 APPLICATION BACKGROUND

There are many applications for the regulators. They are used in domestic installations for residential and commercial uses, for example in the distribution nets of natural gas. It is also used for the distribution of propane gas cylinders and they are required at a mayor scale in industries [1], as for example in bulk transportation trucks, bulk storage plants and finally in motor fuel applications.

The regulator chosen for the investigation in this project is the Sherwood Regulator [2], because it is of major importance in the industrial field for its immediate application in engineering. Sherwood designs all regulators to meet UL Standard 144, and NFPA Pamphlet # 58 [2], uses only the highest quality materials, and all Sherwood Regulators are engineered for dependable pressure stability, correct lockup and uniform delivery pressures.

These regulators have a high level of acceptance in Puerto Rico and at present time most of the information gathered and processed is related to this brand of regulator family stimulating the research in this field.

1.2 TYPES OF REGULATORS

Regulators are classified based on their applications and they can be used for hydraulic and fuel gas systems.

1.2.1 Regulators for hydraulic systems

These systems basically use pressure regulator valves 12.000 series, which are made of plastics, have ¼" adjustable screws and are designed for inverse flow (see Fig. 1.2).

Figure 1.2 Regulators for hydraulic systems [3]

These regulators are easy to operate and have manual flow control. They are excellent in pressurized water conductions.

1.2.2 Regulators for fuel gas systems

For managing combustion of gases there are two big categories: self-operated and pilot-operated regulators.

- **Self-operated or direct regulators.**

In technical terms these are the ones in which a spring is the loading element, which without intervention of any external helps act in a almost punctual form over the center of the diaphragm, and the same spring has the particularity that serves as only adjustment in outlet pressure (Fig. 1.3).

One of the characteristics of this regulator is that it has few movable components. These regulators are subdivided in single stage regulators, first stage, second stage and finally the two stage automatic regulator.

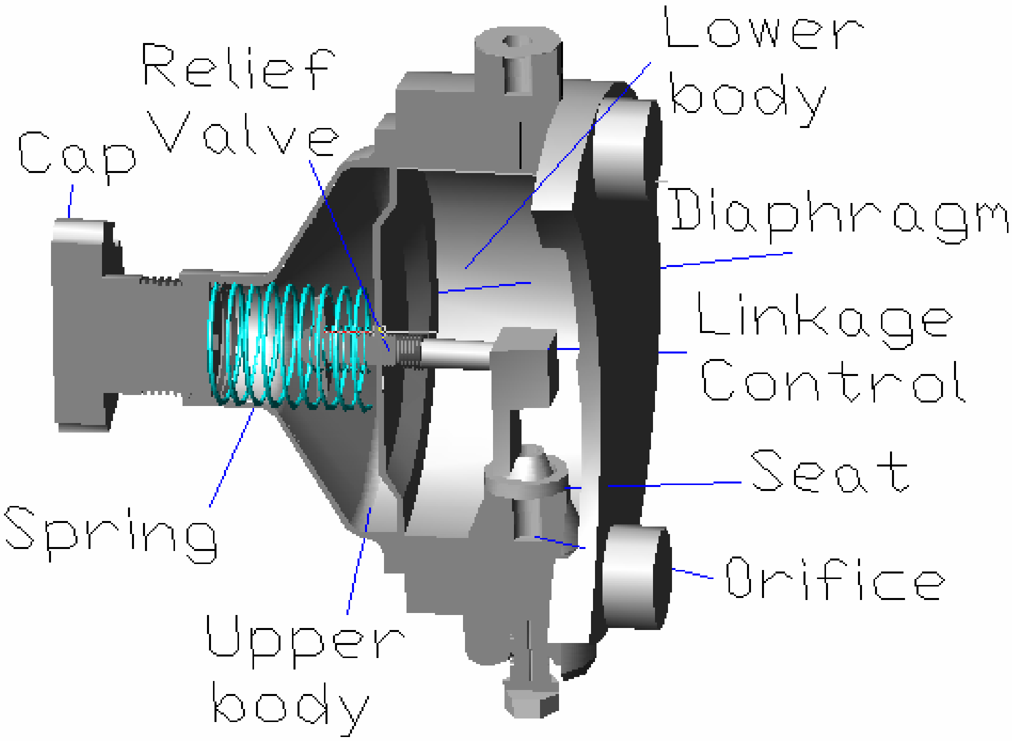

Figure 1.3 Self-operated regulators [1]

Single stage regulator: This is a low pressure regulator and works only in single stage systems, designed to reduce tank or cylinder pressure to 11 "W.C. All Sherwood regulators are equipped with integral relief valve [2]. For easy identification these regulators have in warning label that contains part number and regulator type to make easier the selection. The adjusting range of the outlet pressure is 9 "W.C. - 13 "W.C. Normal factory setting is 11 "W.C.

First stage regulator (color red)**:** This is a high pressure regulator, which works in the two stages systems. These regulators reduce the cylinder pressure or the tank pressure at 10 psig outlet pressure. It should be installed closer to the container or cylinder.

The adjusting outlet pressure range of a Sherwood Regulator is between 5 psig and 15 psig. Normal factory setting is 10 psig.

Second stage regulator (color green**):** This is a low pressure regulator. It is used in two stages systems, and it is installed after the first stage regulator downstream pressure. The adjusting outlet pressure range of regulator is between 9 "W.C. – 13 "W.C. Normal factory setting is 11"W.C.

Two stage automatic regulator: This regulator is connected to two cylinders (Fig. 1.4).

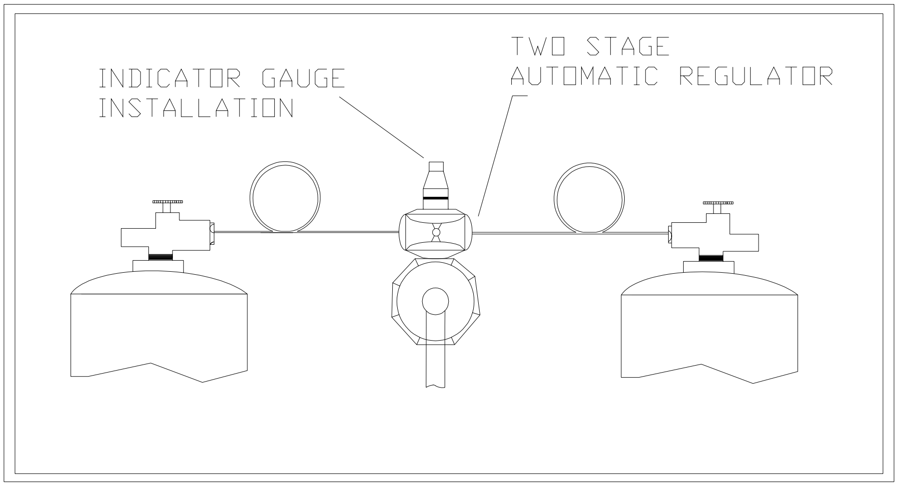

Figure 1.4 Connection for two stage automatic regulator [2]

When the pressure in the cylinder drops to a low level, the regulator automatically switches over to the reserve cylinder and does not interrupt the supply to the appliances. At the same time, the indicator shows a red signal to let the dealer and customer know that the cylinder needs to be replaced.

It is important to identify the indicator small hand and to put the cylinder in service. If there is a red signal, the small hand will indicate an empty cylinder.

When the cylinder is full, the operator will be turning the small hand towards the cylinder. The adjusting outlet range of Sherwood Regulator is between 9 "W.C. – 13 "W.C. Normal factory setting is 11 inches of water column [2].

- **Pilot-operated or indirect regulators.**

These are the ones in which the spring or loading element (Fig. 1.5) is helped by the pressure pilot that is a feedback line from the outlet pressure, and acts over the upper diaphragm surface making it more stable; these regulators are manually operated.

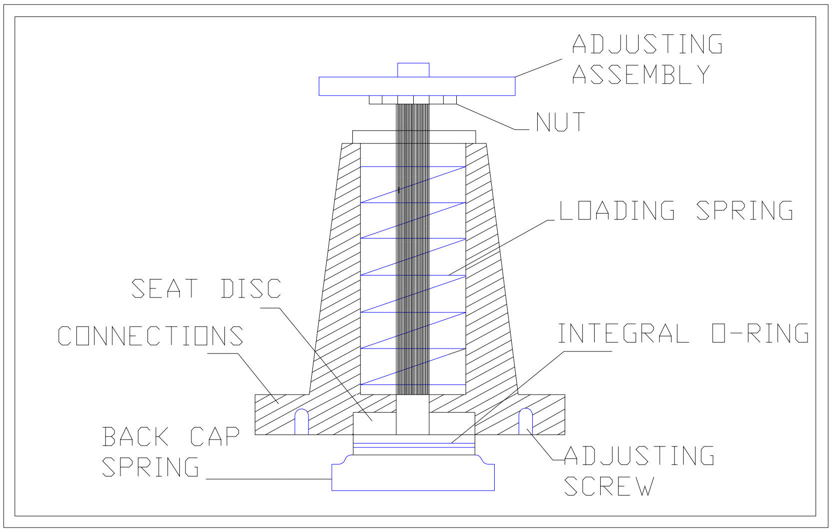

Figure 1.5 Components for pilot-operated regulators [1]

1.3 STATE–OF–ART REGULATOR TECHNOLOGY

Gas pressure regulators are flow control artifacts designed to maintain a constant downstream pressure. The investigation about these regulators has been very important in the liquefied petroleum gas and natural gas industries, and for that reason the development follows in this area.

The following studies have been relevant to the field of research.
Nabi, Wacholder and Dayan [4] presents a physical model that describes the dynamic behavior of a pressure regulator of phase actioning that handles air as fluid. **Latyshev and Maliovanov** [5] developed a mathematical model of a gas pressure regulator connected to a pipe that allows a distribution of gas in the pipelines.

Sanchez, Coronado y Barrera [6] made a study about a device that tests and calibrates pressure regulators for natural gas and LP-Gas. The research has a direct application in the gas industry in Colombia. They developed the design and manufacture of the device to operate under specific parameters.

Dragoljub and Slobodan [7] developed a non-linear dynamic model of a pressure regulator for gas to evaluate the stability and the analysis of transient response. **Bill Hobson** [8] presents a technical paper for selection of regulators to ensure the best balance in a distribution line of gas. He explains the proportional band phenomenon in self-operated regulators and their essential elements. **Chris Carmichael** [9] made a description of factors that affect the regulator's performance, sizing and capacity. **Rick F. Mooney** [10] presents a paper that compares the functioning between the pilot-operated and self-operated regulators and he mention the importance to the safe operation into any gas system. Lastly **Pam Ryan** [11] publishes a technical paper which make to emphasis on instrument-controlled valves for given the components, functioning and their applications.

1.4 PROPOSED PROJECT

The present work is oriented only to the 800 JBC Sherwood Regulator which is a pressure regulator for liquefied petroleum gas. In this project we have learn about the principle of regulator and system and we present an analysis about the behavior, and design of the main components, and finally study the design of calibration system.

1.4.1 Objectives

Research on gas pressure regulators continues today. Relevant information in this area is very restricted from manufacturing companies, therefore the necessity arises of investigating in a specific type of self-operated regulator for an authorized distributor company; for this reason the following objectives are enunciated:

- To study the 800 JBC Sherwood Regulator performance and its operation system. Also some important variables such as diaphragm effect, spring effect, body effect, lockup and inlet-pressure effects will be studied.

- To design the calibration system. This chapter shows calculations that are important to analyze the overall operating system only for the second stage Sherwood Regulator.

1.4.2 General aspects

Related to the regulator principle and system it is indispensable to know the internal functioning and how a regulator system works.

This chapter will give details about the regulation phases because they are vital to understand the general and specific way about its operation. The analysis about the behavior is focused on the gas pressure control, regulator performance and its system. The fluid conducted by this regulator is propane gas, so that we can handle the flow curves in order to interpret their behavior. In the main components design we describe the function of each component of the regulator and how the spring design is made considering the static and cyclic analyses. Finally design specifications are presented.

The design of calibration system has a great importance because it explains the essence of calibration, considering always as a relevant criterion the safety of the system.

In consideration to the complexity and fundamentals of this chapter, now we will make a detailed recount about the device that tests and calibrates the natural gas regulators and liquefied petroleum gas [6], which is essential and gives significant data for the development of this project.

1.4.3 Device definition

It is a device that has the purpose of testing and calibrating natural gas and LP-Gas regulators, in order to develop an efficient system within a limit in the adjustment range of ± 5 % using specifications given by the manufacturer.

This calibration device allows that the regulator can work with flow constant and outlet pressure during its operation. The use of the device is to develop a work in series. The test and calibration system for regulators is ruled by the NTC 2505 and NTC 3838.

1.4.4 Characteristics

Based on functionality, reliability, use and life span of this device, we have considered the following characteristics:

- Versatility: it operates for various types of regulators.
- Practice: efficient in the process.
- Simplicity: very easy handling
- Economic: It satisfied all the requirements without exceeding the cost.

The parameters that intervened directly in the development and functioning of the device were pressure and flow rate. In consequence, for analysis and design, we took basically the following considerations:

- Control the inlet and outlet pressures, which depend on the type of regulator. For this project the emphasis was given on calibration of low pressure regulators.
- The flow has to be at least 30 s.c.f.h approximately (standard cubic foot per hour).
- The maximum pressure for the device to undertake is 120 Psig.

1.4.5 Device operation

For a better understanding of the device, it has been dividend primarily in three parts:

SUBSYSTEM 1
MECHANICAL SYSTEM
SUBSYSTEM 2

The following front view shows the device with its components (Fig. 1.6).

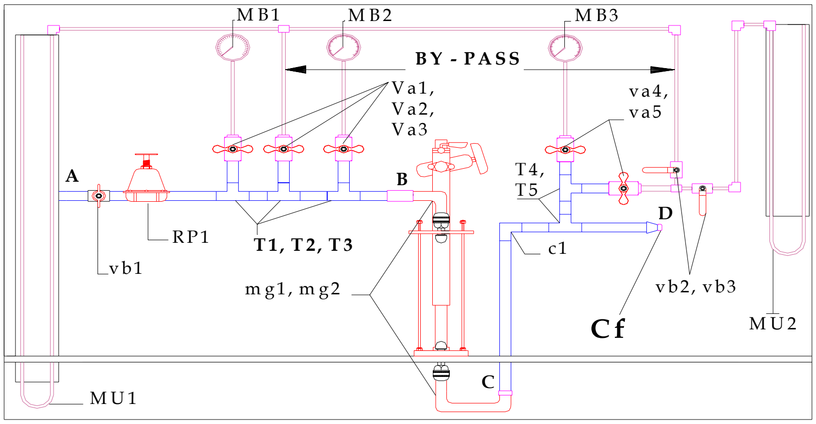

Figure 1.6 Device frontal view [6]

In the front view it shows that the device begins in **A** and finishes in **D** (flow controller **Cf**). This is composed by the following components:

QUANTITY	COMPONENT
3	Bourdon tube manometer (MB1, MB2, MB3).
2	U Manometers (MU1, MU2).
1	Pilot-operated regulator (RP1).
5	Needle valves (Va1, Va2, Va3, Va4, Va5).
2	Ball valves (vb2, vb3).
1	Fast closure valve (vb1).

The mechanical system (rack and pinion) located from B to C (see Fig 1.6).

- **SUBSYTEM 1**

The entry to the subsystem 1 is from point **A** until point **B**. The function of this subsystem 1 is to register the inlet pressures on the 800 JBC Sherwood Regulator to be calibrated (Fig. 1.6).

The components from left to right are as follows:

QUANTITY	COMPONENTS
1	U Manometer (MU1)
1	Fast closure valve (vb1)
1	Pilot-operated regulator (RP1)
2	Bourdon tube manometers (MB1 and MB2)
3	Needle valves (Va1, Va2, Va3)

At first the closure valve **vb1** opens the fluid, which is compressed air, enters through **A**, and due to the high pressure given by the compressor a pilot-operated regulator **RP1** is used (Fig. 1.6) to control the pressure in the test or calibration.

- **MECHANICAL SYSTEM**

The mechanical system is one of the most important parts of the device. This system starts in **B** and finishes in **C (**Fig. 1.6). The system is composed basically of a helical rack and pinion mechanism [6]. Its function is to adjust correctly the regulator with the purpose to prepare it for test and calibration. It is composed of the following components:

- Helical rack and pinion
- Handle
- Moving plate
- Fixed plate
- Seals.

In the mechanical system the rack, the helical pinion and the seals were calculated which are made of a material resistant enough that will not produce detachment of particle that could affect the internal regulators function.

- **SUBSYSTEM 2**

The entrance of the subsystem 2 begins in the point **C** (regulator outlet) to the point **D** (flow controller **Cf**). Its function is to register the outlet pressures of the 800 JBC Sherwood Regulator that will be tested or calibrated (Fig. 1.6). The components in their respective order from left to right are:

QUANTITY	COMPONENTS Y ACCESORIES
2	hoses (mg1, mg2)
1	Elbow ½" (c1)
2	½" T number 4 and number 5(T4, T5)
1	Bourdon manometer number 3 MB3 (Range: 0 psi – 15 psig)
2	Needle valve number 4 and number 5 (Va4, Va5)
2	Ball valves number 2 and number 3 (vb2, vb3)
1	U manometer number 2 MU2 (Range: 0 "W.C – 15 "W.C)

For the calibration process of the Sherwood Regulator the U manometer MU2, that has a measure range between 0 "W.C – 15 "W.C is used. The other manometer which is bourdon tube MB3 will be used only while calibrating regulators of first stage (high pressure regulators).

This subsystem is also composed of a by–pass valve (See Fig. 1.6) that measures the outlet pressure in the MU1 with ranges from 0 "W.C – 28 "W.C. And finally is the flux controller **Cf** (Fig 1.6) which is calculated to obtain the flow rate required in the calibration of the gas regulator, and can not exceed 60 s.c.f.h. (standard cubic foot per hour).

1.4.6 Test and calibration procedure

The general parameters that the device handles are as follows:

Maximum inlet pressure = 100 psi
Maximum outlet pressure = 15 psi
Maximum flow rate = 60 s.c.f.h.
Limit of altitude = 2.600 m.o.s.l (meters over the sea level)
Test fluid: Compressed air
System: Manual system

Maximum displacement = 9.84 in
Minimum displacement = 3.94 in

The mechanism tests and calibrates 800 JBC Sherwood Regulators. The limits in the adjustment range for the outlet pressure of the regulator are between 9 "W.C and 13 "W.C. The set point from the manufacturer must be 11 "W.C. The test procedure begins by putting seals in the mechanical system; then the regulator is positioned applying the displacement limit. The inlet pressure required for the calibration depends on the internal orifice that the Sherwood Regulator specifies. Once the internal pressure is measured, it must be verified if the regulator needs to be calibrated, because it may be the case that needs to be tested and that it operates under normal conditions.

When the flow controller **Cf** is connected, the calibration begins by adjusting the outlet pressure of the Sherwood Regulator, rotating the screw that is located by removing the plastic cap as follows: to increase the pressure, rotate clockwise and to reduce it, rotate it counter clockwise. Then the regulator lockup pressure must be checked. The flow controller **Cf** allows a progressive adjustment, a constant flow (45 s.c.f.h - 55 s.c.f.h). This calculation is very important one in the development of the project because we obtain the equivalent flow rate as real conditions of work. The manufacturer’s calibration point has to be verified due to it present the hysterics phenomena in the main spring. The phenomenon is important because it intervenes in the test and calibration of the gas regulator and can be minimized.

Continuing with the procedure it has to be maintained in test for stabilization, which is in the range between 10 and 20 minutes. After the stabilization time, which are about 15 minutes; the calibration is repeated and the outlet pressure is registered and finally the test and calibration technical card is filled approving the procedure.

The flow controller **Cf** that is used for the test and calibration has orifice number **30 DMS** that was selected by calculations.

1.4.7 Technical Norms of Colombia

The national technical regulation used in this project [6] is:

NTC 2505 (Gas pipelines, installations for gas supply in residential and commercial buildings (second actualization, re-approved in 1999-05-19, p.37).

NTC 3293 Regulators of pressure for equipment that work with gas (first revision, 1995 -07 -26, p. 89).

NTC 3527 Definition and ruling common to the test and artifacts of domestic and commercial use that use combustion gases (first actualization, 1999-05-28, p. 19).

NTC 3538 Mechanical devices, metallic valves for gas (first actualization, 1996–11–27, p. 14).
NTC 3727 Pressure regulators for natural gas (second actualization, 1999, p. 23)

NTC 3838 For gas pipelines (first actualization, 1999–04–28, p. 7)
NTC 3873 Pressure regulators for LP-Gas, 1996 -06 -19, p. 15)

NTC 4282 for pipelines installation with a supply gas in industrial buildings (1997–10–22, p. 47).

2 PRINCIPLE OF REGULATOR SYSTEM

2.1 HOW THE REGULATOR WORKS

The Sherwood Regulator operates internally under two conditions: when lockup pressure is present; which means when there are no flow conditions, and the other condition is for constant flow.

2.1.1 Lockup (No flow condition)

When the regulator is connected and the tank valve is opened, liquefied petroleum gas enters the regulator through the orifice. If there is no apparatus in service and there is no leakage, gas pressure beneath of the diaphragm increases, creating an upward thrust which overcomes the force of the main spring. As the diaphragm rises, the lever action of the linkage mechanism forces the seat to close against the orifice, stopping the inward flow of gas. Lockup pressure is always greater than the delivery pressure or outlet pressure (Fig. 2.1).

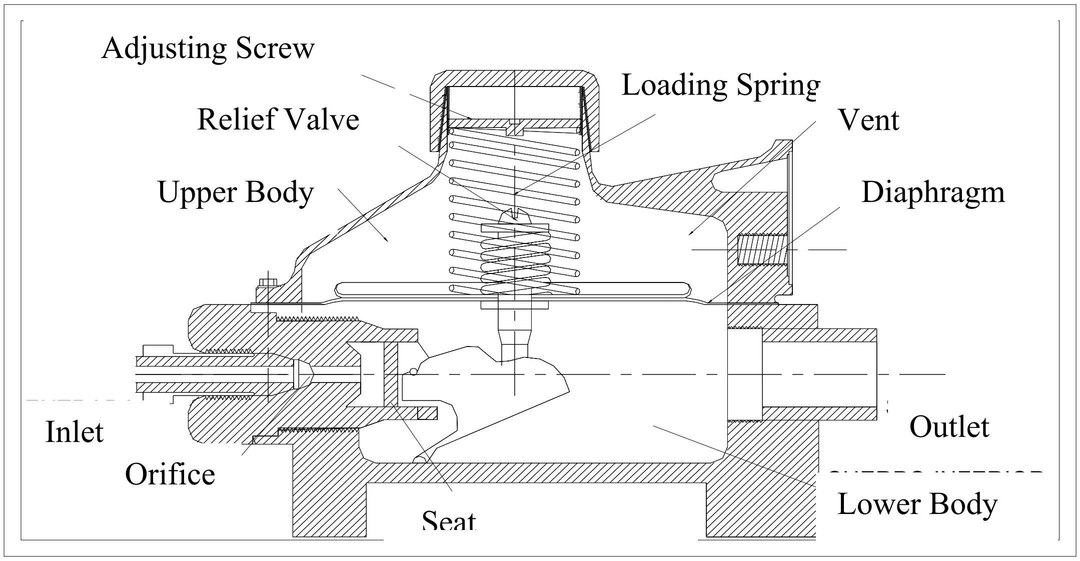

Figure 2.1 No flow condition [2]

2.1.2 Flow Condition (No flow condition)

As gas is used by an appliance, the pressure inside the regulator decreases, allowing the main spring to depress the diaphragm. As the diaphragm moves down, the linkage mechanism pulls the seat back away from the orifice, allowing more gas to come into the regulator and until the service line.

When the diaphragm lowers, the lever removes the seat of the hole, allowing the gas to pass to the regulator, and from here to the service downstream. At this moment it presents the flow conditions.

It is important to note how cautiously the adjustment in the outlet pressure of the Sherwood Regulators is made. Outlet pressure of all Sherwood regulators can be adjusted by turning the adjusting screw in the bonnet clockwise to increase pressure, and counter clockwise to decrease pressure.

As a precaution, never adjust the regulator to compensate the losses caused by a pipeline smaller; the only solution to this problem is to replace the pipeline by an adequate size. Finally, the economic aspect of operation and maintenance needs to be considered. Defining with precision the pressure and flow requirements of the process, their possible variation of the components and their impact in production are the first steps to guarantee a good selection.

2.2 HOW THE REGULATOR SYSTEM WORKS

The system combines certain regulation phases as for the use of natural gas and liquefied petroleum gas.

2.2.1 Regulation phases for natural gas

For the distribution of natural gas there are four types of regulation [12].

Two phase regulation: consists in reducing the inlet pressure from an inlet pressure of 60 psi to an outlet pressure of 7 "W.C; which is the supply pressure at the consumption point.

Three phase regulation (Option 1): in this phase a pressure regulation is made from 60 psi to 1 psi and then from 1 psi to 7 "W.C (Table 2.1).

Three phase regulation (Option 2): in this type of regulation a pressure reduction is made from 60 psi to 5 psi and then from 5 psi to 7 "W.C.

Table 2.1 Accepted regulation outlines for domestic regulation and small business (Natural Gas) [16]

	INLET PRESSURE	**OUTLET**		**PRESSURE**
PHASES	Psi	psi	Psi	inch of W.C
TWO PHASE	60			7
THREE PHASE (Option 1)	60	1		7
THREE PHASE (Option 2)	60	5		7
FOUR PHASE	60	5	1	7
APPLICATION:	**NATURAL GAS**			

Four phase regulation: this type of regulation allows more confidence and stability to the system, and consists in reducing the pressure from 60 psi to 5 psi, and then from 5 psi to a pressure of 1 psi and finally from 1 psi to 7 "W.C (see Table 2.1).

2.2.2 Regulation phases for liquefied petroleum gas

The phases of regulation for propane gas are [12]:

Single phase regulation: this type of regulation allows a reduction in the inlet pressure of cylinder from 100 psi approximately, to an outlet pressure of 11 "W.C which is the supply pressure for gas equipment.

Table 2.2 Accepted regulation outlines for domestic regulation and small business (LP-Gas) [16]

	INLET PRESSURE		**OUTLET**		**PRESSURE**
PHASES	psi	Psi	Psi	Psi	inch of W.C
SINGLE PHASE	100				11
TWO PHASE	100	15			11
THREE PHASE (Option 1)	100	15	1		11
THREE PHASE (Option 2)	100	15	5		11
FOUR PHASE	100	15	5	1	11
APPLICATION:	**PROPANE GAS**				

Two phase regulation: this phase reduces the pressure from the cylinder to a pressure of 15 psi and from 15 psi to an outlet pressure of 11 "W.C (Table 2.2).

Three phase regulation (Option 1): for this type of regulation, a reduction in the tank pressure is made to 15 psi, after from 15 psi to 1 psi and finally from 1 psi to 11"W.C.

Three phase regulation (Option 2): the difference with option one is the reduction of pressure from 15 psi to 5 psi (Table 2.2) and finally a reduction in the pressure is made from 5 psi to 11 "W.C.

Four phase regulation: this phase consists in the pressure reduction by four phases; first the cylinder pressure is reduced to an delivery pressure of 15 psi, then from 15 psi to 5 psi, after the pressure is reduced from 5 psi to 1 psi and finally is regulated from 1 psi to 11 "W.C (inches of water column) which is the pressure for the consumption point.

3 PERFORMANCE ANALYSES

The pressure regulator is a flow control device designed to maintain downstream pressure constant. It must be able to keep the pressure, without altering by changes in the operative conditions of the process. It is very important to mention that the right selection operation and preventive and corrective maintenance of the regulators will guarantee a good performance of the equipment. This chapter will now study the regulator performance and its system.

3.1 REGULATOR PERFORMANCE

The regulator selected is a Sherwood Regulator 800 JBC series, second stage and color green, which is low pressure and manages as fuel liquefied petroleum gas. It is a self-operated regulator that functions with the force equilibrium principle. The forces applied in the high pressure zone **Pi** are balanced with the forces of the low pressure zone **Po** (see Fig. 3.1).

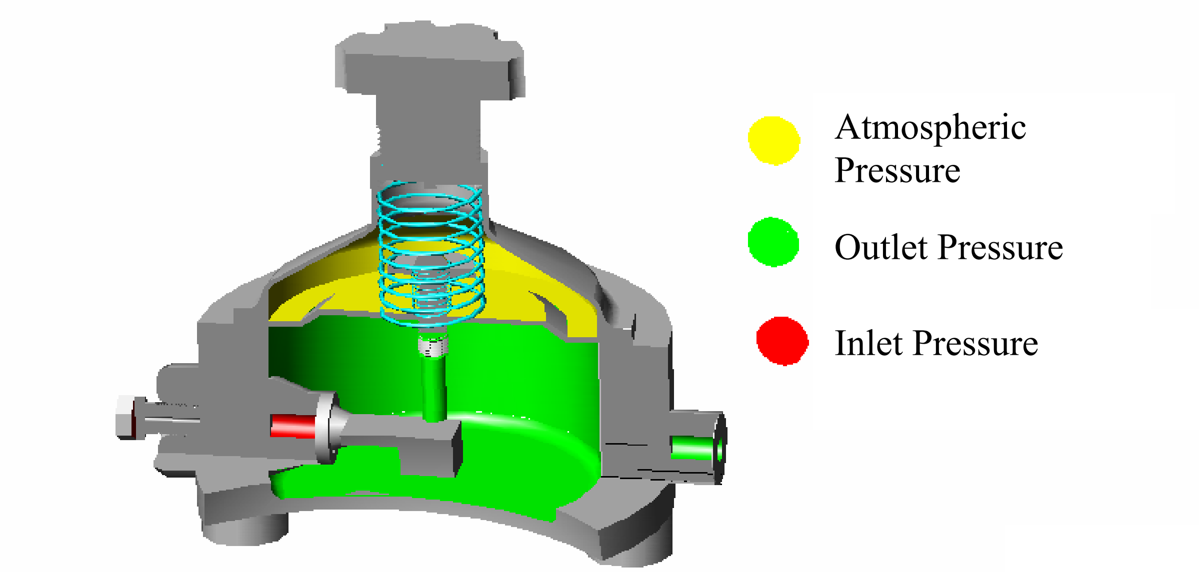

Figure 3.1 Force equilibrium principle

The force equilibrium is caused by the distribution of pressure at unequal areas, according to the following equation:

$$\mathbf{F = PA} \tag{3.1}$$

Where:
F = Force (lbf) or (N)
A = Area (in^2) or (m^2)
P = Pressure (lbf/in^2) or (N/m^2)

According to eq. 3.1, the force that acts in the low pressure zone **Po** is distributed in a bigger surface than the force applied in the high pressure zone **Pi**.
Due to the difference of areas the balance is achieved between both areas:

$$\mathbf{PiAi = PoAo} \tag{3.2}$$

The inlet force **Fi** is considered as opening force, which is balanced as the outlet force **Fo**.

To adjust the downstream pressure, a third force is introduced in the equation; this force is called the control force **Fs** (Fig. 3.1), and it is applied by a spring or artifact that supplies a force.

For the case of this self-operated regulator, the control force is supplied by a spring and it is considered as part of opening force. Therefore the mathematical equilibrium of forces is expressed as follows:

$$\mathbf{Fi + Fs = Fo} \tag{3.3}$$

Where:
Fi = Inlet force
Fs = Control force applied by the spring
Fo = Outlet force

The equilibrium between opening and exit forces into Sherwood Regulator is made while the equipment operates under steady-state flow conditions. Based on equations 3.2 and 3.3, it is recognized that if the inlet pressure remains constant, the changes in outlet pressure are compensated by the changes in the forces applied by the spring, obtaining its balance. The force applied by the spring, governed by the Hooke Law, is expressed in the following equation:

$$\mathbf{F = KX} \tag{3.4}$$

Where:
F = Force (lbf) or (N)
K = spring elasticity constant (lbf/in) or (N/m)
X = spring deformation (in) or (m).

While the lever of the regulator is moved, the spring is deformed, changing the force applied by the spring. Therefore the change in the forces that it applies to the spring intervenes in the delivery pressure, also called outlet pressure.

In the Sherwood Regulator the lever is moved by the interaction of the diaphragm. The lever is related with the diaphragm and its change in position is transferred to the diaphragm, modifying the transverse section area that goes through the running flow (Fig. 3.2). The diaphragm movement is controlled by a spring that intervenes in the opposite side of the area that measures the outlet pressure or pressure to be controlled. The inlet pressure acts over the projected area of the seat that it has area of smaller size.

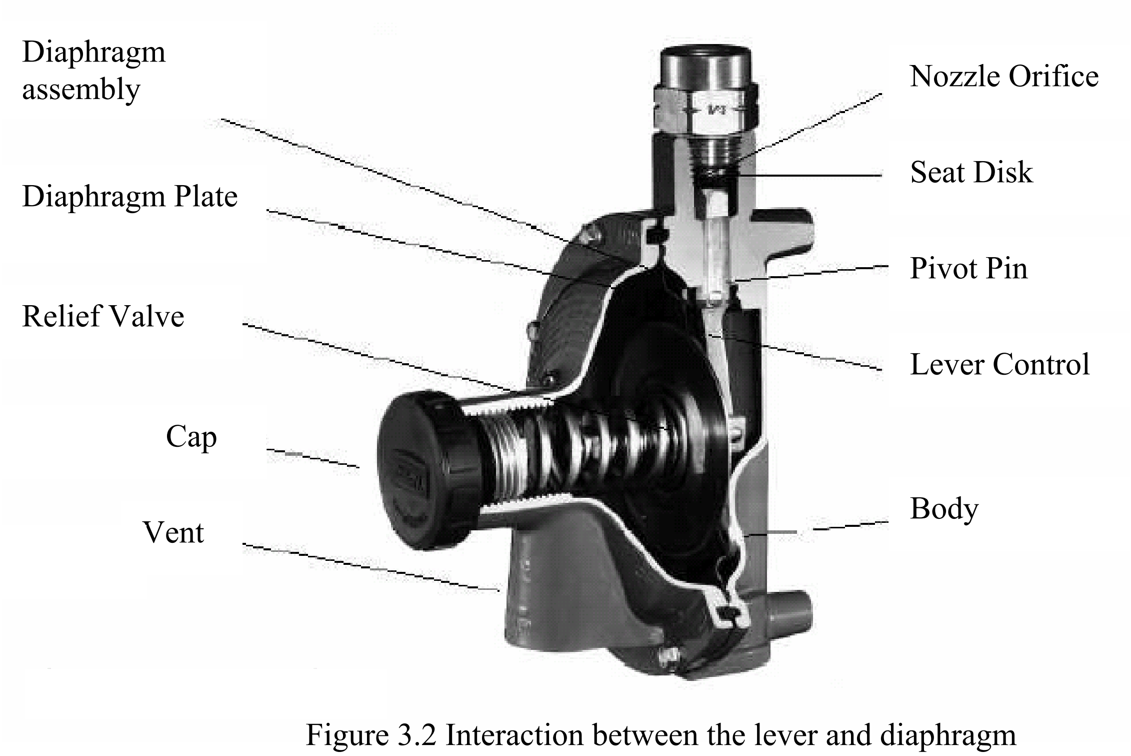

Figure 3.2 Interaction between the lever and diaphragm

To obtain the force balance, the diaphragm area must be bigger than the projected area of the seat. In the design and manufacture of regulators the relationship between a diaphragm/seat surfaces is a very important factor to determine the precision and sensibility of the equipment.

There are different forms of regulators and every basic design is made of three essential elements [12]:

Loading element (helical spring): The loading element of the Sherwood Regulator is the main spring, and these loading element can be used to produce certain effect, such as weight, spring or pressure from an external source. The spring is made of stainless steel or zinc steel and yellow chromed; it makes its function in unaltered way through millions of cycles that it performs in its required life. Some of the advantages are its easy adjustment, diversity of sizes, interchangeability and the fact that its mass is relatively small. The spring is located in the upper body and rests over a metallic plate. Its function is to maintain the set point on outlet pressure.

Sensor element (Diaphragm): the sensor element is an elastic disc that separates the upper and lower body and at the same time makes hermetic the internal regulator. Its main function is to act as sensor mechanism of the gas pressure that acts over the lower face, and transmit the movement generated by the pressure against the loading spring, or when the gas pressure is reduced; transmit the elongation movement of the spring vertically down. These vertical movements up and down are transmitted through the central shaft or stem to the mechanism that moves lengthwise the seat from and towards the orifice.

The diaphragm has a metallic plate that covers almost all the area, and prevents that the spring supported in the diaphragm will hurt it and improves at the same time the sustentation surface of it.

Restricting element (orifice and seat): restricting element is the orifice and the seat, then the responsibility to perform with the condition of a constant demand is performed by the regulator and therefore on the orifice.

The movement of the seat is made from and towards the orifice closing the gas flow or opening it gradually. The orifice is made from metallic materials of low hardness as aluminum or bronze, and does not hurt the seal of the seat. It is installed on a firm manner to the regulator body and it has the task of reducing the gas pressure that flows through it.

The seat as a movable element has the characteristics of the seal from cut valve, it achieves a hermetic seal but does not wear out the orifice by contact, preventing the gas flow (See Fig 2.1), and as it gets closer to or farther from the orifice, it allows more or less inlet flow. In its back it is connected with the mechanism that causes its movement in associated with the diaphragm displacement. With an ideal regulator we could obtain constant outlet pressures under any flow condition without consideration of inlet pressure.

The performance study of the 800 JBC Sherwood Regulator shows that it is not ideal because it is affected directly by five parameters [10] that will be studied in following sections. The parameters that intervene on the performance are the diaphragm, helical spring and inlet-pressure effects. The regulator body and zero flow effect are not significant for the performance.

3.1.1 Diaphragm effect

For a given position of linkage in the Sherwood Regulator, the upward force **Fu** must be in equilibrium with the descending force **Fd.** The forces to be in equilibrium would be the spring acting over the diaphragm acting down and the gas pressure in the diaphragm acting up. Therefore we have:

$$\mathbf{Fu = Fd} \tag{3.5}$$

$$\mathbf{Fu = (Ad)\,(Po)} \tag{3.5a}$$

Where:

Fu = Upward force applied in the diaphragm by the gas.

Fd = Descending force applied by the spring over the diaphragm.

Ad = Diaphragm area.

Po = Outlet gas pressure.

Because **Fd** is not constant, then the diaphragm increases its area while descending because its diameter increases. Figure 3.2 are presented the typical deviations that occur in the diaphragm diameter. This change in the area produces an outlet pressure drop [9]; as it is shown next:

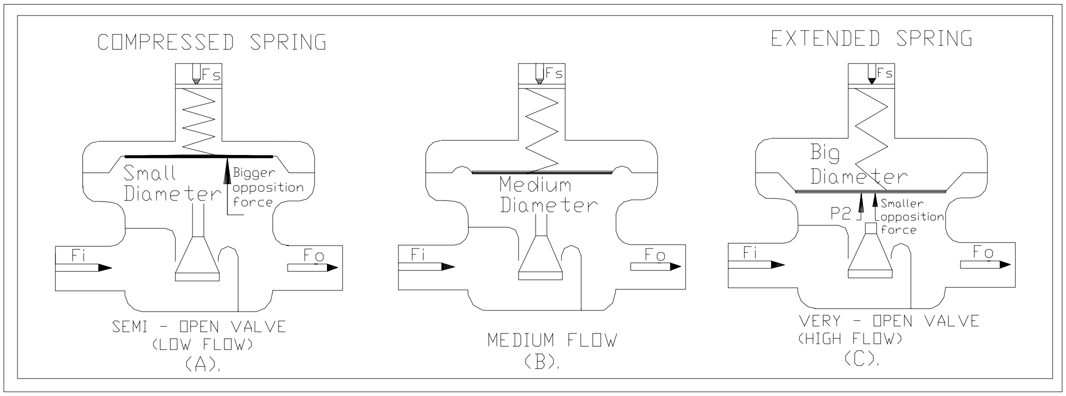

Figure 3.3 Deviation of diaphragm

A first stage regulator has a set point on outlet pressure of 20 psi,

Where:

P_1 = Outlet pressure at 0.25 in. displacement (no change in diaphragm area).

P_2 = Outlet pressure at 0.25 in. displacement (changes in diaphragm area).

K = Elasticity spring constant of 100 lbf/in.

X = Initial spring compression of 1.0 in.

T = Valve displacement of 0.25 in.

Ad_1 = Diaphragm area of 5 in^2 for P_1.

Ad_2 = Diaphragm area of 6 in^2 for P_2.

Combining equations (3.5) and (3.5a)

$$\mathbf{Fu = Fd = Ad.\ P}$$

Then finding and replacing the values for P_1 and P_2, we have:

$$P_1 = Fd / Ad$$

$$P_1 = K (X - T) / Ad_1 = 15 \text{ psig.}$$

$$P_2 = K (X - T) / Ad_2 = 12.5 \text{ psig.}$$

$$\%Pd = P_1 - P_2 = 2.5 \text{ psig. } (16.67 \%)$$

Therefore, we can appreciate that the increase on the diaphragm area reduces the outlet pressure and increases the percentage in pressure drop (16.67 %).

3.1.2 Spring effect

To analyze the spring compression effect over the outlet pressure in the Sherwood self-operated regulator, it is important to start with the Hooke Law:

F = K. X, as mentioned previously in Equ. (3.4).

Now, using the equation:

P = F /A, as mentioned previously in Equ. (3.1); and replacing equation (3.4) into Equ. (3.1),

We have: **P = K X /A** (3.6)

Then we observe that the force that acts under the diaphragm's lower surface is developed in the measured pressure **P_2**, and the opposite force is developed on the spring by compression effect (Fig. 3.3C).

The force applied by a given spring depends only on the compression grade, how much or how low it is compressed. The spring constant **K** is the force that it produces for each inch of compression. To illustrate this, three identical springs are presented with the same constant **K** under different load conditions (Fig. 3.4).

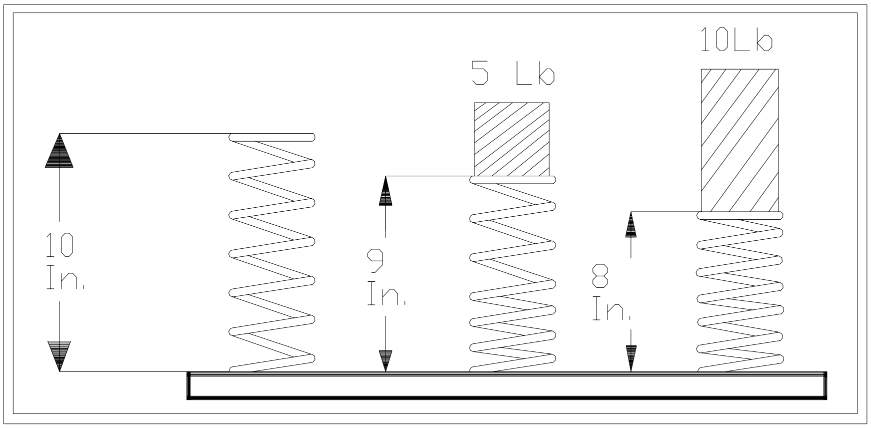

Figure 3.4 spring under different load conditions

When the spring is installed in the Sherwood Regulator, one end remains static and the other rests over the diaphragm and it moves with it. Because of the change in the compression grade by this movement, the force applied by the spring also changes the outlet pressure.

Through the following calculation is illustrated in detail the compression spring effect over the outlet pressure, considering the flow when it is minimum and maximum (Fig. 3.3A and Fig. 3.3C). A second stage 800 JBC Sherwood Regulator presents the following values and it is calibrated at an outlet pressure of 7 "W.C and 11 "W.C.

$K = 9.45$ lbf/in

$Ad = 19.63$ in^2

$X = 1.50$ in, 2.0 in.

For this case, the spring was compressed 1 in and 1.50 in. With these values a data table has been made (Table 3.1). After many tests realized in Colombia, it can be observed that when the demand is decreased, the gas pressure that acts on the lower part of the diaphragm has bigger opposite force (see Table 3.1; positions 5,4, 3 and 2), increasing thereby the outlet pressure from 7 "W.C to 9.62 "W.C, or 2.62 "W.C. above the adjustment pressure.

Table 3.1 spring compression effect on the outlet pressure

POSITION (NG)	Gas Pressure in the diaphragm Po ["W.C]	Spring Compression X (Inches)		Spring Compression X (Inches)	Gas Pressure in the diaphragm Po ["W.C]	POSITION (LP-GAS)
1	10.50	2.00	**LOCKUP PRESSURE**	2.50	13.99	1
2	**9.62**	1.88	***Minimun Flow***	2.38	**13.12**	2
3	8.75	1.75		2.25	12.24	3
4	7.87	1.63		2.13	11.37	4
5	**7.00**	1.50	***Set Point***	2.00	**10.50**	5
6	6.12	1.38		1.88	9.62	6
7	**5.25**	1.25	***Maximum Flow***	1.75	**8.75**	7
8	4.37	1.13		1.63	7.87	8
9	3.50	1.00		1.50	7.00	9
10	2.62	0.88		1.38	6.12	10
11	1.75	0.75		1.25	5.25	11
12	0.87	0.63		1.13	4.37	12

When the demand is increased, the gas pressure that keeps acting in the lower diaphragm surface has smaller opposite force, altering this way the outlet pressure of 7 "W.C to 5.25 "W.C (See table 3.1; positions 5,6,7); 1.75 "W.C under the set point.

From the precedent information we can interpret clearly that between the minimum and maximum flow (see Fig. 3.5), $\mathbf{P_2}$ has lost 4.37 "W.C. Therefore, the regulator has not delivered constant pressure.

This deviation between pressure $\mathbf{P_2}$ (Pressure measured in the diaphragm) at low capacity and $\mathbf{P_2}$ at high or maximum capacity is known as the pressure drop and the amount of pressure drop is known as proportional band [9] that is calculated as follows:

$$\mathbf{PB = P_2(at\ low\ capacity) - P_2(at\ high\ capacity)} \quad (3.7)$$

Replacing the data in the calculation example we have:

$$PB = 9.62 \text{ "W.C} - 5.25 \text{ "W.C} = 4.37 \text{ "W.C}$$

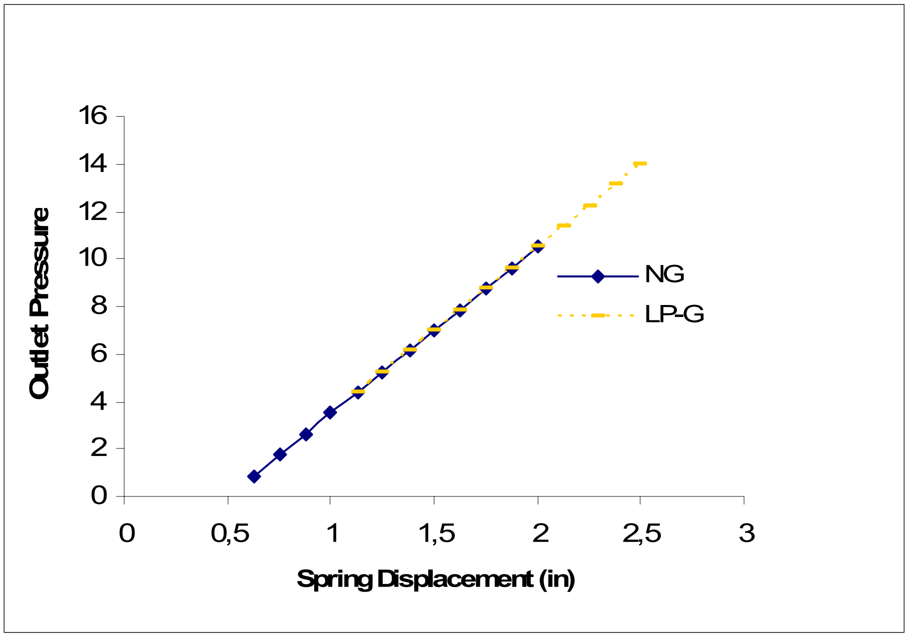

Figure 3.5 Graphical between Po and X

Finally, this effect has been known as the spring effect. To reduce this effect, the correct spring has to be selected with the smallest range that matches the application requirements.

3.1.3 Regulator Body effect

The third factor that affects the Sherwood Regulator performance is called body effect, presented between the components of the regulator and the point where outlet pressure is measured [10]; which are generated by the geometry of its parts. Figure 3.6 presents the combined action of these three effects that reduce the outlet regulator pressure. The third effect is not really significant in the pressure drop.

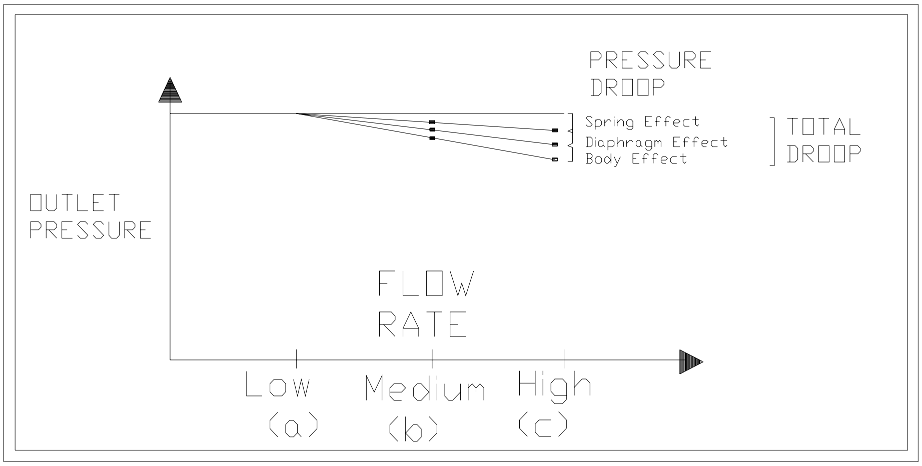

Figure 3.6 Body, diaphragm and spring effects

3.1.4 Zero flow effect

This condition, also called lockup pressure, is normally associated with a safe pressure. When the regulator measures this pressure; it closes and shuts the flow. The lockup pressure depends on whether the seat of the valve is hard or soft and on the amount of force developed by positioning the valve [10].

To obtain a complete lockup pressure seats of soft valve are required. Soft seats are normally made from rubber. This zero flow effect is not significant in the pressure drop but it should be considered in a distribution line of gas in a system.

3.1.5 Inlet-pressure effect

The outlet pressure of the regulator is also affected by the changes in the inlet pressure. In the regulator the inlet pressure acts in the lower part of the linkage control while the outlet pressure acts on the upper part. Therefore, a pressure drop over the linkage control area is presented, meaning that there is a force that acts in the same direction as the pressure in the diaphragm and that has to be added to it. This means that while the inlet pressure is increased, related to the initial conditions, the outlet pressure will descend. Figure 3.7 shows this behavior.

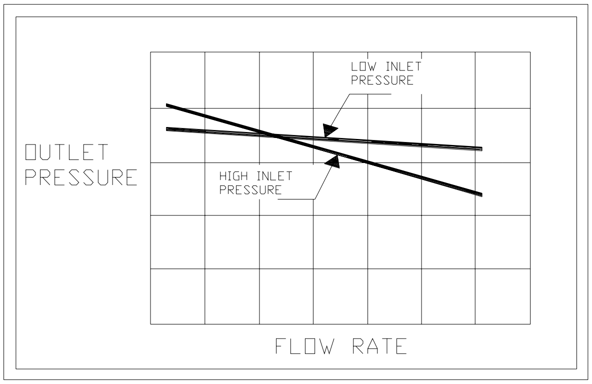

Figure 3.7 Inlet-pressure effect

Assuming the following values for the Sherwood regulator, we have:

Ad = Diaphragm area = 10 in²

Av = Relief valve area = 1 in²

Pi = Inlet pressure = 10 psig

Po = Outlet pressure = 1 psig

Fu = Upward force applied in the diaphragm by the gas.

Fd = Descending force applied by the spring over the diaphragm.

We use the following equation to find **Fd** [12]:

Fd = Force applied over the relief valve + Force in the diaphragm.

$$Fd = Av.\ (Pi - Po) + Ad.\ Po \qquad (3.8)$$

Replacing the values obtained in Equ. (3.8), we obtain:

Fd = $1\ in^2.\ (10\ lbf/in^2 - 1\ lbf/in^2) + (10\ in^2\ .1\ lbf/in^2)$

Fd = 19 lbf.

Now, considering that the inlet pressure increases to 11 psi:

$$Fd = Fu$$

$$19 = 1.\ (11 - Po) + 10\ (Po)$$

19 – 11 = 9. Po

8 /9 psig = Po

0.89 psig = Po

Therefore we can identify that the outlet pressure is 0.89 psi and it decreases from 1 psi. This means that the pressure drop is 0.11 psi due to an increase of 1 psi in the inlet pressure.

3.2 REGULATOR SYSTEMS PERFORMANCE

The system performance is based on the way as the regulation is made using the different types of regulation for propane gas handling. Next, an explanation is given about the performance in the two methods that are most frequently used in liquefied petroleum gases, which are single stage and two stages regulation.

3.2.1 Single stage regulation performance

Basically for the good performance in this type of regulation, gas pressure incoming directly from the tank must be reduced to the supply pressure which is 11 "W.C through one regulator called the single stage regulator, and that is identified in the Sherwood brand with the blue color. In consequence, all the system will be studied starting with the first artifact that is shown in the internal system (Fig. 3.8). This is a container, also called the propane gas storage tank. To obtain properly the dimensions of the storage tank and the pipes, the total load/consumption in BTU must be determined. The total load is the sum of all the gas consumption in the installation and it is calculated adding the consumption in BTU of all the devices.

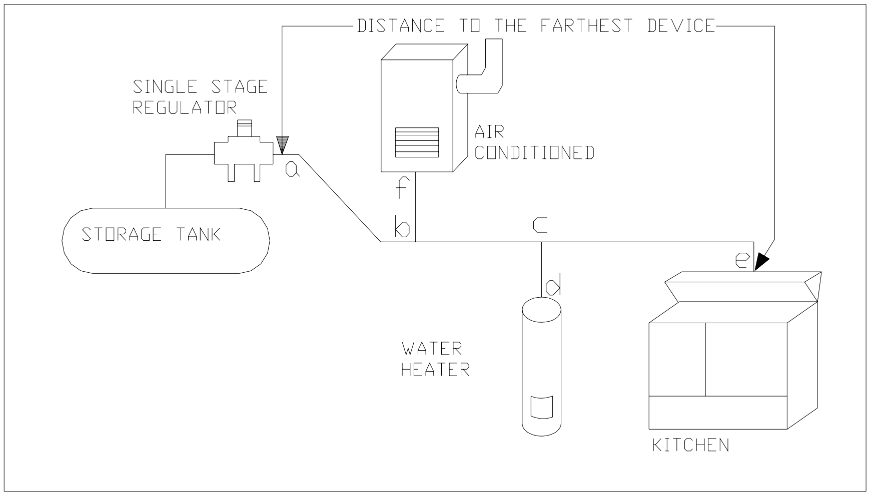

Figure 3.8 Internal pipes system for propane gas in single stage regulation [13]

The total consumption in BTU can be obtained in the badge of the device or in the manufacturer literature. Also the appropriate number of cylinders must be determined. One must be cautious in selecting the most appropriate location and that it is safety approved under the reliance of local and state regulations; the NFPA 58 (National Fire Protection Association 58), and the storage and handling of liquefied petroleum gas. Once these considerations are obtained, the following simple method must be performed to insure the selection of the right sizes in the internal tubing system for propane gas. The steps to follow in this method are following:

1. Determine the total demand of gas in the system, adding the inflow in BTU/hour of the devices and the appropriate demand for future devices.

2. For tubing after of the second stage regulator or single stage:

A. Measure the length of the pipes required from outlet of the regulator to the most distant device. There is no other measure to obtain the dimensions.
B. Make a simple schematic drawing of the tubing system (Fig. 3.8).
C. Find the flow capacity for every section of piping system. Using table **3.2** select the appropriate diameter of the pipes for each section using the values in BTU/hour for the

length determined in step 2-A. If the exact length is not found in the table, use the next higher length. Do not use any other length for this simple purpose; simply select the size that represents at least the required capacity for each section of the pipeline.

Table 3.2 First stage and second stage or integral twin stage pipe sizing [13]

		Length of pipe or tubing, Feet									
Size of pipe or copper tubing, Inches		**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Copper tubing (D)	(3/8)	49	34	27	23	20	19	----	----	----	----
	(1/2)	110	76	61	52	46	42	38	36	33	32
	(5/8)	206	141	114	97	86	78	71	67	62	59
	(3/4)	348	239	192	164	146	132	120	113	105	100
	(7/8)	536	368	296	253	224	203	185	174	161	154
Iron tubing (D)	(1/2)	291	200	161	137	122	110	102	94	87	84
	(3/4)	608	418	336	287	255	231	212	198	185	175
	1	1146	788	632	541	480	435	400	372	349	330
	1 - (1/4)	2353	1617	1299	1111	985	892	821	764	717	677
	1 - (1/2)	3525	2423	1946	1665	1476	1337	1230	1144	1074	1014
	2	6789	4666	3747	3207	2842	2575	2369	2204	2068	1954
		125	**150**	**175**	**200**	**225**	**250**	**275**	**300**	**350**	**400**
Copper Tubing (D)	(3/8)	----	----	----	----	----	----	----	----	----	----
	(1/2)	----	----	----	----	----	----	----	----	----	----
	(5/8)	----	----	----	----	----	----	----	----	----	----
	(3/4)	----	----	----	----	----	----	----	----	----	----
	(7/8)	----	----	----	----	----	----	----	----	----	----
Iron Tubing (D)	(1/2)	74	67	62	58	54	51	48	46	43	40
	(3/4)	155	141	129	120	113	107	101	97	89	83
	1	292	265	244	227	213	201	191	182	167	156
	1 - (1/4)	600	544	500	465	437	412	392	374	344	320
	1 - (1/2)	899	815	749	697	654	618	587	560	515	479
	2	1731	1569	1443	1343	1260	1190	1130	1078	992	923
Total length of piping from outlet of first stage regulator to inlet of second state regulator furthest away. Data calculated per NFPA # 54 & 58											

The following graphs show the material of tubing, lengths and the diameters to make the respective selection.

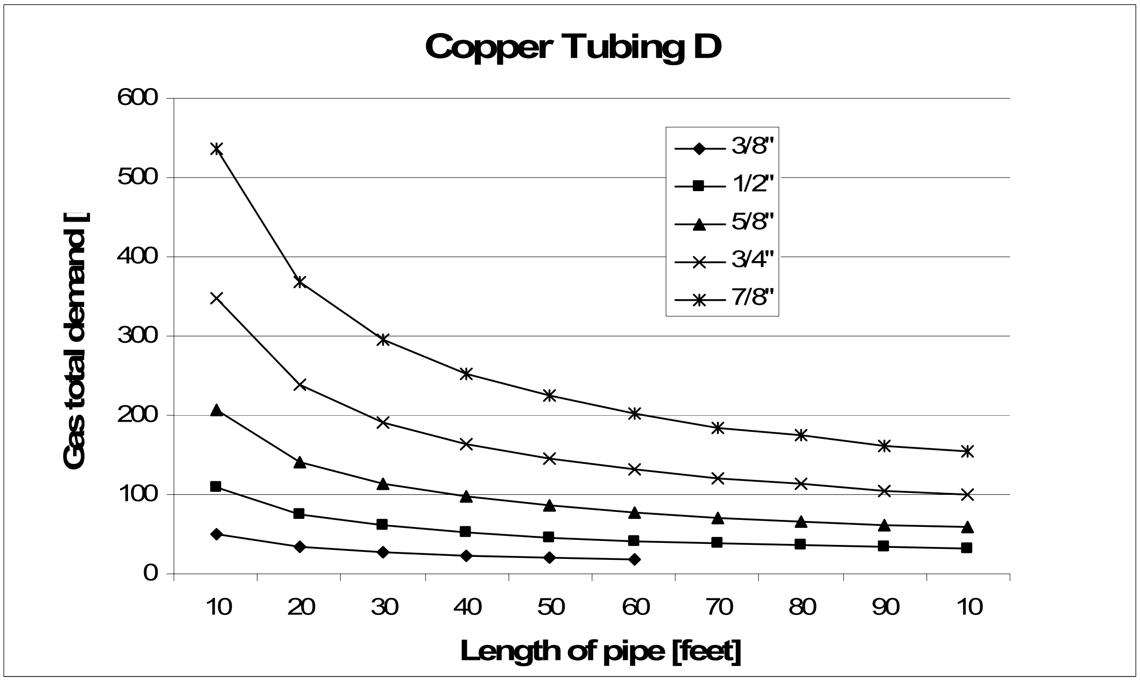

Figure 3.9 ***Graph*** **BTU/hr Vs Length (copper)**

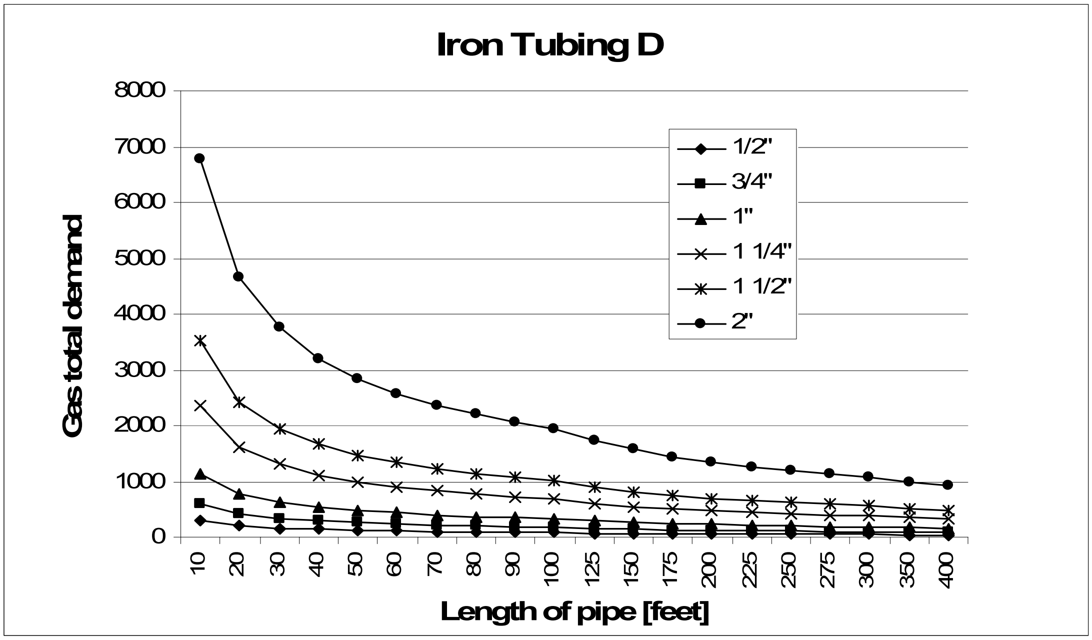

Figure 3.10 ***Graph*** **BTU/hr Vs Length (Iron)**

3.2.2 Two stage regulation performance

This type of regulation is basically composed of two regulators that control the gas pressure and allow more stability and efficiency of the system (Fig. 3.11).

The first stage regulator intervenes directly in the pressure control of the storage tank; it is a high pressure regulator identified with the red color in the Sherwood mark and the second is a low pressure regulator; its color is green for the same trade mark and it provides constant delivery pressure of 11 "W.C in the different consumption points.

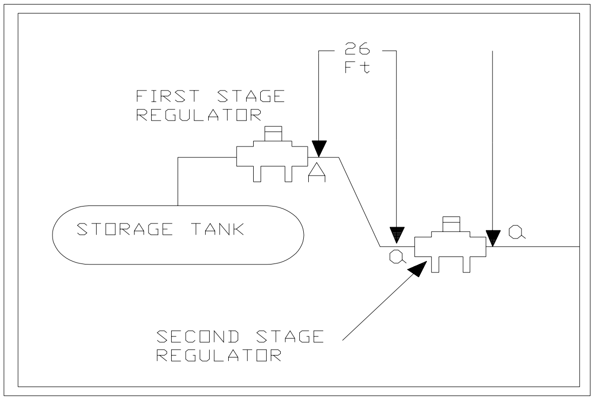

Figure 3.11 Internal tubing systems for propane gas in two stage regulation [13]

Also for the performance of this type of regulation the dimensions of the storage tank and tubing must be obtained; as in the one phase regulation determining the load/total consumption in BTU.

Next, the appropriate number of cylinders must be found, and finally the most accessible location for the operation following regulation requirements.

Following these considerations, now the correct size of the tubing on internal systems design for liquefied petroleum gas must be selected.

The steps are similar to the first stated previously in single stage regulation performance.

1. Determine the total demand of gas in the system

2. For pipes between regulators of first and second stage:

A. In a simple system with only one regulator of second stage, measure the length of the pipe required between the outlet of the first stage regulator and the entry of the second stage regulator. Select the pipe or tubing required according to the corresponding table.

B. For systems with multiple second stage regulators, measure the length of tubing required to reach the second stage regulator there is farthest. Make a simple design and measure each section of the pipeline using the table required.

3.3 GAS PRESSURE CONTROL

In a gas system the control actions are essential. For this reason the pressure can be measured using diverse instruments, the manometer being one of the most common. Figure 3.10 presents the diagram of a manometer. Instead of pressures expressed in lbs/in^2; these state low, high and OK, representing the last one the desired level of pressure.

Any deviations in relation to the OK point will require an immediate corrective action. Figure 3.8 presents a valve incorporated in the system.

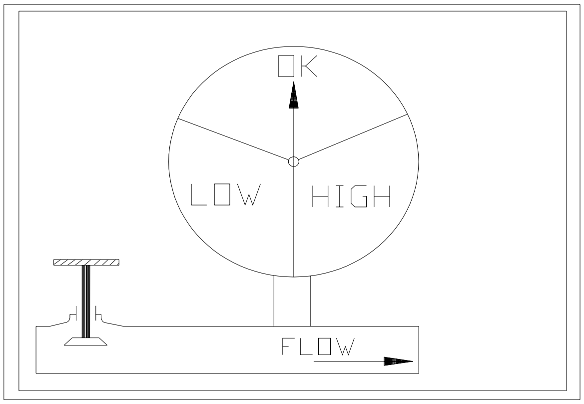

Figure 3.12 Bourdon manometer with valve incorporated

A change in the reading of the manometer from OK to high means that too much gas is passing through the valve. This warns that it is required to close the valve. If the valve is closed completely the pressure will start to decrease until the manometer states low. At this point the valve is opened and the opposite process will occur.

In the previous example, the action was "on - off". The valve was opened or closed, but it is obvious that having the manometer and control over the valve it is possible to perform small changes to keep the pressure in the desired value.

Again, the regulator has its three elements:

- The manometer and the operator as sensor elements
- The valve as restricting element and
- The operator as response element when performing the operation with manual regulation

The three control actions of a regulator are:

- On - Off
- Proportional
- Proportional + adjustment

The "on - off" action is the described previously. Next, the proportional action is described.
If the manometer of the figure 3.12 is replaced by the illustrated in the figure 3.13, it can be appreciated that the fifty line represents the desired level of pressure and that a series of lines that vary in a range between 0 psi – 100 psi represents the possible variations of pressure; besides, an indicator is added to the system in the valve that has the same numbering of the manometer with the terms "closed" and "open" that correspond to one hundred and zero respectively.

In other words, the position of the valve is proportional to the reading in the manometer.

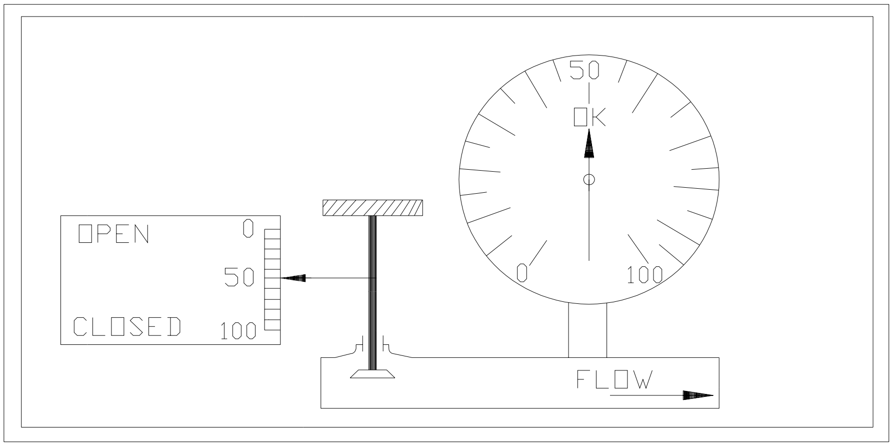

Figure 3.13 Bourdon manometer with valve and indicator incorporated

If the operator, for example, changes the position of the valve in one line, then the pressure would be changing between 45 psi and 55 psi.

The third control action is "proportional + adjustment". Under the same previous conditions, the operator must open the valve one line for each drop line in the manometer, and then open the valve more until OK is shown in the manometer regardless of its position.

In this case the initial movement of the valve is proportional to the change of position in the manometer, but after the valve is adjusted the measuring element or sensor is taken to the desired pressure level.

4 PRINCIPAL COMPONENT DESIGN

4.1 FUNCTION DESCRIPTION OF EACH COMPONENT IN A REGULATOR

Independent of the external shape of the regulators; all of them have in their basic internal components as follows:

Lower body, upper body, diaphragm, spring, restricting element and relief valve.

4.1.1 Lower body

It is the cap or internal chamber of a regulator (Fig. 4.1). It supports the connections for inlet and outlet gas flow. It is usually built of aluminium casting, aluminium alloy, heavy casting of Zinc, or cast iron, and covered with painting that avoids corrosion. The principal function is to protect the restricting element and mechanism that interconnects it with the diaphragm.

4.1.2 Upper body

It is the cap or upper chamber. It is manufactured with the same material as the lower body and it is also protected against corrosion. The central part of it has the shape of a tower that supports the loading spring (Fig. 4.1).

This tower has a bonnet cap; the adjusting screw increases or decreases pressure, and lastly the upper body houses in one of its borders a component called vent.

4.1.3 Diaphragm

It is an elastic disk that separates the upper and lower body and at the same time makes the Sherwood Regulator internal area hermetic. Its main function is to operate as sensor mechanism of gas pressure that acts over the lower face, and transmits the movement generated by the pressure against the loading spring, or when the gas pressure is reduced; transmits the elongation movement of the spring on down vertical direction (Fig. 4.1).

4.1.4 Spring

The spring is manufactured of stainless steel or zinc steel and yellow chromed; it makes its operation constant through millions of cycles that it performs in its lifecycle; the spring is located in the upper body and rests over a metallic plate.
Its main function is to maintain the set point in the outlet pressure (Fig. 4.1).

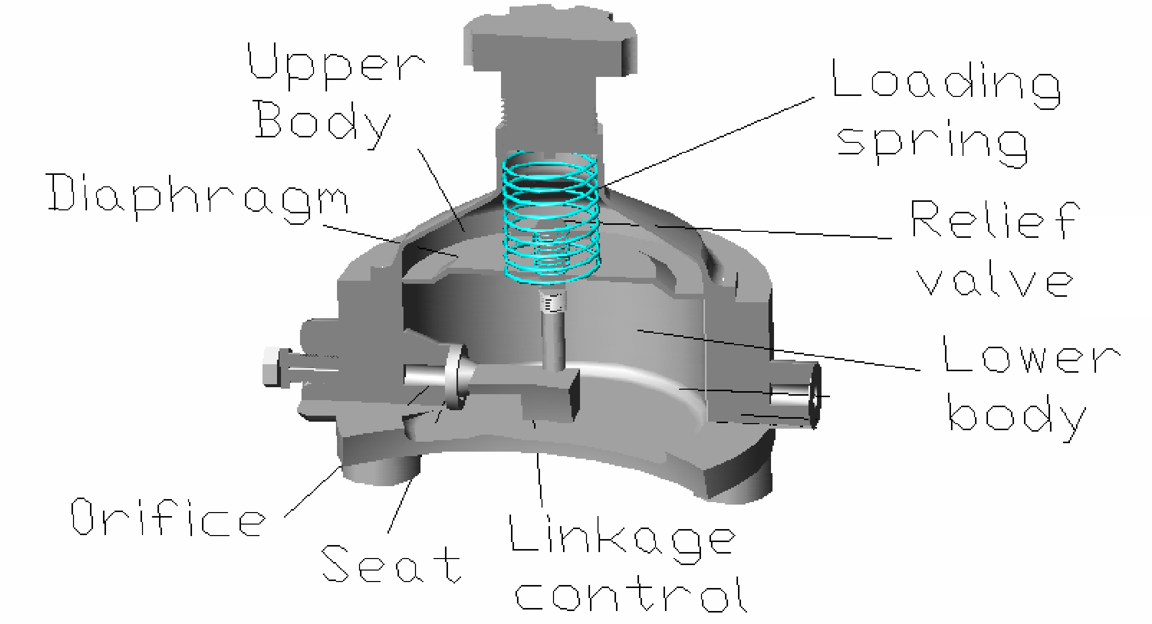

Figure 4.1 Components in a regulator

4.1.5 Restricting element (orifice and seat)

All the gas systems are based on the pressure control; the responsibility to perform with the condition of a constant demand is performed by the regulator and therefore on the orifice as restricting element.

The orifice is made of aluminium or bronze and it has the function of reducing the gas pressure that flows through it. That seat which is the movable element performs a hermetic seal but it does not wear out the orifice by contact, it has a function to obstruct the gas flow (Fig. 4.1).

This seat begin to make the displacement for closing the orifice, it allows controlling inlet flow.

4.1.6 Vent

The component is an integral part of the upper body and it is presented in different sizes that depend whether the regulator has or not a relief valve.

When the regulator has a relief valve, then this valve is activated automatically if there are present high pressures allowing gas flow into upper body to be expelled to the exterior through the vent.

The vent has an external surface of mesh protector manufactured of stainless steel, which has function to impede the access of insects and dirt to the internal regulator; allowing quick gas exit to the atmosphere.

4.1.7 Relief valve

This component is located in the upper body into the central axis that crosses the diaphragm. It has the function of preventing an increase in the regulator internal pressure. That component works as safety factor (Fig. 4.1). Next the real structure is shown from the Regulator Sherwood to which were made the tests in Colombia.

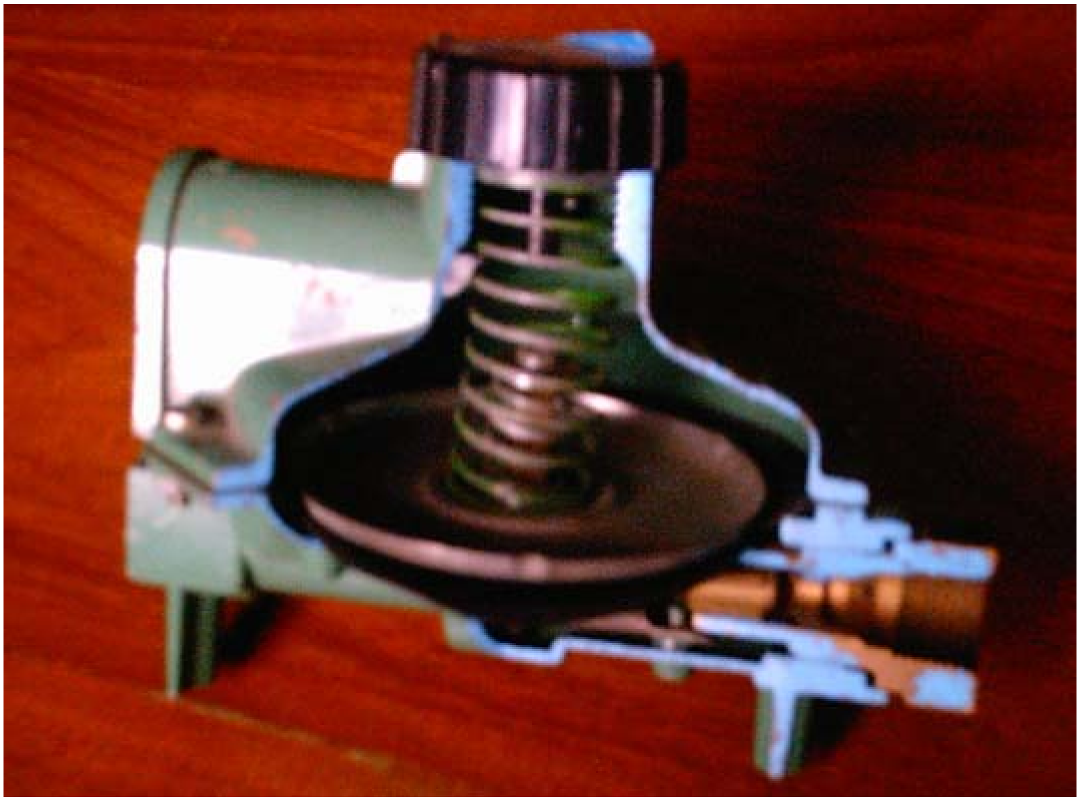

Figure 4.2 Sherwood Regulator Structure

4.2 HELICAL SPRING DESIGN

The design of a helical spring for the Sherwood Regulator is presented in this chapter. The loads can be conveniently classified into static, cyclic and dynamic [15]. When a load is static, the spring will work between specific loads just some few times; in other cases the spring can remain under loads by lingering time, which is the case presented in this design where the spring has a permanent axial load that is transmitted by the 11 "W.C for the factory setting. In cyclic applications the spring can be subjected to cycles among load points of 10^4 and 10^9.

Lastly when dynamic load is employed the application speed of the load is high and it produces a transitory wave in the spring. That's analysis is for static load and cyclic condition.

4.2.1 Analysis for static load

This is a compression helical spring that has the following technical specifications:

Material: ASTM A227 (Wire of steel to the carbon cold-working) [15].
Closed and grinding ends [15].

$N_a = 8$

$N_t = N_a + 2 = 10$

$L_f = 4.0 in$

$Do = 1.0 in$

d = 0.112 in

D = Do – d = 0.888 in

C = D/d = 7.93

For most of the springs, C will vary approximately from 6 to 12; for C < 4 will be difficult to fabricate and for C > 12 the spring tends to bulge [15].

The spring constant K and solid height Ls [21] should be determined:

$$K = \frac{d^4 G}{8D^3 Na} \tag{4.1}$$

$$K = \frac{(0.112)^4 (11.5x10^6)}{8(0.888)^3 (8)}$$

$$K = 40.38 lbf / in$$

$$Ls = (N_t + 1)d \tag{4.2}$$

$$Ls = (10 + 1)(0.112 in)$$

$$Ls = 1.232 \, in$$

Now the shearing stress τ should be found with the next equation that applies so much for static load as dynamic [17]:

$$\tau = Ks\frac{8FD}{\pi d^3} \tag{4.3}$$

Where Ks is a factor of correction by shear-stress that is defined for the equation

$$Ks = \frac{2C+1}{2C} \tag{4.4}$$

$$Ks = \frac{2(7.93)+1}{2(7.93)}$$

$$Ks = 1.06$$

Now, replacing the value obtained in Equ. (4.5)

$$\tau = Ks\frac{8FD}{\pi d^3} \tag{4.5}$$

$$\tau = 1.06\frac{8(20lbf)(0.888in)}{\pi(0.112in)^3}$$

$$\tau = 34122.03lbf/in^2$$

$$\tau = 34.12ksi$$

In table 4.1 is selected a material *wire stretched cold* $A227$ for the spring where A=137 ksi and m=0.201; with this values the minimum stress resistance S_{ut} is calculated.

$$S_{ut} = \frac{A}{d^m} \tag{4.6}$$

$$S_{ut} = \frac{137kpsi}{(0.112)^{0.201}}$$

$$S_{ut} = 212.73Kpsi$$

Table 4.1 Constants to calculate minimum stress resistances of typical steels for springs [17]

Constants to calculate minimum stress resistances of typical steels for springs				
			INTERCEPTION	
MATERIAL	ASTM Number	M EXPONENT	A Ksi	A Mpa
Wire for musical rope	A228	0.163	186	2060
Wire temperate in oil	A229	0.193	146	1610
Wire stretched cold	A227	0.201	137	1510
Al chromo-vanadium	A232	0.155	173	1790
Al chromo-silicon	A401	0.091	218	1960

Source: Associated Spring-Barnes Group, Design Handbook.

So then this value of S_{ut} is substituted in the equation of Joerres [14]:

$$S_{sy} = 0.45 S_{ut} \tag{4.7}$$

$$S_{sy} = 0.45(212.73 Kpsi)$$

$$S_{sy} = 95.73 Kpsi$$

Therefore the safety factor n is

$$n = \frac{S_{sy}}{\tau} \tag{4.8}$$

$$n = \frac{95.73 Ksi}{34.12 Ksi}$$

$$n = 2.81$$

4.2.2 Analysis for cyclic load

This helical spring of compression has the following technical specifications:

Material: ASTM A232 (Wire of steel to the chrome vanadium) [15].
Squared and ground end, left hand [20].

Number of active spires $N_a = 8$

Total number of spires $N_t = N_a + 2 = 10$

Free longitude $L_f = 4.0 in$

External diameter $Do = 1.0 in$

Diameter of the wire d = 0.080 in

Mean diameter D = Do – d = 0.92 in

Spring index C = D/d = 11.5

To calculate springs, C will vary approximately from 6 to 12; for C < 4 will be difficult to fabricate and for C > 12 the spring tends to the bulge [15].

The spring constant K and solid height Ls [21] should be determined:

$$K = \frac{d^4 G}{8 D^3 Na} \tag{4.1a}$$

$$K = \frac{(0.080)^4 (11.5x10^6)}{8(0.92)^3 (8)}$$

$$K = 9.45 lbf / in$$

$$Ls = (N_t + 1)d \tag{4.2a}$$

$$Ls = (10 + 1)(0.080 in)$$

$$Ls = 0.88 in$$

Now the shear stress amplitude τ_a and the mean shear stress τ_m should be founds with the next equations that applies so much for cyclic load; this analyses takes in consideration an infinite duration [17]:

$$\tau_a = Kb \frac{8F_a D}{\pi d^3} \tag{4.3a}$$

$$\tau_m = Ks \frac{8F_m D}{\pi d^3} \tag{4.3b}$$

Where:

Kb = factor of Bergstrasser

Ks = factor of correction for shear stress

Fa = stress amplitude

Fm = mean stress

Kb is calculated for the equation:

$$Kb = \frac{4C+2}{4C-3} \tag{4.9}$$

$$Kb = \frac{4(11.5)+2}{4(11.5)-3}$$

$$Kb = 1.12$$

Now Ks is calculated, as mentioned previously in equation (4.4).

$$Ks = \frac{2C+1}{2C}$$

$$Ks = \frac{2(11.5)+1}{2(11.5)}$$

$$Ks = 1.04$$

The values of Fa and Fm are defined for the equations

$$Fa = \frac{F\max - F\min}{2} \tag{4.10}$$

$$Fm = \frac{F\max + F\min}{2} \tag{4.11}$$

The spring will work with a maximum load $F\max$ of 23.63 lbf and minimum load $F\min$ of 16.54 lbf (See table 3.1); therefore $Fa = 3.55lbf$ and $Fm = 20.09lbf$, now replacing all the obtained values in equations (4.3a) and (4.3b).

$$\tau_a = Kb\frac{8F_aD}{\pi d^3} \tag{4.3a}$$

$$\tau_a = 1.12\frac{8(3.55lbf)(0.92in)}{\pi(0.080in)^3}$$

$$\tau_a = 18.19Ksi$$

$$\tau_m = Ks\frac{8F_mD}{\pi d^3} \tag{4.3b}$$

$$\tau_m = 1.04\frac{8(20.09lbf)(0.92in)}{\pi(0.080in)^3}$$

$$\tau_m = 95.60Ksi$$

In table 4.1 is selected a material ASTM A232 for the helical spring where A=173 ksi and m=0.155; with this values the minimum stress resistance S_{ut} is calculated.

$$S_{ut} = \frac{A}{d^m} \tag{4.6a}$$

$$S_{ut} = \frac{173kpsi}{(0.080)^{0.155}}$$

$$S_{ut} = 255.90Ksi$$

Now using the equation of Joerres; the shear module to the rupture $S_{su} = 0.67S_{ut}$

$$S_{su} = 0.67S_{ut} \tag{4.12}$$

$$S_{su} = 0.67(255.90Ksi)$$

$$S_{su} = 171.45 Ksi$$

So then this value of S_{ut}, limit of fatigue $S_{se} = 45 Ksi$ or $S_{se} = 67.5 Ksi$ (obtained values for Zimmerli investigator) [17], τ_a and τ_m should be substituted in the next equation for find the safety factor n.

$$n = \frac{S_{se} S_{su}}{\tau_a S_{su} + \tau_m S_{se}} \tag{4.11}$$

$$n = \frac{67.5 Ksi (171.45 Ksi)}{(18.19 Ksi)(171.45 Ksi) + (95.60 Ksi)(67.5 Ksi)}$$

$$n = 1.21$$

The safety factor is 1.21, it is appropriate for the design that is subjected to cyclic load. This helical spring will allow the handling of natural gas fuel that is use for another type of regulator.

4.3 DESIGN SPECIFICATIONS

The design specifications for the spring helical designed can be appreciated in the following tables.

Table 4.2 Helical spring for static load design specifications

Material:	ASTM A227
K	40.38 lbf/in
Ls	1.232 in
Na	8
Nt	10
Lf	4.0 in
Do	1 in
d	0.112 in
D	0.888 in
C	7.93
Type of ends:	Closed and grinding ends

Table 4.3 Helical spring for cyclic load design specifications

Material:	ASTM A232
K	9.45 lbf/in
Ls	0.88 in
Na	8
Nt	10
Lf	4.0 in
Do	1 in
d	0.080 in
D	0.92 in
C	11.5
Type of ends:	Squared and ground end, left hand

When comparing the tables of the design specifications for the helical spring (Fig 4.2 and Fig 4.3), you can appreciate that some specifications have the same similarity. The spring that was used in the tests was the calculated in cyclic load, for the condition in this case.

5 DESIGN OF CALIBRATION SYSTEM

This design of calibration system can be operated only for the 800 JBC second stage Sherwood Regulator. The design specifications involved in the calculation, allows a better use and safety system.

5.1 CALIBRATION SYSTEM

The main parameters of calibration system used in the test are as follows:

Inlet pressure: 1 psig, 5 psig and 15 psig.
Outlet pressure: 11 "W.C.
Test fluid: Compressed air

The design of calibration system is composed basically of a piping line for inlet flow; the Sherwood Regulator which will be calibrated, one piping line for outlet flow and lastly the flow controller orifice **0c** (Fig. 5.1).

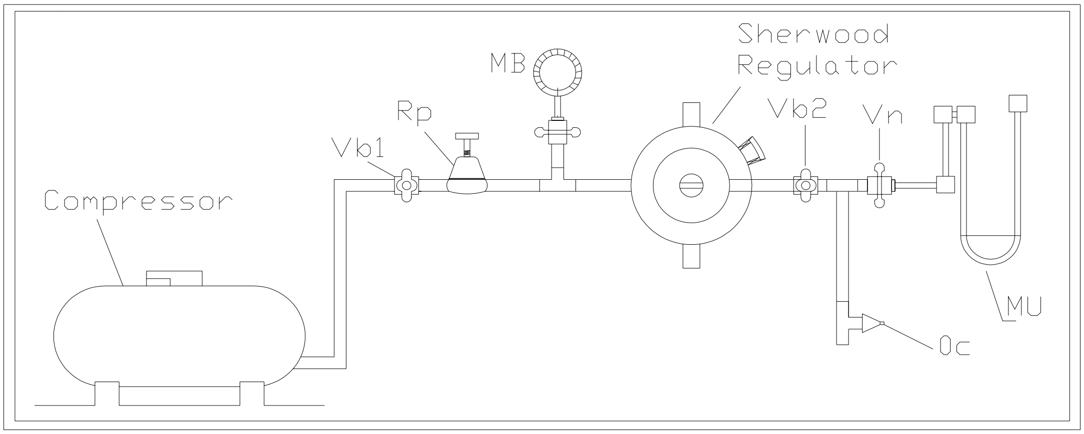

Figure 5.1 Calibration system

The following table shows the components of the calibration system.

Table 5.1 Components of calibration system

QUANTITY	COMPONENTS
1	Compressor
2	Ball valves (Vb)
1	Pilot-operated regulator (Rp)
1	Bourdon manometer (Range: 0 psig – 30 psig)
1	800 JBC Sherwood Regulator
1	Needle valve (Vn)
1	U Manometer (0 “W.C – 11 “W.C)
1	Flow controller orifice (**0c**)

5.2 ORIFICE CALCULATION

The objective of this orifice calculation is to obtain the equivalent flow rate of liquefied petroleum gas and natural gas by using compressed air.

5.2.1 Orifice calculation for LP-Gas

The correction factor is found, according to the following equation [13]:

$$Fc = \sqrt{G_{LP-G} / G_A} \tag{5.1}$$

$$Fc = \sqrt{1.53 / 1.0}$$

$$Fc = 1.24$$

Where:

Fc = Correction factor

G_{LP-G} = Specific gravity of the LP-Gas

G_A = Specific gravity of the Air

Q_A = Theoretical flow rate

Now, we use the value Fc and the flow rate in calibration of 50 s.c.f.h (standard cubic foot per hour) to find Q_A.

$$Q_A = Q_{LP-G}(1.24) \tag{5.2}$$

$$Q_A = 50 \text{ s.c.f.h. } (1.24)$$

$$Q_A = 62 \text{ s.c.f.h}$$

Thus, replacing the value obtained in Equ. 5.3, we obtain:

$$Q = 1658.5[C][A]\left[\frac{h}{G}\right]^{0.5} \tag{5.3}$$

$$A = \frac{Q_A}{[1658.5][C]\left[\frac{h}{G}\right]^{0.5}}$$

Where:

Q = Flow rate through of the orifice

Cn = Coefficient of nozzle (0.9)

A = Orifice area (in^2)

h = Test pressure ("W.C.)

G = Specific gravity of Gas (Air)

$$A = \frac{62}{[1658.5][0.9]\left[\frac{11}{1.0}\right]^{0.5}}$$

$$A = 0.01252 \ in^2$$

The orifice area is 0.01252 in^2 and now should be selected by table 5.2 [16] to find the orifice diameter.

Table 5.2 Orifices DMS

ORIFICE DMS	DIAMETER (in)	AREA (In^2)	ORIFICE DMS	DIAMETER (in)	AREA (in^2)
1	0.2280	0.04083	36	0.1065	0.00891
2	0.2210	0.03836	37	0.1040	0.00849
3	0.2130	0.03563	38	0.1015	0.00809
4	0.2090	0.03431	39	0.0995	0.00778
5	0.2055	0.03317	40	0.0980	0.00754
6	0.2040	0.03269	41	0.0960	0.00724
7	0.2010	0.03173	42	0.0935	0.00687
8	0.1990	0.03110	43	0.0890	0.00622
9	0.1960	0.03017	44	0.0860	0.00581
10	0.1935	0.02941	45	0.0820	0.00528
11	0.1910	0.02865	46	0.0810	0.00515
12	0.1890	0.02806	47	0.0785	0.00484
13	0.1850	0.02688	48	0.0760	0.00454
14	0.1820	0.02602	49	0.0730	0.00419
15	0.1800	0.02545	50	0.0700	0.00385
16	0.1770	0.02461	51	0.0670	0.00353
17	0.1730	0.02351	52	0.0635	0.00317
18	0.1695	0.02256	53	0.0595	0.00278
19	0.1660	0.02164	54	0.0550	0.00238
20	0.1610	0.02036	55	0.0520	0.00212
21	0.1590	0.01986	56	0.0465	0.00170
22	0.1570	0.01936	57	0.0430	0.00145
23	0.1540	0.01883	58	0.0420	0.00139
24	0.1520	0.01815	59	0.0410	0.00132
25	0.1495	0.01755	60	0.0400	0.00126
26	0.1470	0.01697	61	0.0390	0.00119
27	0.1440	0.01629	62	0.0380	0.00113
28	0.1405	0.01550	63	0.0370	0.00108
29	0.1360	0.01453	64	0.0360	0.00102
30	**0.1285**	**0.01297**	65	0.0350	0.00096
31	0.1200	0.01131	66	0.0330	0.00086
32	0.1160	0.01057	67	0.0320	0.00080
33	0.1130	0.01003	68	0.0310	0.00075
34	**0.1110**	**0.00968**	69	0.0292	0.00067
35	0.1100	0.00950	70	0.0280	0.00062

Hence, **A = 0.01297** in^2**, D =** $0.1285\ in$ and the orifice number is **DMS 30**.

Lastly the flow rate $Q_{A'}$ to test is calculated [6]:

$Q = 1658.5[C][A]\left[\frac{h}{G}\right]^{0.5}$; as mentioned previously in Equ. (5.3)

Where:

Q = Flow rate through of the orifice (s.c.f.h)

Cn = Coefficient of nozzle (0.9)

A_T = Orifice area by table (in^2)

h = Test pressure ("W.C.)

G_{LP-G} = Specific gravity of the converted Gas (LP-Gas)

$$Q_{A'} = 1658.5[C][A_T]\left[\frac{h}{G_{LP-G}}\right]^{0.5} \tag{5.3a}$$

$$Q_{A'} = 1658.5[0.9][0.01297]\left[\frac{11}{1.53}\right]^{0.5}$$

$$\mathbf{Q_{A'} = 52\ s.c.f.h}$$

Now, the orifice calculation for natural gas is presented.

5.2.2 *Orifice calculation for NG*. The correction factor is found, according to the following equation [13]:

$$Fc = \sqrt{G_{NG}/G_A} \tag{5.1b}$$

$$Fc = \sqrt{0.6/1.0}$$

$$Fc = 0.775$$

Where:

Fc = Correction factor

G_{NG} = Specific gravity of the Natural Gas.

G_A = Specific gravity of the Air.

Q_A = Theoretical flow rate

Now, we use the value Fc and the flow rate in calibration of 50 s.c.f.h to find Q_A:

$$Q_A = Q_{NG}(0.775) \tag{5.2b}$$

$$Q_A = (50 \text{ s.c.f.h})\,(0.775)$$

$$Q_A = 38.75 \text{ s.c.f.h}$$

Thus, replacing the value obtained in Equ. 5.3, we obtain:

$$Q = 1658.5[C][A]\left[\frac{h}{G}\right]^{0.5} \tag{5.3}$$

$$A = \frac{Q_A}{[1658.5][C]\left[\frac{h}{G}\right]^{0.5}}$$

Where:

Q = Flow rate through of the orifice

C = Coefficient of nozzle (0.9)

A = Orifice area (in^2)

h = Test pressure ("W.C.)

G = Specific gravity of the Gas (Air)

$$A = \frac{38.75}{[1658.5][0.9]\left[\frac{7}{1.0}\right]^{0.5}}$$

$$A = 0.00981\ in^2$$

The orifice area is 0.00981 in^2 and now should be selected by table 5.2 [17] to find the orifice diameter.

Hence, **A = 0.00968** in^2**, D = 0.1110** in and the orifice number is **DMS 34**. Lastly the flow rate $Q_{A'}$ to test is calculated [6]:

$Q = 1658.5[C][A]\left[\frac{h}{G}\right]^{0.5}$; as mentioned previously in Equ. (5.3)

Where:

Q = Flow rate through of the orifice (s.c.f.h)

C = Coefficient of nozzle (0.9)

A_T = Orifice area by table (in^2)

h = Test pressure ("W.C.)

G_{NG} = Specific gravity of the converted Gas (NG)

$$Q_{A'} = 1658.5[C][A_T]\left[\frac{h}{G_{NG}}\right]^{0.5} \tag{5.3a}$$

$$Q_{A'} = 1658.5[0.9][0.00968]\left[\frac{7}{0.6}\right]^{0.5}$$

$$Q_{A'} = \mathbf{49.35\ s.c.f.h}$$

5.3 TEST AND CALIBRATION PROCEDURE

The test procedure begins verifying the inlet pressure required for the calibration of the Sherwood Regulator that may be of 1 psig, 5 psig or 15 psig; in these tests the inlet pressure is 15 psig.

It must be verified because it could be operating under normal conditions and then calibration is not necessary.

The flow controller orifice **0c** should be connected before to start the test. The spring that required the calibration is tested for displacements different; therefore the tests were made for twelve positions of the spring using a flow rate of **52 s.c.f.h** (LP-Gas) and **49.35 s.c.f.h** (NG).

The calibration starts adjusting the outlet pressure of the regulator by rotating the screw located inside the plastic cap. It is calibrated as follows: to increasing the pressure, rotate the screw clockwise and to reduce it, rotate it counter clockwise.

The limits in the adjustment range for the outlet pressure of the regulator are between 9 "W.C. and 13 "W.C. The set point is 11 "W.C and it should be verified because of the hysteresis phenomena presence in the loading spring.

This phenomenon can be minimized with the stabilization time, which is about twenty minutes. After this time the calibrations is repeated and the test is finished.

5.4 RESULTS

These results have been obtained after many tests. The figure 3.5 shows that the displacement of the helical spring presents changes in the outlet pressure. Hence, it is possible to appreciate the spring compression effect and their influence in the regulator.

This analysis is development with the same spring for liquefied petroleum gas and natural gas, therefore for the tests an orifice was used for each type of fuel. Next it is shown in the table 5.3 the orifices and the flow rates that intervened in the different tests.

Table 5.3 Orifices and flow rates for the tests

Liquefied	Petroleum	Gas	LP-Gas		Natural	Gas	NG
Area (in²)	Diameter (in)	Orifice Number	Flow Rate (s.c.f.h)	Area (in²)	Diameter (in)	Orifice Number	Flow Rate (s.c.f.h)
0.01297	0.1285	DMS 30	52	0.00968	0.1110	DMS 34	49.35

The graph (Fig. 3.5) shows us the spring compression effect on the outlet pressure in the displacement range between 0 in and 2.50 in. The range is small and it allows that the spring works for LP-G and natural gas; with the design specifications corresponding. In the graph it can be appreciate; the phenomenon of proportional band is 4.37 "W.C. into of the two cases (LP-G and NG).

6 CONCLUSION

6.1 CONCLUSIONS

I order to probe and calibrate any kind of pressure gas regulators in Puerto Rico, it is necessary to implement a device able to operate two variables which are pressure and flow rate. In the analysis and design of this device it is important to make different considerations such as safety factor for the whole system, the appropriate flow rate based on the type of regulator, and flow control. Finally, if the design and manufacture of this device is required, it is mandatory to follow the standards and norms of Puerto Rico.

The self-operated regulator stills in continuous research due to the importance in the gas industry and sectors alike. Knowing the different regulation stages and the day to day problems in the industrial security, it is possible to improve the design of complex distribution lines for LP-gas and natural gas.

Knowing the parameters directly related with the Sherwood Regulator performance, it is possible to see the complexity of this self-operated regulator type, which several tests were done to finally verify the essential elements and prove where the performance increases and in what proportion. The performance of the 800 JBC Sherwood Regulator is based on the diaphragm, spring, and inlet pressure. During the tests a bigger emphasis was made on the helical spring and other parameters were studied following the equation analysis under operative restrictions.

The spring effect can show the different deviations, the increment at the diaphragm area allows the decrease in the outlet pressure, followed by an increment in the pressure drop that can be calculated based on the conditions of the process.

The effect of the helical spring compression was analysed over the outlet pressure in the regulator, taking in consideration the maximum and minimum flow, the spring elasticity constant, the area of the diaphragm and displacements; it was also possible to obtain data for computing finally the pressure drop and to relate the helical spring behaviour when is employed not only as a liquefied petroleum gas but also as a natural gas.

The pressure drop of Sherwood Regulator was calculated and its value is 0.11 psi due to an increment of 1 psig in the inlet pressure.

To obtain a better regulator systems performance it is recommended to use single stage or two stage regulation that depend on the application residential, commercial or industrial type.

The helical spring was designed for cyclic load with safety factor of 1.21 and through this spring was possible to relate the propane gas and propane gas fuel that are shown in table 3.1.

Different controlled tests have been realized in Colombia, they have shown that the spring designed and manufactured for the Sherwood Regulator can be used to supply natural gas as a fuel.

Determination of the orifice diameter allows the using of the orifice controller **0c** for LP-Gas and natural gas, according to the test and calibration in the 800 JBC Sherwood Regulator.

For the design and manufacture of self-operated pressure regulators, the relationship between the diaphragm area and the seat area is a relevant factor for determining the precision and sensibility of the equipment.

6.2 FUTURE WORK

- To optimize the design according to the requirements of the manufacturing company or business that distributes it.
- To manufacture and test the regulator.

7 REFERENCES

[1] **Rego Products.** 1993.
http://www.regoproducts.com

[2] **Sherwood LP-Gas Products.** 1999.
http://www.Sherwoodvalve.com/pdf/lpg.pdf

[3] **Regulators for hydraulic systems.**
http://www.google.com

[4] **Nabi A, Wacholder E and Dayan J.** 1997. Dynamic Model for a Dome–Loaded Pressure Regulator. Journal of Dynamic Systems, Measurement, and Control, 290/Vol 122, June 2000.

[5] **Latyshev I, Maliovanov V and Petrov A**. 1987. Dynamics of a gas pressure regulator with attached piping. Aviatsionnaia Tekhnika (ISSN 0579–2975), Vol. 3, 87-90. (Source: **STI**).

[6] **Sánchez L, Coronado L and Barrera O. A.** 2001. Diseño y construcción de un dispositivo para probar y calibrar reguladores de gas natural y GLP. Tesis B.S. Universidad Incca de Colombia, Bogotá D.C., BT 5351 CDU 622.279, Marzo 15/2001, 450 pp.

[7] **Dragoljub V and Slobodan R.** 2001. Dynamic model of gas pressure regulator. Journal of Mechanics, Automatic Control and Robotics, Vol 3, **Nº** 11, pp. 269-276. UDC 533.15 (045).

[8] **Bill Hobson.** 1997. Careful analysis should guide gas pressure regulator choice. Pipe Line & Gas Industry Journal, June 1997, http://www.afms.org/gaslib.htm

[9] **Chris Carmichael.** 1996. Gas regulators work by equalizing opposing forces. Pipe Line & Gas Industry Journal, Dec 1996.

[10] **Rick F. Mooney.** 1999. Pressure regulator selection based on performance, design. Pipe Line & Gas Industry Journal. May 1999, http://www.askache.com/inTechY2.htm

[11] **Pam Ryan.** 1997. Instrument-controlled valves precisely regulate high flows. Pipe Line & Gas Industry Journal. Oct 1997.

[12] **Gas Natural E.S.P,** Principios de regulación, dimensionamiento y selección de Reguladores. Información del fondo de empleados de gas natural E.S.P "FAGAS", 1ª edición, 177 pp.

[13] **LP–Gas Serviceman's Manual,** 1993. Engineered Controls International, Inc., ECII. http://www.regoproducts.com/Old/LPmanual.htm

[14] **Shigley E. J. and Mischke C. R.** 1990. Mechanical engineering design, McGRAW-HILL, Inc., U.S.A, 5th edition, 856 pp.

[15] **Shigley E. J. and Mischke C. R.** 1995. Elementos de maquinaria MECANISMOS, McGRAW-HILL/Interamericana de México, S.A de C.V, 1ª. Edición, Tomo 1, 217 pp.

[16] **SAENA de Colombia Ltda**. 1983. http://www.empresario.com.co/saena/

[17] **Shigley E. J. and Mischke C. R.** 1990. Diseño en ingeniería mecánica, McGRAW-HILL/Interamericana de México, S.A de C.V, 5ª. Edición, 883 pp.

[18] **Erdman A. G. and Sandor G. N.** 1991. MECHANISM DESIGN Analysis and Synthesis, Prentice Hall, Englewood Cliffs, New Jersey 07632, 2nd edition, 631 pp.

[19] **Norton Robert L.** 1999. DESIGN OF MACHINERY An Introduction to the synthesis and Analysis of Mechanisms and machines, McGRAW HILL Inc., U.S.A, 2nd edition, 809 pp.

[20] **Shigley E. J.** 1963. ENGINEERING DESIGN, McGRAW HILL Inc., U.S.A, 1st edition, 883 pp.

[21] **Juvinall R. C. and Marshek K. M.** 2000. FUNDAMENTALS OF MACHINE COMPONENT DESIGN, JOHN WILEY & SONS, Inc., U.S.A, 3rd edition, 888pp.