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GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

ENERGY RECOVERY AT NATURAL GAS PRESSURE REDUCTION STATIONS

M. Sc. Thesis by

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Department of Mechanical Engineering

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İnan Uğur YÜCEER

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M.Sc. THESIS EXAMINATION RESULT FORM

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2020, 9 September **İnan Uğur YÜCEER**

ENERGY RECOVERY AT NATURAL GAS PRESSURE REDUCTION STATIONS

ABSTRACT

The energy need of our world increases day by day, but it is seen that the resources are decreasing. For this reason, we need to use our energy more efficiently in every field. This is inevitable, especially for our country, which provides the majority of its energy needs as imported. It is essential to examine all stages of energy consumption to study efficiency and recovery. The amount of natural gas usage in the world and our country is increasing over the years. Natural gas, which is consumed in many areas, enters our country through the national distribution network. Natural gas transported with high pressure is reduced to the desired pressure value for consumers with pressure reduction and measurement stations. In these stations, natural gas is filtered, heated before pressure drop, flow rate measured, and pressure reduced. Gas pressure is reduced by throttling. Meanwhile, sudden drops in the temperature of the gas are observed due to the Joule-Thomson effect. This undesirable situation can damage the pilot controlled regulator due to freezing of the water vapor contained in the gas and the formation of hydrate. Natural gas is heated before it enters the regulator to prevent this. In studies on energy recovery in natural gas stations, it is recommended to use vortex pilot gas heaters in the station to reduce the cost of this preheating process. In this study, the advantages of using a vortex tube and its effect on cost have been examined through a station in Ankara. Using the data of this station for the years 2016-2019, preheating fuel consumption before and after the use of the vortex tube was calculated, and the consumption amounts were compared. In addition, artificial neural network modeling has been made in the study. After completing the training of the model with the data for the specified years, a test was carried out on a monthly value of 2020. Thus, the effectiveness of the vortex tube application in energy recovery was supported, and a resource was provided to other stations to calculate the savings they would achieve if they used a vortex tube.

Keywords: Vortex tube, artificial neural network, natural gas stations.

DOĞAL GAZ BASINÇ DÜŞÜRME İSTASYONLARINDA ENERJİ GERİ KAZANIMI

ÖZ

Gün geçtikçe dünyamızın enerji ihtiyacı artmakta fakat kaynakların azaldığı görülmektedir. Bu nedenle her alanda enerjimizi daha verimli kullanmamız gerekmektedir. Özellikle enerji ihtiyacının büyük çoğunluğunu dışa bağımlı olarak sağlayan ülkemiz için bu durum kaçınılmazdır. Enerji tüketiminin tüm aşamalarını inceleyerek verimlilik ve geri kazanım üzerine çalışmak önem arz etmektedir. Dünya ve ülkemizde doğal gaz kullanım miktarı yıllara göre artmaktadır. Bir çok alanda kullandığımız doğal gaz ulusal dağıtım şebekesi üzerinden ülkemize giriş yapar. Yüksek basınç ile taşınan doğal gaz, basınç düşürme ve ölçüm istasyonları ile tüketiciler için istenilen basınç değerine düşümü sağlanır. Bu istasyonlarda doğal gaz filtrelenir, basınç düşümü öncesi ısıtılır debisi ölçülür ve basıncı düşürülür. Gaz basıncının düşürülmesi kısılma ile sağlanmaktadır ve bu esnada Joule-Thomson etkisine bağlı olarak gazın sıcaklığında ani düşüşler gözlemlenir. Bu istenmeyen durum, gazın içinde bulunan su buharının donması ve hidrat oluşması nedeniyle pilot kontrollü regülatöre hasar verebilir. Bunu önlemek amacıyla doğal gaz, regülatöre girmeden önce ısıtılır. Doğal gaz istasyonlarında enerji kazanımı üzerine yapılan araştırmalarda bu ön ısıtmanın işlem maliyetini düşürmek için istasyonda vorteks pilot gaz ısıtıcıları kullanımı tavsiye edilmektedir. Bu çalışmada, vorteks tüp kullanımın avantajları ve maliyet üzerindeki etkisi Ankara'da bulunan bir istasyon üzerinden incelenmiştir. Bu istasyona ait 2016-2019 yıllarına ait veriler aracılığıyla vorteks tüp kullanım öncesi ve sonrası ön ısıtma yakıt tüketimleri hesaplanarak tüketim miktarları karşılaştırılmıştır. Ayrıca yapılan çalışmada yapay sinir ağı modellemesi yapılmıştır. Belirtilen yıllara ait veriler ile modelin eğitimi tamamlandıktan sonra 2020 yılına ait bir aylık değer üzerinden test yapılmıştır. Böylece enerji geri kazanımı konusunda vorteks tüpü uygulamasının etkililiği desteklenmiş ve diğer istasyonlara vorteks tüpü kullanmaları halinde sağlayacakları tasarrufu hesaplamada bir kaynak sunulmuştur.

Anahtar Kelimeler: Vorteks tüp, yapay sinir ağı, doğal gaz istasyonları.

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NOMENCLATURE

Roman Letter Symbols

c	Specific heat, kJ/kgK
h	Enthalpy, kJ/kg
$\dot{m}$	Mass flow rate, kg/s
$\dot{m}$	Mass flow rate, kg/s

Greek Letter Symbols

η	Efficiency (%)
μ	Joule-Thomson coefficient
ν	Specific volume of fluid, m^3/kg

Acronyms

ANN	Artificial Neural Network
bcm	billion cubic meters
BOTAŞ	Petroleum Pipeline Company
CNG	Compressed Natural Gas
LHV	Lower heating value
LNG	Liquefied Natural Gas
MEP	Mean Error Percentage
R^2	Absolute Fraction of Variance
RMS	Reduction and Measurement Station
RMSE	Root Mean Square Error
VT	Vortex Tube
VPGH	Vortex Pilot Gas Heater

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CHAPTER 1

INTRODUCTION

Energy has become one of the main factors affecting the economic, political, and social development of countries and their relations with other countries in its world today. Besides, the increase in consumption of energy and the expectation that this continued increase causes the desire of the countries to access their energy resources cheaply, uninterruptedly, and reliably.

It should not be forgotten that natural resources are not unlimited. It is predicted that with the rapid increase in the world population, it will double in 2050 and will reveal an energy demand in proportion to this increase. Considering that resources are limited and energy costs are increasing, it becomes clear how important energy recovery is.

Energy efficiency simply means using or consuming less energy and the most important factor is energy conservation. Energy conservation is essential to minimize the amount of consumed energy and usage of current energy losses. Methods such as preventing energy losses in heat, gas, steam, air, and electricity, recovery, and evaluation of various wastes, or reducing energy demand without decreasing production value with advanced technology, are energy efficiency issues.

1.1 Fundamentals of Natural Gas and Properties

Natural gas seemed a mysterious event before people understood what it was. Many civilizations have been amazed at the burning of underground gas leaks, for example, due to lightning strikes, and these events have been the root of many superstitions, a sign created from the depths of the earth. Natural gas leaks were found in Iran between 6000 and 2000 BC. The first use of gas in history was by the Chinese, and they used flames from gas leaks. By determining the areas where there are gas leaks, they carried the gas to various regions with pipelines made of bamboo and obtaining salt from seawater by boiling. Marco Polo detected the source of the fire at Zoroastrian temple that has been burning for centuries is natural gas. Natural gas was not known in Europe

until 1659. Its first discovery was in England. Coal gas was used commercially so natural gas has not been popular. Natural gas was first introduced to modern production and consumption techniques in the United States. In 1815, natural gas was discovered in a salt-brine well. In 1821, William Hart drilled the first natural gas well in the United States. At first, it carried the gas with wooden pipes and then replaced it with lead pipes. The first industrial use was salt production in West Virginia, USA, in 1841. Fredonia Gas Light Company, which is the first commercial enterprise, was founded in New York in 1858. In the 1920s seamless steel pipes which are used today were produced. These pipes with their high strength helped to transport gas under higher pressures and in larger quantities. The growth in gas use is in the early twentieth century. With the shortage of crude oil in the late 1960s and early 1970s, natural gas became the center of fossil energy resources. Since natural gas is a clean fuel today, it is extremely important for heating, cooking, and electrical energy production [1][2].

Natural gas is included in fossil fuels. It has been formed as a result of millions of years of natural transformation in the lower layers of the earth and can be used without any treatment as it is removed from its source. Figure 1.1 shows a schematic diagram of earth crust's regions, which represent the gas reserves and drilling rig [3][4].

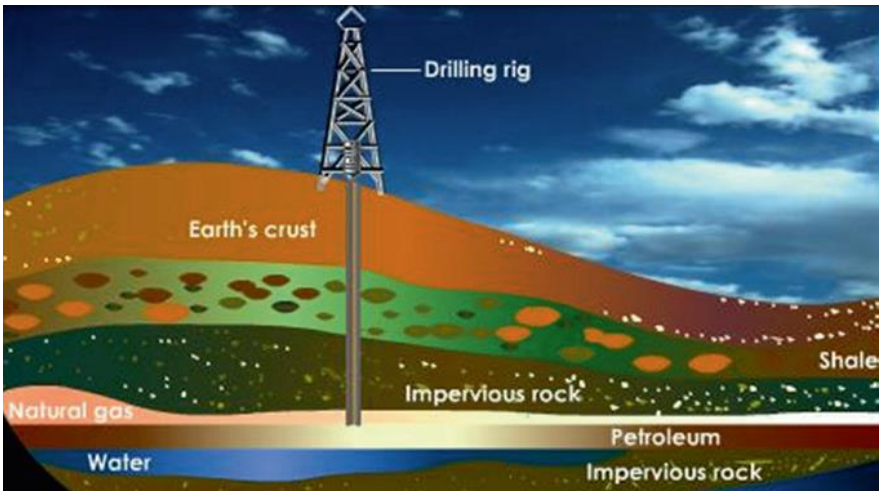

Figure 1.1 Natural gas reserves profile[3].

Natural gas contains mainly methane (CH_4) (90% and above) and lower rates of ethane (C_2H_6), propane (C_3H_8) and other heavier hydrocarbons, low rates of nitrogen (N_2),

oxygen (O_2), carbon dioxide (CO_2) may contain impurities such as sulfur compounds and water. The composition of gas depends on the reservoir in which they are produced. Table 1.1 shows that gas composition and combustion characteristics [4].

Table 1.1 Composition of natural gas [3].

Fuel composition and properties	**Natural gas**	**Energy crop (switch grass)**	**Typical wood gas**	**Agricultural wastes**
Methane (CH_4)	93.77	4.,50	4	4.4
Ethane (C_2H_6)	2.6	0	0	0
Propane (C_3H_8)	0.37	0	0	0
Butane (C_4H_{10})	0.1	0	0	0
Higher hydrocarbons	0	1.89	0	2.8
Carbon monoxide (CO)	0	15.25	18	10.2
Carbon dioxide (CO_2)	1.02	17.77	10	14.8
Hydrogen (H_2)	0	4.18	19.5	11.7
Water vapour	0	0	4	5.7
Nitrogen (N_2)	2.14	56.41	44.5	50.4
Wet fuel molecular weight (kg/kmol)	17.1	29.2	23.7	-
Lower heating value (kJ/kg)	46,787	3,913	5,622	5,094
Lower heating value (kJ/Nm^3)	35,679	5,103	5,977	6,053
Stoich air/fuel ratio (volume based)	9.51	1.16	1.31	1.41
Energy content of stoich mixture (kJ/Nm^3)	3,396	2,358	2,583	2,514
Approximate temperature rise of stoich mixture (K)	2,411	1,669	1,882	1,788

Its most important feature is that it is a clean fuel and less harmful to the environment. Since it is in the form of gas, it creates a better mixture with air and easily burn. When the air-gas mixture burns completely, it creates a blue flame. Since it is in the form of

gas, it has the possibility to be controlled more precisely. Another feature of it is colorless, odorless, non-toxic, and lighter than air. Insomuch it is odorless, its leakage cannot be detected or noticed, and some scent material is specially added. Tetrahydrothiophene (THT) or tert-butyl mercaptan (TBM) are used as an odorant agent. Other chemical and physical properties of natural gas can be seen in Table 1.2.

Table 1.2 Properties of natural gas [1].

Properties	Value
Relative molar mass	17-20
Carbon content, weight %	73.3
Hydrogen content, weight %	23.9
Oxygen content, weight %	0.4
Hydrogen/carbon atomic ratio	3.0-4.0
Relative density, 15 °C	0.72-0.81
Boiling point, °C	-162
Autoignition temperature, °C	540-560
Octane number	120-130
Methane number	69-99
Stoichiometric air/fuel ratio, weight	17.2
Vapor flammability limits, volume %	May.15
Flammability limits	0.7-2.1
Lower heating/calorific values, MJ/kg	38-50
Stoichiometric lower heating value, MJ/kg	2.75
Methane concentration, volume %	80-99
Ethane concentration, volume %	2.7-4.6
Nitrogen concentration, volume %	0.1-15
Carbon dioxide concentration, volume %	1.May
Sulfur concentration, weight % ppm	<5
Specific CO_2 formation, g/MJ	38-50

Natural gas is an energy source that is more compatible with the environment, does not pollute the air, and does not harm the environment compared to other fossil energy sources. Natural gas does not produce waste materials such as sulfur oxides and carbon particles that pollute the air when it burns.

When natural gas is cooled to approximately -164 °C at atmospheric pressure, it liquefies, and its volume shrinks 600 times. The liquefied natural gas is called Liquefied Natural Gas (LNG). Since pollutants are removed during liquefaction, LNG Natural Gas is cleaner compared to natural gas. Liquefied Natural Gas can be stored and transported in special tanks. Highly pressurized natural gas by compressors is

called Compressed Natural Gas (CNG). It provides energy-saving since it is more suitable for automatic control during combustion. When mixed with air, the burning limits are between 5% and 15% by volume. In order for the natural gas to burn, its mixture with air must be in an appropriate ratio. The best combustion mixture is 9% Natural Gas and 91% air. The ignition temperature of natural gas is about 650 °C.

1.2 Natural Gas Market in the world and Turkey

Natural gas has an important place among energy resources due to its strategic and commercial advantages. The natural gas market is an international market that covers resource management and marketing methods on a country basis. International conventions on natural gas supply and demand between countries are common. In addition, each country has its own regulations that determine the distribution and trade of natural gas. Figure 1.2 shows the large-scale natural gas trade in the world in 2018.

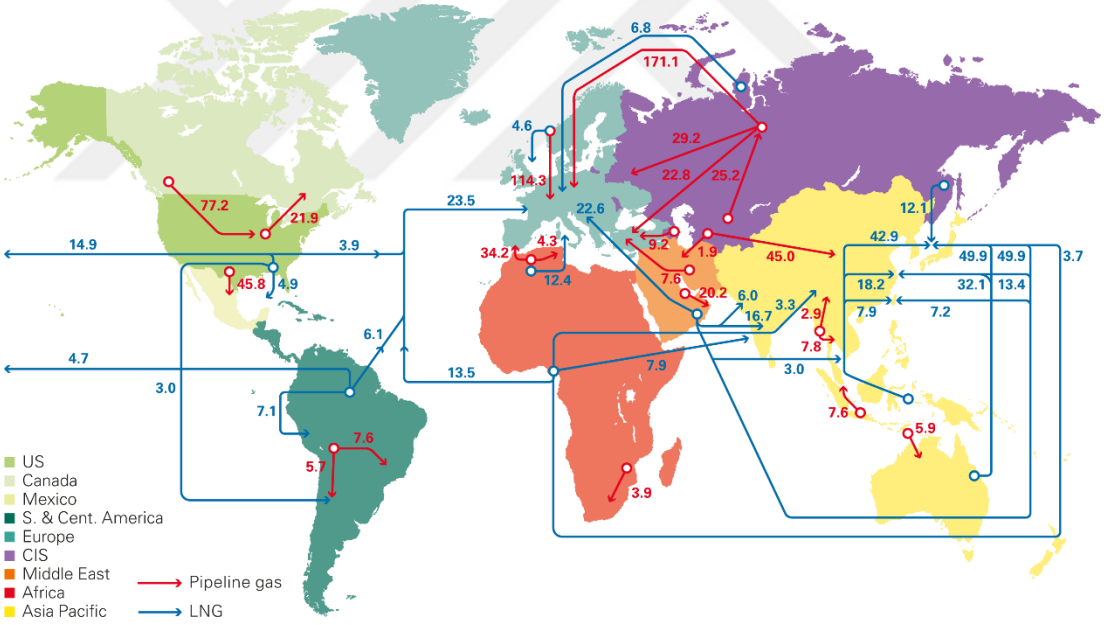

Figure 1.2 Natural gas trade in the world in 2018 (trade flows worldwide (billion cubic meters)) [5].

World natural gas reserves, which were 193.1 trillion m^3 in 2016, increased by 0.2% in 2017 and were recorded as 193.5 trillion m^3. 40.9% of the world's natural gas reserves are in the Middle East, 30.6% in Eurasia, 10% in the Asia Pacific, 7.1% in Africa, 5.6% It is located in North America, 4.2% in Central and South America, and

1.5% in Europe (Figure 1.3). The natural gas reserve of OECD (Organization for Economic Co-operation and Development) countries is 17.8 trillion m^3 and it is 9.2% of the total reserve.

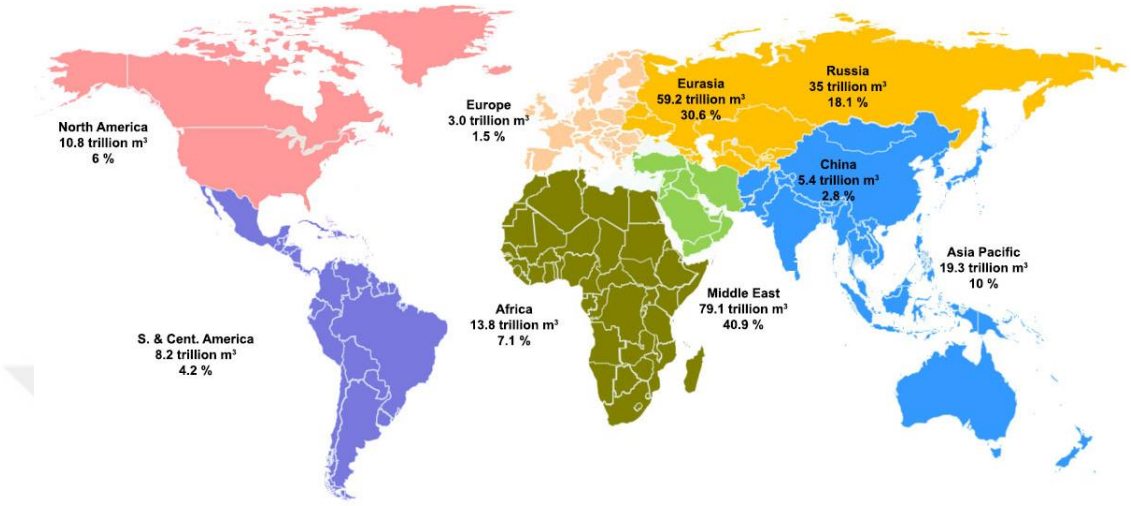

Figure 1.3 Distribution of world proved natural gas reserves in 2017.

It has been developed in three different scenarios in the studies on the future of gas in the energy world. It was observed that the use of gas increased in these scenarios. The first scenario is called the modern Jazz scenario. According to this, the use of gas in the world is supported by environmental problems and increased sector awareness. As a result, gas is the world's primary energy source until 2050. Gas demand will grow by over 70% between 2014-2050. The second one, the Unfinished Symphony scenario, is more focused on decarbonization and contributes greatly to the carbon removal of the electricity sector by increasing gas use. In the longer term, renewable energy is gradually being introduced. The last scenario is Hard Rock. Coal has an important role in the Hard Rock scenario because it is abundant and cheap. Gas use is supported by environmental concerns. Figure 1.4 shows the gas demand according to these scenarios [6].

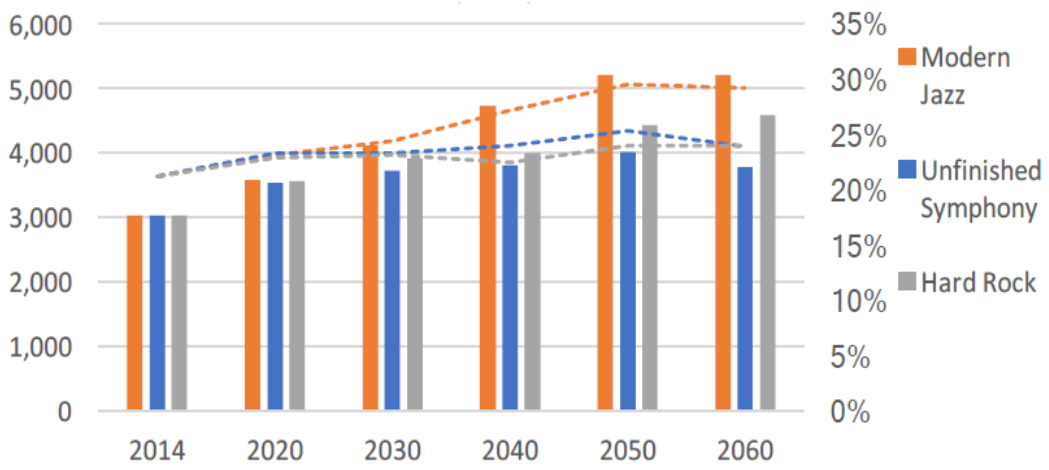

Figure 1.4 Gas demand(bcm) and market share[6].

According to WEC (2017) report about 2016 data, 22% of the electricity produced in the world is from natural gas. 3.3% of the fuel needs of the transportation sector was provided by natural gas. It is predominantly preferred in sectors such as heavy transportation, ship transportation, it can be used in direct combustion engines as natural gas, as well as CNG (compressed natural gas) and LNG (liquefied natural gas) in the transportation industry. 21.6% of the natural gas produced in the world is generally used for heating purposes in buildings [6].

Figure 1.5 shows the production and consumption of natural gas from regions around the world in 2018 [5].

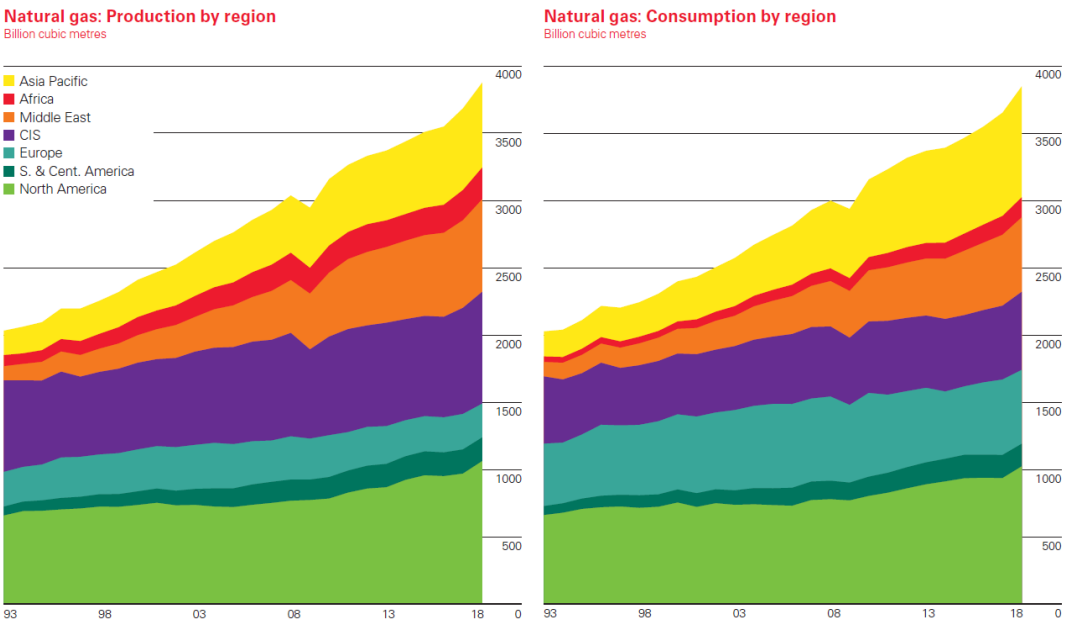

Figure 1.5 The production and consumption of natural gas [5].

The first natural gas reserves in Turkey were detected in Kırklareli in 1970 and began to be used in Pınarhisar Cement Factory in 1976. The natural gas reserve discovered from the Mardin Çamurlu field in 1975 was used in the Mardin Cement Factory in 1982. The limited reserve sources prevented an increase in consumption. In 1984, Turkey and Russia signed a gas delivery agreement, and natural gas initiated to use for domestic and industrial purposes. The first time, natural gas was used in Ankara in 1988. In 1992, the gas market expanded to Istanbul, Bursa, Eskisehir, and Izmit [2].

4646 numbered Natural Gas Market Law which forms the legal framework of Turkey's natural gas market, import, distribution, storage, wholesale, export, transmission, compressed natural gas (CNG) distribution, and transmission makes it mandatory to obtain a license to perform market activities. Natural gas exploration and production (E&P) activities are performed within the framework of Turkish Petroleum Law No. 6491 and E&P and operation licenses are given by the General Directorate of Petroleum Affairs [7].

The natural gas production of Turkey between 2008 and 2018 years is shown in Figure 1.6. Production decreases over the years. The highest natural gas production amount

was realized as 969 million Sm^3 in 2008. The lowest production level was come in sight in 2017 with 367 million Sm^3.

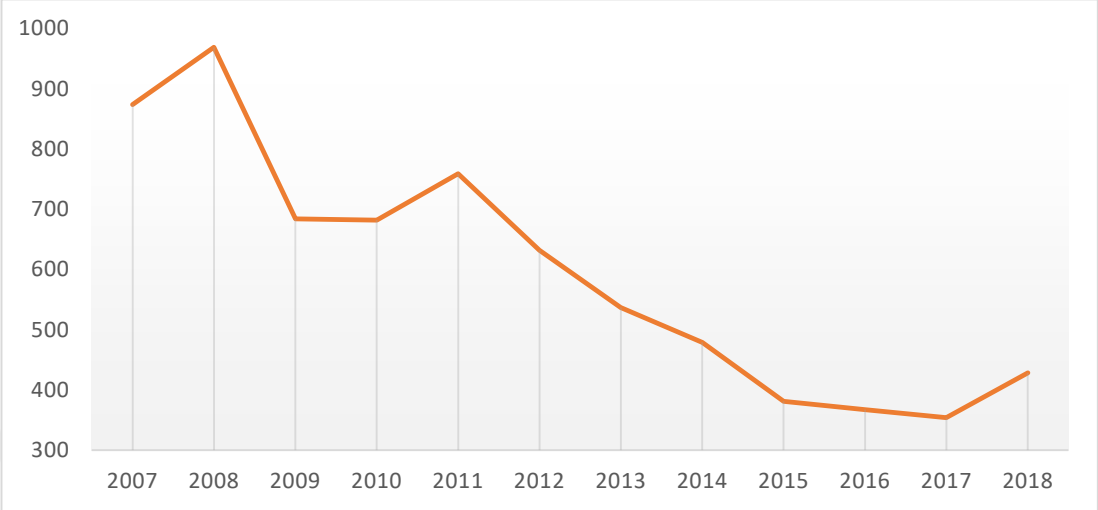

Figure 1.6 Production of natural gas between 2008-2018 (Million Sm^3) [7].

Table 1.3 shows monthly natural gas production of 2018 years by provinces. It is seen that the highest production is made in the fields in Tekirdağ with a share of 41.19% as the natural gas production areas are examined. Thereafter comes Istanbul with 36.57% and Çanakkale with 10.16%.

Table 1.3 Monthly natural gas production by provinces in 2018 (Million Sm^3)[7].

Provinces/Months	January	February	March	April	May	June	July	August	September	October	November	December	Total
ADANA	0.4	0.36	0.52	0.25	0.13	0.02	0	0.08	0	0	0	0	1.76
ADIYAMAN	0.05	0.04	0.12	0.06	0.05	0.03	0.06	0	0.08	0.09	0.03	0.02	0.63
ÇANAKKALE	3.52	4.91	5.7	3.83	3.91	3.81	3.49	3.3	2.88	3.21	2.7	2.25	43.51
DÜZCE	0.81	0.5	0.68	0.89	0.87	0.79	0.81	0.73	0.63	0.64	0.57	0.53	8.45
EDİRNE	0	0.01	0	0	0	0	0	0	0	0	0.01	0.03	0.05

Table 1.3 (Continued) Monthly natural gas production by provinces in 2018 (Million Sm^3)[7].

Provinces/Months	January	February	March	April	May	June	July	August	September	October	November	December	Total
HATAY	0	0	0.03	0	0	0	0	0	0	0	0	0	0.03
İSTANBUL	7.95	7.57	8.92	13.6	14.08	13.53	13.95	14.53	15.8	16.09	15.28	15.3	156.6
KIRKLARELİ	3.5	2.87	2.88	2.44	2.96	3.47	3.33	3.16	3.14	3.25	5.12	4.63	40.75
TEKİRDAĞ	16.76	14.37	15.6	14.8	14.51	13.38	13.89	11.84	14.03	13.44	14.99	18.78	176.39
TOTAL	32.99	30.63	34.45	35.87	36.51	35.03	35.53	33.64	36.56	36.72	38.7	41.54	428.17

National natural gas consumption amounts according to years are given in Table 1.4. The change in the amount of natural gas consumption between years 2009-2018 is analyzed, it is clear that there is an increase of approximately 15.000 million Sm^3 in 10 years as consumption has decreased occasionally compared to the previous year.

Table 1.4 Total natural gas consumptions by years (Million Sm^3) [7]

Year	Consumption (million Sm3)	Change from Previous Year (%)
2009	35.219	-4.47
2010	37.411	6.22
2011	43.697	16.8
2012	45.242	3.53
2013	45.918	1.5
2014	48.717	6.1
2015	47.999	-1.47
2016	46.48	-3.16
2017	53.857	15.87
2018	49.329	-8.41

The natural gas consumption amount was estimated at 54.523.999.692 Sm^3 in 2018. It was realized as 49.328.933.112,03 Sm^3, with a deviation of 9,5 % in Turkey.

In figure 1.7 shows the share of sectoral consumption in 2018. Through the sectoral distribution of natural gas consumption percentage in 2018 is examined, consumption for the household is 25.75%, consumption for the conversion sector is 36.89%, and consumption for the industry is 24.30%.

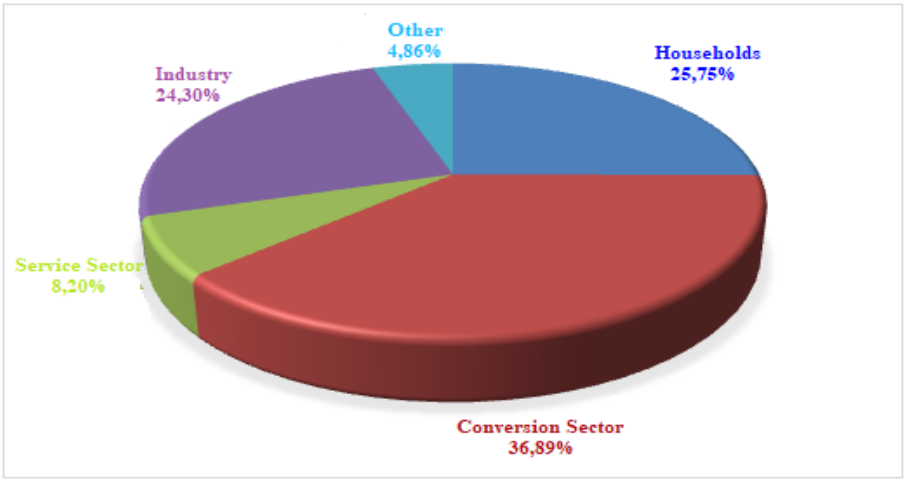

Figure 1.7 Share of sectoral consumption in 2018 (%) [7].

The changes in the monthly sectoral consumption amounts of 2018 are shown in Figure 1.8. The sector that varied the most in terms of monthly consumption values is the household. Household consumption decreases rapidly from the top to the bottom in the January-June period and increases rapidly in the September-December period. The monthly consumption amount of natural gas in the industrial sector generally follows a stable trend. It is observed that the amount of natural gas used in electricity production increased in the second half of the year.

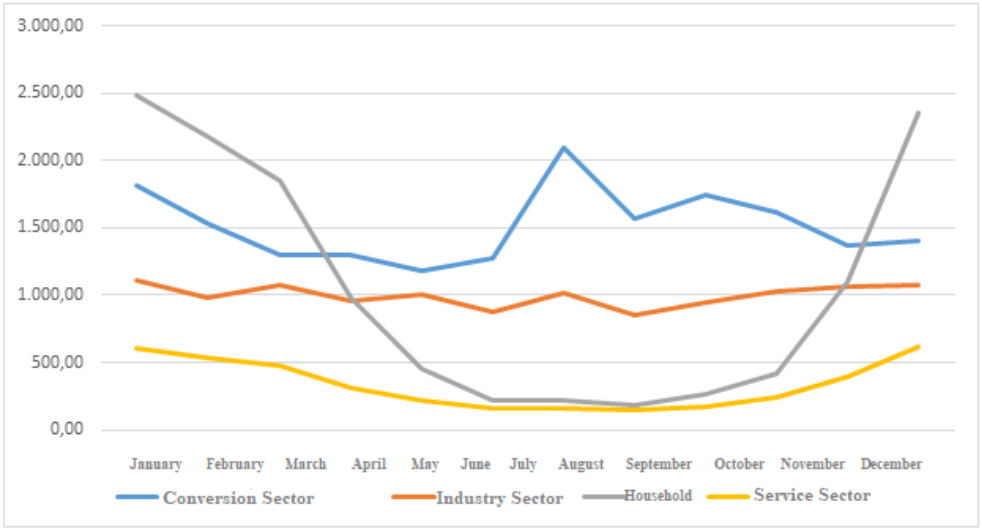

Figure 1.8 Monthly changes in sectoral consumption in 2018 (Million Sm^3) [7].

Through the consumption amounts of natural gas subscribers in 2018, it is seen that natural gas consumption reached the highest value in January (2.365.98 million Sm^3) during the winter period. In 2018, the lowest month of household consumption is in August (173.83 million Sm^3). This situation is shown in Figure 1.9.

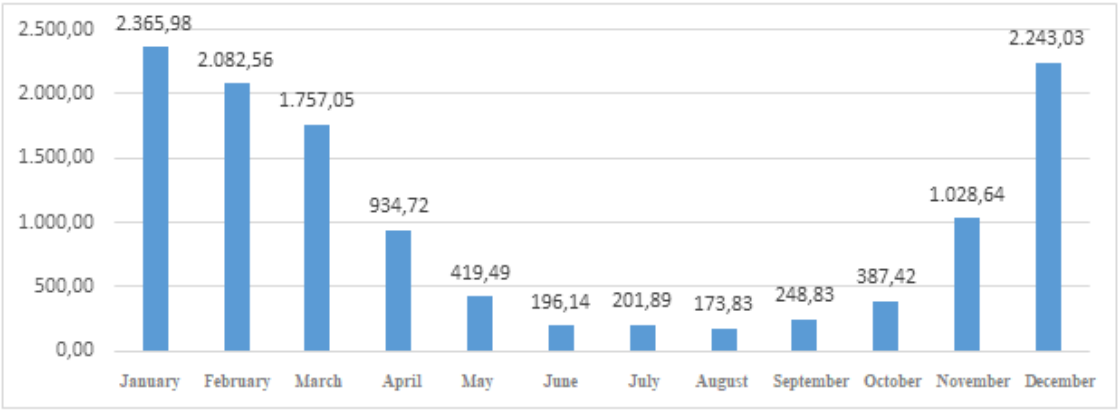

Figure 1.9 Monthly consumptions of natural gas subscribers in 2018 (Million Sm^3) [7].

When all the production and consumption data given above are evaluated, it is seen that the amount of natural gas produced does not meet the consumption. The natural gas produced in Turkey meets only 1% of the total natural gas demand in Turkey. The remaining 99% of the natural gas demand for Turkey is supplied from abroad. Natural

gas imports are made with pipe gas and LNG. The percentage of Turkey's natural gas import by source country in 2018 is shown in figure 1.10. Turkey is a dependent country on gas import, and the main source country for gas import is Russia.

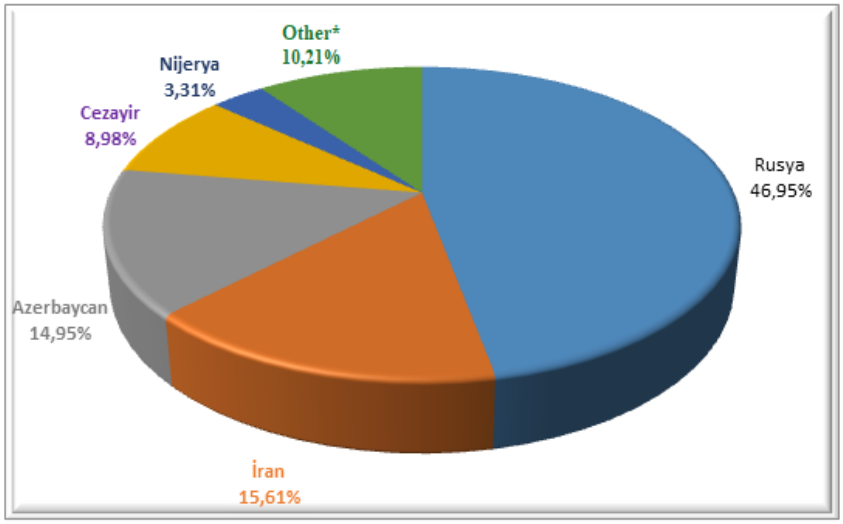

Figure 1.10 Share of imported natural gas by source country in 2018 (%) [7].

The amounts of natural gas import between 2013-2018 years are shown in Table 1.5, according to the gas type. The share of LNG in total import increases, and also the amount of imported pipeline gas in 2018 increases compared to the amount of imported pipeline gas in 2017.

Table 1.5 Amount of natural gas import (million Sm^3) and shares (%) between 2013-2018 [7].

Gas Type	Pipeline Gas		LNG		TOTAL
Year	Amount	Share (%)	Amount	Share (%)	Amount
2013	39419.44	87.08	5849.54	12.92	45268.98
2014	41981.41	85.22	7280.87	14.78	49262.28
2015	40778.11	84.21	7648.96	15.79	48427.08
2016	38724.48	83.54	7627.68	16.46	46352.17
2017	44484.67	80.52	10765.28	19.48	55249.95
2018	39032.13	77.51	11328.45	22.49	50360.58

There is four international natural gas supply transmission line in Turkey. These are seen in Figure 1.11.



Figure 1.11 Natural gas transmission lines.

Russian Federation – Turkey Natural Gas Main Transmission Line

Russia and the Republic of Turkey signed an agreement on September 18, 1984. This 845 km long line starts from the Bulgarian border and follows the Haimtabat, Ambarlı, Istanbul, Izmit, Bursa, Eskişehir and Ankara route. A total of 14 billion m^3 gas supply is provided through this line.

Russia- Samsun – Ankara Natural Gas Transmission Line (Blue Stream)

This line was opened under the agreement signed between BOTAŞ and Gazexport on December 15, 1997. It starts from Samsun and extends to Ankara. The total line length, including the Black Sea crossing, is 871 km. 16 billion m^3 natural gas is imported annually through this line. In addition, there is a branch pipe splits from Çorum

Sungurlu and reaches Düzce. On the pipeline, there are Çorum compressor station and Durusu main measurement station.

Azerbaijan – Turkey (Shah Deniz I) Natural Gas Pipeline

This line was opened with an agreement signed between BOTAŞ and SOCAR on March 12, 2001. The deal is for 6.6 billion m^3 natural gas purchases. This line allows the gas transfer from Shah Deniz production field in Azerbaijan to Turkey, 690 km in length, and has a capacity of 20 billion m^3. This line is connected with the Eastern Anatolia Natural Gas Pipeline near Horasan, and the gas is transported to the West side.

East Anatolian Natural Gas Main Transmission Line

This line was opened with an agreement signed on August 8, 1996, between Iran National Gas Company (NIGC) and BOTAŞ. According to the agreement, 9.6 billion m3 of gas will be purchased. The line starting from Doğu Beyazıt reaches Ankara by following the route Kars, Erzurum, and Sivas. With a branch, natural gas is supplied to Seydişehir via Kayseri and Konya through this line. There are compressor stations in Doğubayazıt, Erzincan, Sivas, and Mucur and Gürbulak main measurement station on the East Anatolia Natural Gas Main Transmission Line [8].

By the end of 2018, Turkey's natural gas distribution network is 137,535 kilometers. Natural gas is used in 81 provinces and 510 districts in Turkey. In 2018, the total number of subscribers was 15,400,892, of which 96% are residential subscribers [9].

From 1929 to 1988, coal gas was used in Ankara. The coal gas was made by the General Directorate of EGO with the help of the coal gas factories in Güvercinlik and Maltepe. In order to prevent increased air pollution in Ankara, studies on transition to natural gas, which is a cleaner, cheaper and safer fuel, started in 1985. In 1988, the first natural gas distribution of Turkey begun contiguous area in Ankara by the agreement with Ankara Metropolitan Municipality and BOTAS. Güvercinlik and Maltepe coal gas plants were closed in 1990 with the increase of using natural gas. The natural gas distribution authority was transferred to Başkent Doğal Gaz Dağıtım A.Ş. in 2007 to carry out Ankara natural gas distribution activities by EGO. Then, it was

transferred to the Privatization Administration in 2009 for privatization. Privatization was completed in 2013. Ankara is the first natural gas distribution province, and the second-largest distribution company of Turkey is in there.

1.3 Aim of the Study

This study is on the positive effects of the vortex tube used for energy recovery in natural gas pressure reduction stations. For this purpose, the amount of fuel consumption between 2016-2020 in a station with vortex pilot gas application in Ankara was examined. First of all, the fuel consumption has been calculated analytically. Since the heat losses are not calculated exactly here, an acceptable difference has emerged. Then, the fuel consumption was calculated again with the assumption that there is no vortex tube, and the fuel consumption amounts of these two cases were compared. Based on this, the economic gain has been revealed by calculating fuel consumption costs. In addition, it has been shown how long the vortex pilot gas heater covers its own costs with the savings provided. The aim here is to reveal the savings provided by vortex tube application. The temperature of the gas decreases during pressure reduction, so the sudden drop in temperature can cause the water vapor in the gas to freeze, damaging the equipment in the station. Therefore, natural gas must be heated before the pressure is reduced. The vortex tube is used as a vortex pilot gas heater, which significantly reduces the preheating load. Finally, an artificial neural network modeling has been carried out in order to be a resource for other stations to calculate the savings of the vortex tube application. In the modeling, the amount of gas passing through the station, station entrance gas temperature, station inlet gas pressure, station outlet gas pressure, and lower calorific value are taken as input. Training of the network was made with the data of 2016-2019. Data for 2020 were used to test the network.

In the first part of the thesis, general features of natural gas, usage, and consumption information are given. Also, studies on energy saving in natural gas stations were examined.

In the second part, natural gas stations and their basic equipment and functions are mentioned. In this section, pressure drop and its effects are discussed in detail.

In the third chapter, the general features of the vortex tube and its use as a pilot gas heater are explained. Fuel consumption is calculated analytically. General information about artificial neural networks has been given and a network model has been created.

In the fourth chapter, fuel consumption values are compared. The effect of using a vortex tube on the cost was investigated. The proximity of the training and test outputs of the artificial neural network to the real values were examined.

In the fifth chapter, the results of the thesis are evaluated.

1.4 Review of Related Works

In this section, studies on energy efficiency in natural gas pressure reduction stations and research using natural gas with vortex tube are summarized.

Köse [10] research investigates the recoverability of energy lost in natural gas pressure reduction stations in Trakya. Vortex tube can be used at pressure reduction stations with regulators and heater to reduce the energy consumption required to heat natural gas and to provide cooling function if necessary. Expansion turbine application is economically suitable in pressure reduction stations above an average natural gas flow rate of 20.000 m^3/h. Vortex tube application is economically more convenient in stations below this flow rate. The preheating process of natural gas can also be performed using devices called "Vortex pilot gas heaters" operating under the existing pressure drop at the station. The middle part of these devices is a vortex tube. The heat energy of the hot gas is transferred to the pilot gas passing through the heat exchanger mounted on the walls of the vortex tube. Some of the produced heat flux is used to heat the pressure drop inlet nozzles to prevent freezing. There is some benefit of using vortex tubes for pressure reduction and measuring stations. Firstly, it fulfills the pressure reducing function and/or reduces the load of the pressure regulators, that they ensure their more reliable and stable operation. Then it eliminates/reduces the required energy consumption to heat the gas. Moreover, its cooling load provides to perform various cooling functions.

Yılmaz et al. [11] conducted another research. The preliminary evaluation and economic analysis were made regarding the possibility of using a vortex tube at

Erzurum-1 RM/A station by them. The amount of natural gas given to the city by heating in Erzurum RMS/A station between 11.01.2007 and 26.07.2007 is 49,193,363 m^3 (average 70 bar). The amount of natural gas spent to heat this natural gas is 700,612 m^3 (at 300 mbar counter working pressure). If vortex tubes are used to heat natural gas, such natural gas will be saved and sold. The electrical energy used by burners and pumps in the heater system to burn natural gas will also be saved. In addition, environmental pollution caused by flue gas emissions thrown into the atmosphere as a result of the combustion of this natural gas will be prevented.

Kibritçi [12] studied technical and economic analysis of how to save or recover energy that consumed at the pressure reduction stations. The first investment cost of the vortex tube, which is one of the methods that can be applied to save heating gas at RM-A stations, is five times higher than the electric heater usage method and 3.5 times higher than the pilot heat exchanger method. The operating cost of the vortex tube is 33 times lower than the electrical heater usage method and ten times smaller than the use of different heat exchangers for pilot heating. According to these values, although the initial investment cost is high, the operation and maintenance costs are very low, so energy savings can be achieved with low cost by using a vortex tube.

Shaikhutdinov [13] proposed improving the efficiency of gas-distributing stations by adding a vortex tube. Theoretically, a vortex tube can be used alone as a pressure reducer. However, vortex tubes are not used solely, as the station must operate with a strictly defined outlet pressure. It can be used as a gas cleaner or separator. The gas must be cleaned and dried before entering the station. When the dimensions of the vortex tube are properly designed, gas purification can be done. The hot exit gas stream from the tube is passed directly to the pressure regulator's body, which prevents hydrate formation, thereby preventing freezing of gas in the regulators during the section where the gas passes.

Guo et al. [14] developed a new heating system because of the low thermal efficiency and high fuel consumption of water bath heaters. For this, a vortex tube, ejector, and ambient air heat exchanger are used. The pressure drop is provided by the vortex tube. By separating energy in the vortex tube, a hot and cold stream is obtained. Cold stream temperature is also 30-50 °C low compared to the ambient temperature. This current

absorbs the heat in the ambient air with the ambient air heat exchanger. An ejector is used to close the loop and redirect this current back into the vortex tube. The effects of the cold mass fraction of the vortex tube and the ejector's entrainment ratio were investigated experimentally in Guo et al. research. The results of the research show that the ejector entrainment ratio plays an important role in system performance. System performance is determined the difference between cold stream from the vortex tube and ambient air. Also, the results show that the vortex tube works as designed. It was observed that there was a temperature increase of about 10 °C in the hot stream compared to the ambient temperature, and the cold stream temperature decrease more than 20 °C compared to the ambient air. The energy-saving capacity of the system was calculated by changing gas exhaust amounts. The performance of the ejector can be increased by consuming more gas to get more temperature increase. However, it resulted in a lower energy saving rate. Compared to the throttling valve system, an energy-saving rate of higher than 0.35 can be achieved.

Ghezelbash et al. [15] examined the amount of fuel consumption of the city gate station using vortex tube and vertical ground heat exchanger(VGHX). For this purpose, the vortex tube and VGHX were installed on the system before the heater. A vortex tube was used instead of the throttle valve to decrease pressure. Vortex tube separated the entering gas into a cold stream and hot stream. The cold stream was warmed by transferring geothermal heat with shell and tube heat exchanger. The heated cold stream was mixed with the hot stream outgoing from the vortex tube and went towards the heater at low pressure. The cold fraction was set at 0.8, and the cold stream temperature was constantly settled at 1 °C to prevent the formation of hydrate. Square and L-shaped configurations were used to examine the effect of VGHX on energy saving, and the L-shaped configuration showed that its thermal performance was better than the square. This system has the potential to save energy up to 88%, and a payback period is approximately 4.5 years.

Kargaran et al. [16] have proposed that usage of the throttle valves to reduce the high-pressure natural gas was wasting the gas energy. By using a vortex tube instead of a throttle valve, both pressure drop and cold flow can be satisfied. The energy decomposition effects were studied experimentally using natural gas and air in the

vortex tube. The amount of cooling capacity created by natural gas passing through the vortex tube was calculated. Natural gas is delivered to customers as approximately 5 bar then it is reduced to 1 bar. During this process, the temperature will be decreased in 2 K. Vortex tubes can only be used to reduce the pressure since the temperature difference is small. However, it can be used for cooling purposes for high consumers, such as hotels or restaurants.

Jafargholinejad et al. [17] have examined six nozzle vortex tube's numerical modeling under city gas station conditions by methane gas flow. In this study, in order to see the optimum and effective performance of the vortex tube, the appropriate diameter/length ratio and pipe length/nozzle diameter ratio were selected. When the results were examined in a wide range of cold fractions, it was concluded that the increase in the cold fraction increased the hot outlet gas temperature. Also, the temperature difference between inlet and outlet was higher for air than methane gas for almost all values of the cold fraction. In fact, the airflow resulted in slightly higher hot output temperature and lower cold output temperature. The vortex tube is an energy-saving device, whether it is used in city gas stations instead of heaters. Moreover, it prevents freezing. It can also be used in the refrigeration cycle to liquefy and convert compressed natural gas into liquefied natural gas.

Zabihia et al. [18] have examined the decrease of heater gas consumption by the installation of a new temperature controller to check out the exit of the second regulator. Data of outlet temperature, inlet pressure, outlet temperature, and outlet pressure were collected from Akand city gate station for 12 months. These data were simulated to examine the economic benefits of the HYSYS software that is used as a simulation of steady-state and dynamic due in industry, process design, modeling of performance, and optimization. It is recommended to set the outlet temperature of the gas leaving the second regulator to 15 °C to prevent excessive energy consumption during preheating. This can reduce heater gas consumption by about 65%. After using the new temperature controller, it was concluded that the amount saved was over $ 43,000 per year for the company.

Özgür [19] has researched the working principle of vortex tubes, the criteria affecting its performance, and the industrial usage areas. In the study, it was stated that the vortex tube

can be used as a simple alternative solution that does not require maintenance at the gas drying process.

Uraltaş [20] has researched that the amount of gained electrical energy when an appropriate expansion turbine was installed in Esenyurt RS-A (Type A pressure regulating station). Yearly gas values, inlet-outlet pressure values, and inlet-outlet temperature values of this station were obtained for the estimation. It was determined that an average of 5,510 kWh (5.51 MWh) electricity was produced annually when double-stage radial turbine modeling with an installed capacity of 25 MW was performed at the station. The generated electricity can be sold within the scope of production from renewable energy sources. Furthermore, it was detected the installed expansion turbine system had a four-year payback period.

Keleşoğlu [21] has investigated whether it is possible to recover the energy at the pressure reduction stations consumed in the compressor stations in the high pressure natural gas transmission lines. He has recommended using a radial turbine instead of throttle valves (regulator) to reduce the pressure of natural gas. Each Joule of energy spent for preheating will be fully recycled from mechanical to electrical energy. Approximately every 1 unit preheating cost is covered by a 4 unit electrical energy recovery. This shows the profitability of energy recovery from the expansion of natural gas. In our country, an average of 73.37 MWh of energy is consumed for natural gas transmission at the compressor stations located in the main lines. The stations that provide ideal conditions for installing radial turbines have been determined to RM-A stations, which are the exit points of transmission lines. It has been determined that 16.70 MWh of energy can be recovered from nine RM-A stations in which radial turbines can be installed in Turkey.

CHAPTER 2

PRESSURE REDUCTION AND MEASUREMENT STATIONS

The stations where the pressure of natural gas is reduced, adjusted, and the amount of natural gas measured, are called pressure reduction and measurement stations (abbreviation RMS). The functions of these stations are cleaning of mechanical impurities (dust and particles), water and condensates of natural gas; heating the gas before reducing the pressure; reducing the inlet pressure of gas to the required outlet pressure level, odorizing the gas, measuring the gas flow rate, etc. Type A stations are also called city gate stations and the legal delivery point of the gas received from the supplier. The inlet pressure of these stations is guaranteed by the transmission company (in our country BOTAŞ), which operates the national transmission network within a certain pressure range (35-75 bar). The outlet pressure varies depending on the operating pressures of the distribution companies (12-19 bar) and the pressure required by the facilities. All basic equipment (regulator, meter etc.) in the stations are designed with at least one backup. Figure 2.1 shows an overview of the type A station.



Figure 2.1 The overview of type A station.

The natural gas from the A type stations are transferred to the regional stations (B type stations) through the steel pipes in the pressure range of 12-19 bar. In B type stations,

4 bar lines at the output of stations are designed and transferred to special consumption services as separate lines according to the desired pressure. The gas exiting from the B type station is transported to the service boxes or C type stations through polyethylene lines. Here, it is subjected to a separate regulation process in the service box or C type station according to the purpose of the industrial or household application, and it is presented to the customer by reducing the pressure to 21 mbar for residences and 300 mbar for industrial applications.

2.1 Basic Equipment of A-Type Station

- Inlet valve - Controls the station entering line
- Filters – Filters incoming the natural gas
- Meters - Measures natural gas passing through the line
- Heat Exchanger - Heats natural gas
- Regulator - Reduces the pressure of natural gas in the line
- Outlet valve - Controls the station output line

Inlet Valve

The inlet valve group controls the inlet gas flow without any adjustment. In case of alarm (fire alarm, high pressure at station exit), it automatically stops the flow in line with the signals received from the control center [20].

Figure 2.2 shows the inlet valve of the type A station.



Figure 2.2 Inlet valve of the type A station.

Filters

Natural gas enters the station through the inlet valve and used to clean solid and liquid particles inside it. Filters are usually installed in double lines, and at least one works according to the situation. Filters are manufactured to clean 90% of particles that 5 microns and larger [22].

Filters can be cyclone type or cartridge type.

The pressure loss in the cyclone filter should not exceed 400 mbar, and the efficiency of the filter should be at least 98% for solid particles larger than 8 microns. The cyclone filter assembly should be positioned just after the inlet valve assembly[23]. In cyclone type filters, solid or liquid particles inside the gas are separated using the centrifugal force. Gas containing solid and liquid particles flows into the tube bundle consisting of pipes of equal diameter after entering the filter. Here, it is divided into gas streams of equal speed. Then each flow arm begins the rotary movement with the cyclone propeller blade. A large rotational speed and force occur. Solid and liquid particles, which have a higher density than gas, hit the wall of the cyclone under the effect of centripetal force and gather under the filter. Gas comes out of the upper part [12].

Figure 2.3 shows cyclone filter group of the type A station.



Figure 2.3 Cyclone filter group of the type A station.

In the cartridge filters, the gas is passed through materials such as polyester fabric and cotton tin order to separate the gas and the particles it contains. The pressure drop in this type filter should be less than 100 mbar. Although the layer of dust accumulated on the cartridge can causes high pressure drop. For this reason, the cartridges should be cleaned with compressed air at regular intervals and replaced if necessary.

Meters

Meters are devices that measure the amount of gas passing through natural gas pipelines. The measurement at the station is provided in two different sections. In the first part, there is a turbine meter group, which is the basis for commercial measurement. In the second part, there is an ultrasonic meter to check the measurement accuracy. The turbine meter operates at full capacity, and it consists of two lines due to the flow regulator. It is sufficient that the ultrasonic meter consists of a single line. Pressure and temperature indicators should be available in the measurement section to make the necessary measurements and controls [22].

Turbine meters work on the principle of volume amount, which is proportional to the number of turbine turns. On the other hand, ultrasonic meters are a type of counter

with no moving parts in it. 3, 4, 5 way audio provides high precision measurement in defined models. It is used to verify the measurement of other meters [20].

Figure 2.4 shows metering group of the type A station.



Figure 2.4 Metering group of the type A station.

Heaters

Natural gas first comes to the heater in the regulator section. According to gas laws, when the pressure drops suddenly, the temperature of the natural gas will decrease in parallel. At a pressure drop of 1 bar, the temperature drops approximately in the range of 0.4-0.6 °C. When the gas temperature drops below the condensation temperature, it causes the formation of water and hydrocarbon liquids. To prevent this, the natural gas is heated before the pressure is reduced. The heaters are mounted as double lines with their backup [22].

Figure 2.5 shows the heater of the type A station.

Detailed explanation about heaters is in section 2.4.



Figure 2.5 Heat exchanger of the type A station.

Regulator

Natural gas enters the pressure reduction section after heaters. In this section, the gas is adjusted to the desired outlet pressure set. Two pressure reducing lines are installed, one is backup, and the other is in operation. The function of the regulator as a control element is to limit the stream of the gas passing through the system, although the inlet pressure and flow rate are variable, and to ensure that adjust the gas pressure is brought to the desired value at the output [22].

Figure 2.6 shows an overview of the regulation group of the type A station.

There are three regulation lines at the selected station. One of these lines is backup to be activated in case of any failure.



Figure 2.6 Regulation group of the type A station.

Outlet Valve

Outlet valve controls the outlet gas flow without any adjustment. In alarm situations (such as fire alarm, high pressure at the station exit), it automatically stops the flow in line with the signals received from the control center [12].

Also, before the outlet valve, the THT, which is an odorant agent, is added to the gas from the scenting unit.

2.2 Pressure Regulators and Their Properties

The regulator is the pressure control mechanism, which includes a sensor, a controller, and a valve. Since it is mechanical, it does not require an external energy source. Pressure regulators show high performance in gas control applications. Stable control is achieved because its response is faster than the process. It operates with small deviations in the adjusted values [24].

The major function of a gas pressure regulator is to adjust the amount of gas that flows through to match system demands by keeping the system pressure (regulator outlet pressure) within acceptable limits.

A typical gas pressure regulation system is shown in Figure 2.7. The regulator is placed before a valve or an equipment that adjusts the amount of gas desired from it [25].

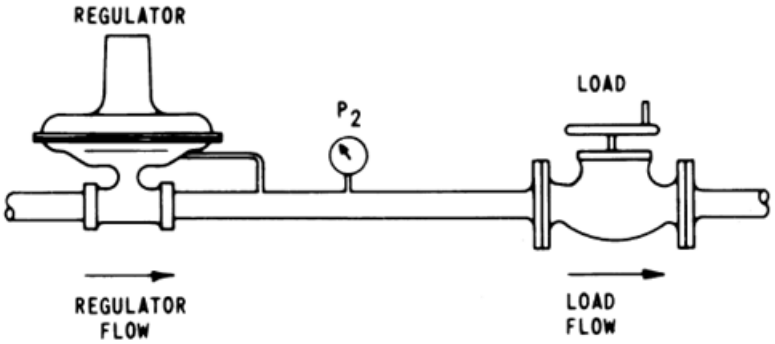

Figure 2.7 Typical gas pressure regulator [25].

If the amount of load flow decreases, the amount of the regulator flow should also decrease. Otherwise, the regulator supplies gas to the system and P_2 pressure increases. On the other hand, when the amount of load flow increases, due to the lack of gas in the outlet line, the amount of regulator flow should be increased in order to keep P_2 pressure constant. As it can be understood from this system, the regulator keeps the output pressure constant by filling the gas even with the amount of gas drawn from the equipment in the consumer. The regulator is generally not capable of responding immediately to regulator flow. If so, there would be sudden changes in the outlet pressure. Therefore, fluctuation in P_2 outlet pressure with sudden gas consumption changes is an expected situation. One of the questions to be asked when choosing a regulator for an application is how the regulator performs in dynamic flow conditions [25].

The job of the regulator is to modulate the flow required into the system at the desired pressure. One of the basic elements of the regulator is the restricting element that modulates the gas passing through the regulator into the system and provides a variable restriction for this. In Figure 2.8, a typical restricting element is shown schematically. This element is usually a kind of valve. The valve used can be a single-port globe valve, a cage style valve, butterfly valve, or any type [25].

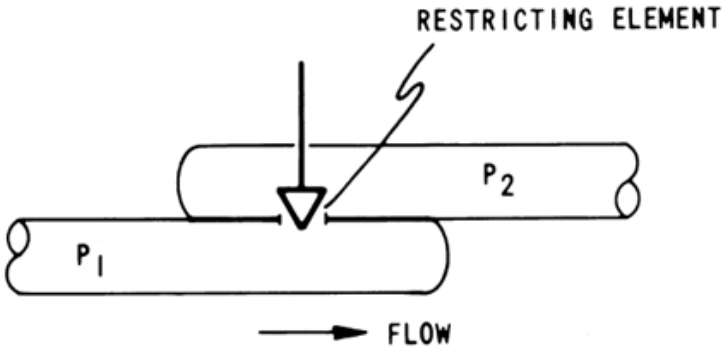

Figure 2.8 A typical restricting element[25].

In order to provide the variability of this restricting, some kind of load must be applied on the restricting element. Thus, as the second basic element, we can say that it is the loading element that provides the required force to the restricting element. The loading element can be one of many different materials such as weight, spring, diaphragm, piston. The element, which is shown in Figure 2.9, consists of diaphragm and spring, is the most known and applied loading element type [25].

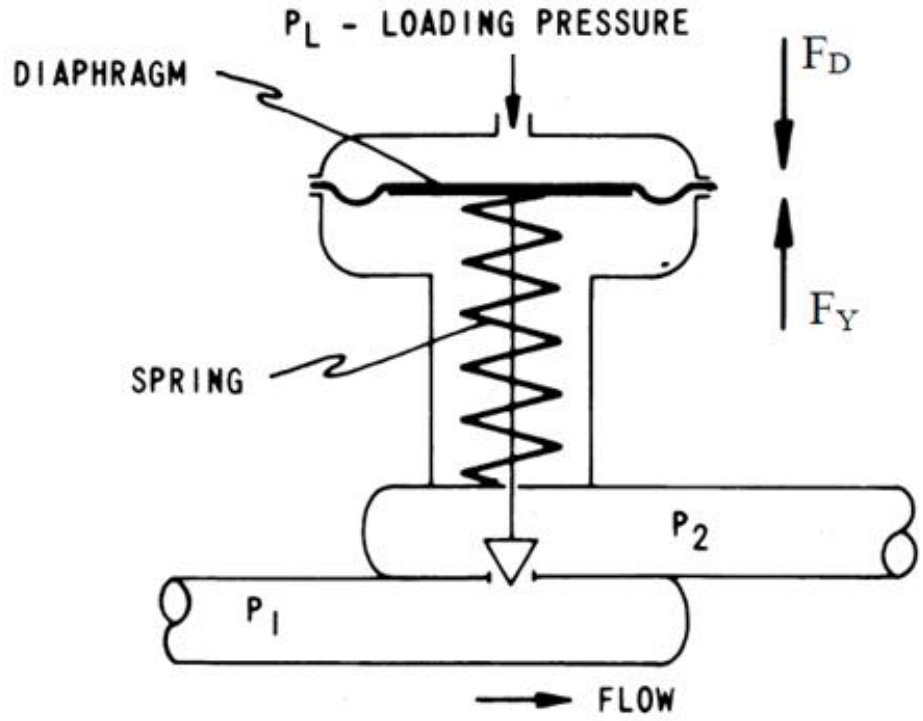

Figure 2.9 Loading element[25].

The loading force, which will provide the necessary movement to the restrictive element, is obtained by applying the loading pressure (P_L) on the diaphragm. The spring applies reverse load force to overcome the weight of the moving parts and to regulate with a force slightly greater than the pressure force. It is possible with a measurement element that matches the amount of gas drawn by the system and the amount of gas passing through the regulator, that is, the gas flow is adjusted correctly, indicating that these two streams are equalized. System pressure P_2 is directly related to the equalization of these two flows. If the restricting element supplies gas to the system more than necessary, P_2 pressure will increase, and if it supplies less than necessary gas, the pressure will decrease. Using this relationship, a measurement can be made as to whether the regulator is providing the required flow [25].

The diaphragm is the most used type of measuring element and acts not only but also as a measuring element. If this typical measuring element is added to the previously selected load and restraint elements, a complete regulator is obtained, as shown in Figure 2.9. If the restricting element supplies more gas to the system than necessary, P_2 will increase ($F_Y > F_D$). The diaphragm as a measuring element, senses this increase in outlet pressure and creates a force in response that compresses the spring. With this force, the restricting element reduces the amount of gas going into the system and the system reaches equilibrium ($F_Y = F_D$). If the regulator cannot send the required gas to the system, P_2 pressure decreases, in this case, the diaphragm responds by reducing the force (F_D) applied on the spring. Thus, the spring defeats the reduced diaphragm force and opens the restriction element for more gas to enter the system, and the system tries to reach equilibrium again. This example shows that regulators have three basic parts that reduce gas pressure. These are restriction group, load group, and measurement group. No matter how complex a system is, it basically contains these three elements [12, 25].

Restriction Element

The restriction element is a kind of valve, and its purpose is to limit the flow. It is possible to change the pressure in the system from high to low through the throat formed by the valve. The pressure difference occurring along the valve creates a potential energy difference that ensures the flow of the gas. In general terms, as long

as the pressure difference is increased throughout the valve, the amount of gas passing by the potential energy increases. In reality, this is true up to a certain critical value. Figure 2.10 shows how the pressure is distributed across the valve under flow conditions in a typical regulator. In order to create a significant restriction point on the valve line, the valve flow area is chosen significantly smaller than the flow area of the pipe. If it is desired to achieve a steady flow through this system, the amount of gas passing through this limited area must be kept equal to the amount of gas passing through the entire pipe.[25]

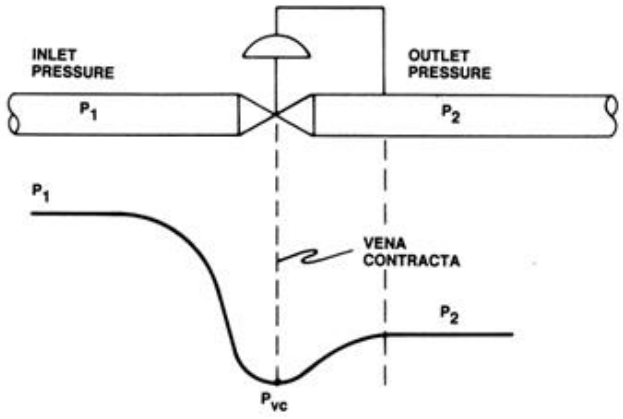

Figure 2.10 Pressure profile of a valve [25].

Loading Element

Many of the regulators are spring-loaded. The spring-diaphragm pair are the most common loader elements used. In terms of design, there are many spring factors such as material, spring diameter, wire diameter, free spring length and number of turns. However, in gas sector, there is only one spring factor, which is the spring constant. The spring constant (k) is defined as the amount of force required to compress the spring by 1 unit. The most important advantage of using a spring is to provide loading force in one direction. The energy required to compress the spring must be provided in the other direction. This force is usually obtained by the outlet pressure acting on the diaphragm. The outlet pressure is determined by the spring taking a restrictive position according to the set value. In this case, the spring and its corresponding pressure are in equilibrium. Depending on the gas flow rate changes, the outlet

pressure also changes. With this change, a difference is created between the spring force and the control pressure, in which direction (on-off) and how much the restrictive element will move [25].

Measuring Element

The commonly used gas pressure measuring element is the diaphragm. The diaphragm is a simple, economic, versatile, easy-to-maintain measuring element that does not need any other part to move. In other words, the same diaphragm can act as both a measuring element and a loading element without the need for another element. As seen in Figure 2.11, loading pressure (P_L) is applied to the entire outer surface of the diaphragm. The diameter of this diaphragm, on which pressure is applied, is equal to the inside diameter of the upper cap. This does not mean that the pressure on the entire outer surface is useful in terms of the loading force of the entire area. In reality, if the situation is re-analyzed and examined, the only available area is the diaphragm plate. Only the pressure force generated in this area can actually be transmitted to the spring. If it is thought that the pressure is applied like this, it is again mistaken. In order to find the correct answer, the section of the diaphragm that remains in the space between the plate and the cover should be examined. Here the diaphragm does not have any support and it will take a concave shape with the effect of pressure [25].

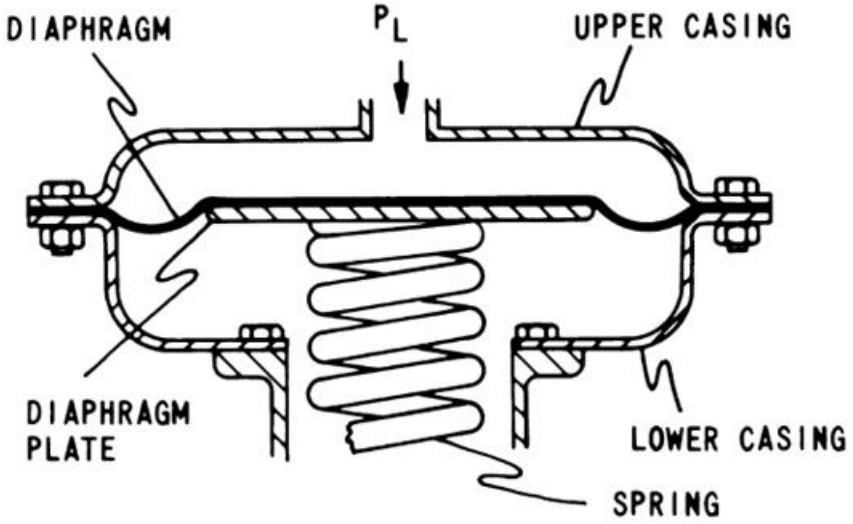

Figure 2.11 Diaphragm assembly [25].

Figure 2.12 shows how the pressure is evenly distributed over the concave shape of the diaphragm. When this figure is examined, it is seen that the tangent is horizontal only at one point. The dashed line perpendicular to this point divides the diaphragm fold into two parts. Since the diaphragm is a flexible material, tension and compression forces do not occur. The only force that occurs is the tension force, which occurs at any point parallel to the diaphragm. If the intersection point in Figure 2.12 is taken into consideration, the tensile force will be horizontal at this point where the tangent is horizontal [25].

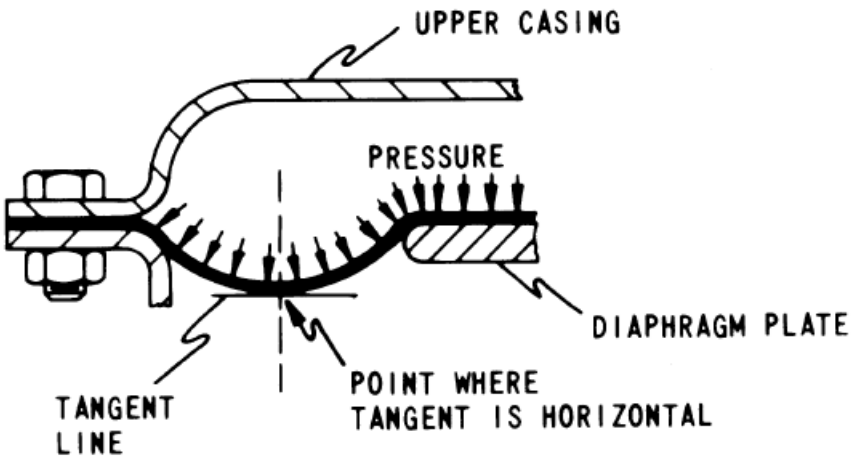

Figure 2.12 Section of diaphragm [25].

2.2.1 Types of Pressure Reducing Regulator

Spring-Loaded Regulator

Spring-loaded regulators are more common to use than other types since they are economical and straightforward structure. They also have an extremely fast dynamic response. It is among the main disadvantages that it is difficult to adjust, and it reacts sensitively to sudden shock and vibration. Figure 2.13 shows the design of a spring operated regulator. The valve is normally closed. Turning the adjustment screw compresses the spring and opens the valve. Increasing the downstream pressure acts under the diaphragm, thereby raising it and closing the valve. Spring compression is adjusted to provide the desired downstream pressure in the demand flow [25].

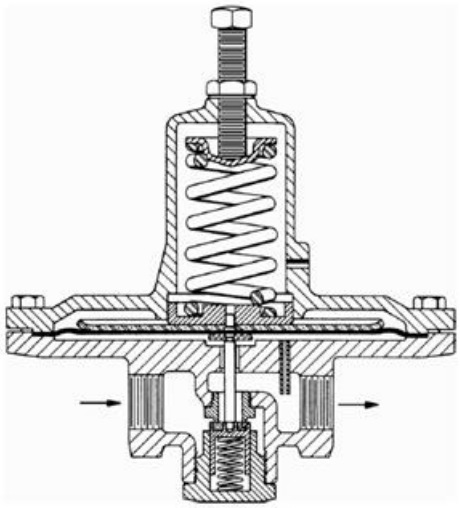

Figure 2.13 Spring-loaded regulator.

Spring loaded regulators can have very precise (±1%) control below 0.07 bar as the lowest set pressure. The highest pressure can be controlled up to 34.5 bar with an accuracy of 10% to 20%. Figure 2.14 shows operation scheme of spring-loaded regulator [26].

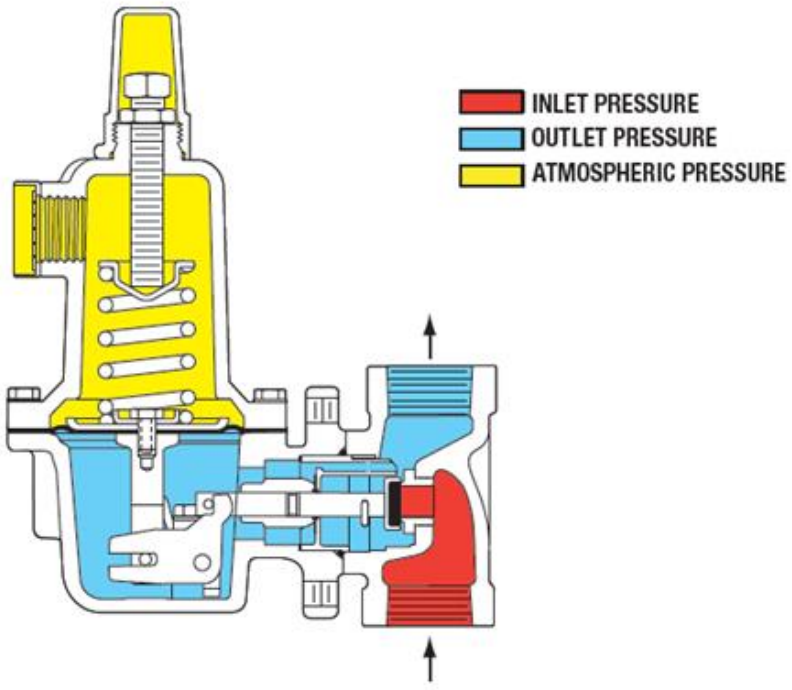

Figure 2.14 Operation schematic of spring-loaded regulator.

Pilot-Operated Regulators

The tasks of high efficiency pilots and pilot regulators are to activate the valve mechanism and control the gas flow. The pilot system monitors the outlet pressure changes and creates a loading pressure to move the valve mechanism by comparing it with the value set with the pilot spring. A typical pilot consists of a pressure-sensitive, fast-acting dual diaphragm, as shown in Figure 2.15. The spring force that gives motion to this diaphragm assembly is the difference between the P_L loading pressure and the P_2 output pressure. This diaphragm adjusts the flow rate that goes through the regulator according to changes in P_2 outlet pressure. The maximum opening size of the variable orifice shown in the figure should be greater than the opening size of the fixed orifice shown as a hole through the upper diaphragm. It supplies the system with the atmospheric pressure generally taken from the inlet of the regulator. If the outlet pressure P_2 is increased, the nozzle opening of the variable orifice decreases and in this case the flow in the fixed orifice becomes larger than that of the variable orifice. This indicates that there is an inverse proportion between the loading pressure P_L and the outlet pressure P_2. In this way, highly efficient pilots can be designed that can detect the slightest changes in P_2 outlet pressure and, in turn, close and open the variable orifice. In other words, very small decreases in P_2 pressure can cause big changes in P_L pressure [25].

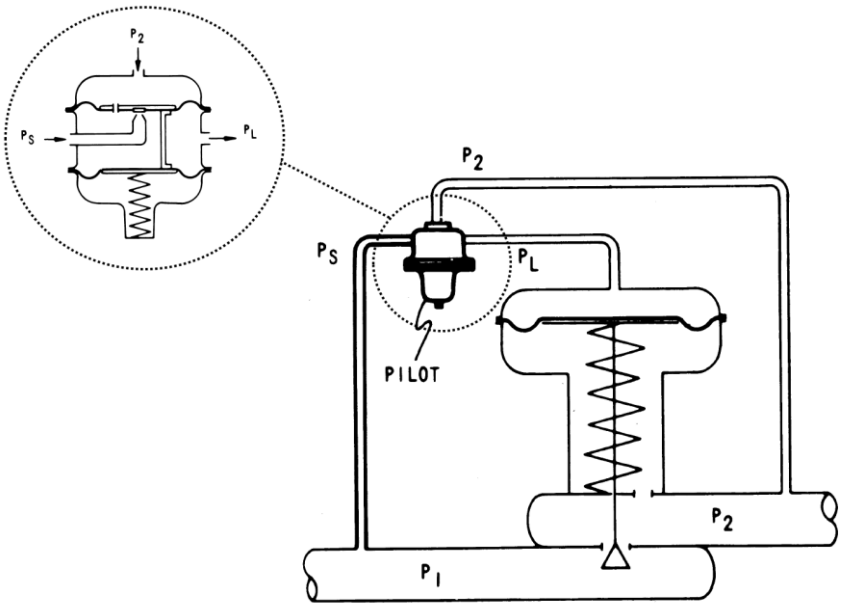

Figure 2.15 Pilot amplifier and pilot operated regulator [25].

The pilot-loaded regulator consists of two stages devices. The first stage controls the pressure on the diaphragm of the main regulating valve that is a spring operated pilot regulator. The second stage is also a spring-operated regulator, but that controls the main valve stem. One of its advantages is that the actuating fluid that operates the pilot regulator is at the upstream pressure. This advantage provides the operating mechanism with a higher power level. The gas trip is very short and reduces this drop. More accurate regulation is possible with this design. Figure 2.16 shows that the pilot regulator can be integral or external. It controls the pressure of a diaphragm that operate the main valve [24].

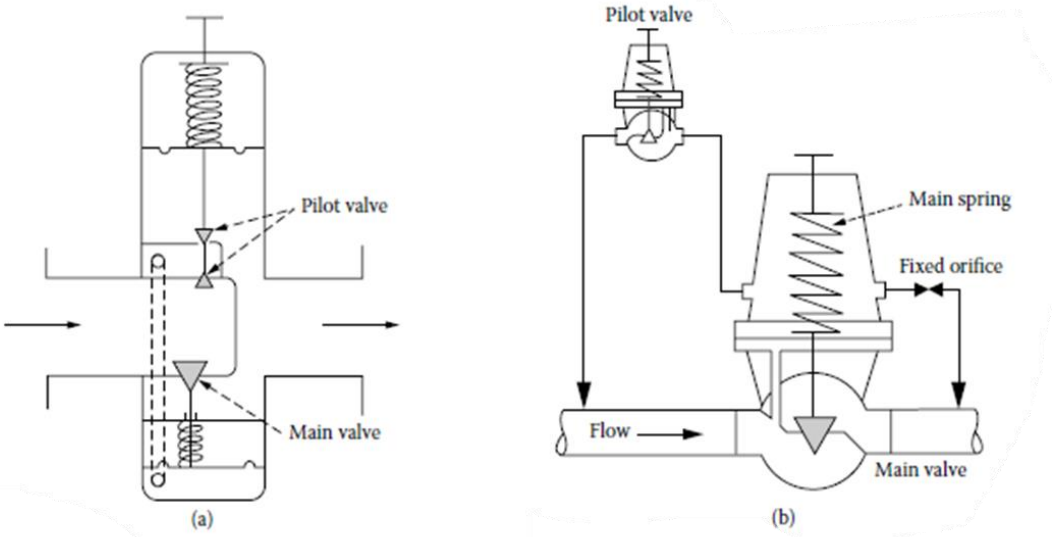

Figure 2.16 Schematics of integral(a) and external(b) pilot regulator.

Pilot operated regulators are preferred for high flow rates or where precise pressure control is required. Figure 2.17 shows operation scheme of pilot-operated regulator [26].

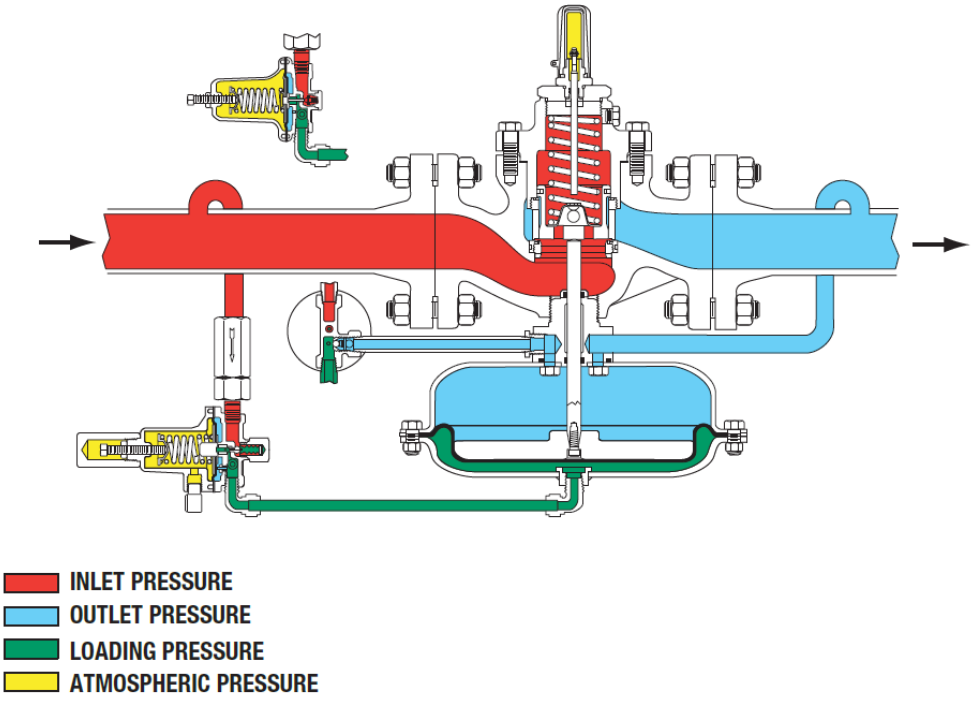

Figure 2.17 Operation schematic of pilot-operated regulator.

2.2.2 Purpose of Regulation

The purpose of regulation is to meet the changing gas demand and to provide a pressure drop. Meantime, depending on the increasing or decreasing consumption, it is necessary to keep the pressure on the outlet side to the desired value regardless of the pressure on the inlet side. For this, the spring force in the regulator is used. Regulation is provided by changing the orifice cross-section area in the inlet section according to the pressure in the output section with the force applied by the spring. Natural gas coming from high pressure creates a constant pressure on the spring during regulation. As much as the pressure enforced by the pressure on the diaphragm, the spring applies force to the diaphragm. So there is a constant static force on the spring.

2.3 Joule-Thomson Effect

As a fluid passes through a restriction cross section such as a porous plug, a capillary tube or a valve its pressure drops. The enthalpy remains steady during the throttling process. In general, the temperature of the fluids decreases significantly as a result of throttling. However, there are cases where the temperature of the fluid may be steady or increase during the throttling process (such as figure 2.18). The variation of the temperature of the fluid during the throttling process, enthalpy is constant, is determined by the Joule-Thomson coefficient (μ) [27].

$$\mu_{JT} = \left(\frac{\partial \mathrm{T}}{\partial \mathrm{P}}\right)_h \tag{2.1}$$

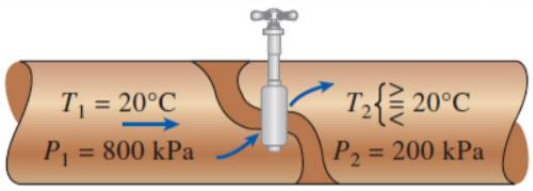

Figure 2.18 Schematic **t**hrottling process[27].

In other words, the Joule-Thomson coefficient is a range of the changes of temperature with pressure on a process at constant enthalpy. The values that μ will take during a throttling process are shown below.

- $\mu < 0$ temperature increases
- $\mu = 0$ temperature remains constant
- $\mu > 0$ temperature decreases

If the above equation is examined carefully, it is seen that the Joule-Thomson coefficient shows the slope of the constant enthalpy curves in the T-P diagram. A fluid with a known temperature and pressure (hence known enthalpy) is passed through a throttle valve to measure the pressure and temperature downstream. If this method is repeated with valves with different flow cross-sectional area, different T2 and P2 values are obtained. If these values are marked in the P-T diagram and integrated with a curve, a constant h curve is obtained as shown in figure 2.19. It is possible to draw different constant h curves by changing the upstream values to the throttle valve as shown in figure 2.20 [27].

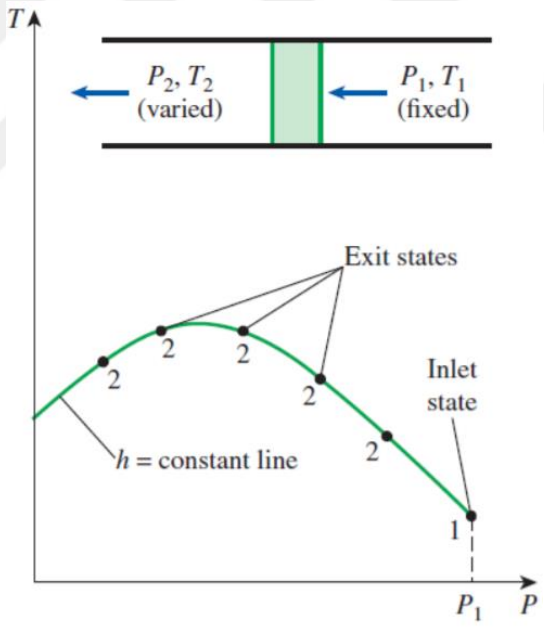

Figure 2.19 h=constant line on P-T diagram [27].

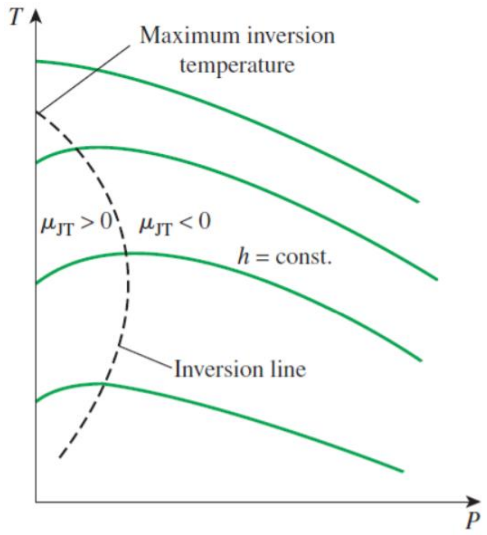

Figure 2.20 Constant-enthalpy lines on T-P diagram.

In the T-P diagram, some of the constant enthalpy curves pass through points where the slope or the Joule Thomson coefficient is zero. The curve passing through zero slope points is called the inversion curve. The temperature at the point where the inversion curve intersects the constant enthalpy curve is known as the inversion temperature. The temperature at the point where upper part of the inversion curve crosses the P = 0 line (T axis) is the maximum inversion temperature. Note that the slopes of the constant curves h=constant lines are negative (μ <0) on the right side of the inversion curve and, positive on the left side of the inversion curve (μ> 0). In other words, for a fluid that is to the right of the inversion curve, the temperature rises during the throttling process. For a fluid to the left of the inversion curve, the temperature decreases during the throttling process. As seen from Figure 2.19, fluids below the maximum return temperature provide cooling effect [27].

The throttling of the gas in a station is provided with reducing the cross-section area for gas stream in the regulator. It is assumed the pressure regulator is adiabatically insulated because this process is very short. The ratio between the change in relative temperature and the change in pressure can be determined since the temperature and pressure of the gas before and after the pressure drop are known. This ratio is also Joule–Thomson coefficient. Hereby, the Joule–Thompson coefficient of about 5 K/MPa is defined for natural gas. The pressure drop at these stations is several MPa.

Therefore, the temperature may fall below 0 °C. This drop in temperature can cause the following problems with the operation of its regulators and other station elements.

- corrosion, the result of condensation of water vapor contained in the gas;
- instability and lock the device as a result of water vapor crystallization in the regulator;
- freezing of the elements of a regulator, such as the pilots;
- formation of hydrates which have a negative effect on the equipment performance. In an intense case, hydrates may reduce the station capacity.

Avoiding these problems is an important factor in ensuring that the station operates safely. It is connected with the preheating of natural gas before the pressure is reduced [28].

2.4 Heater (Indirect Water Bath Heater)

Gas fired water bath heaters, a common heater type, are utilized in heating at lower temperature (approximately 65-121°C) and are used mainly for heating of oil and natural gas. Gas-fired water bath heater is an indirect process heater type. It designed for heat production without direct contact. Figure 2.21 shows main parts of it, such as the process coil, firetube and, heating media (water, glycol, or salts) [29].

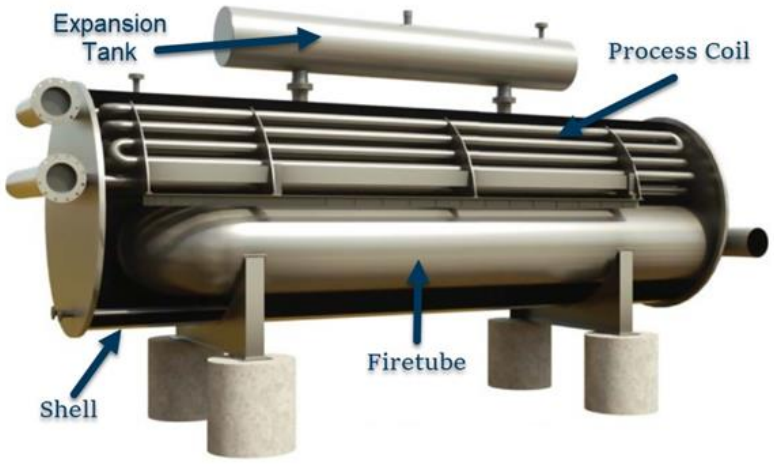

Figure 2.21 Main parts of heater [29].

The indirect water bath heater generates the heat in the combustion chamber and transfers it to process flow with heat media that can be water, a mixture of water and glycol, steam. The heat transfer is uniform because of exothermic environment. This type of heater is most common in pressure reduction stations. Figure 2.22 shows the immersed heater scheme in water. The main reason for using this type of heaters is the heating of the high pressure gas that their pressure is reduced in the stations. The drop in gas pressure also causes a decrease in temperature. In these heaters, process flow pipes (high pressured natural gas for our pattern) are immersed in the exothermic environment that is water or water-glycol mixture. The firetube transfers the heat released from the burner into the exothermic environment, and the process pipes that process fluid in it heat up [30].

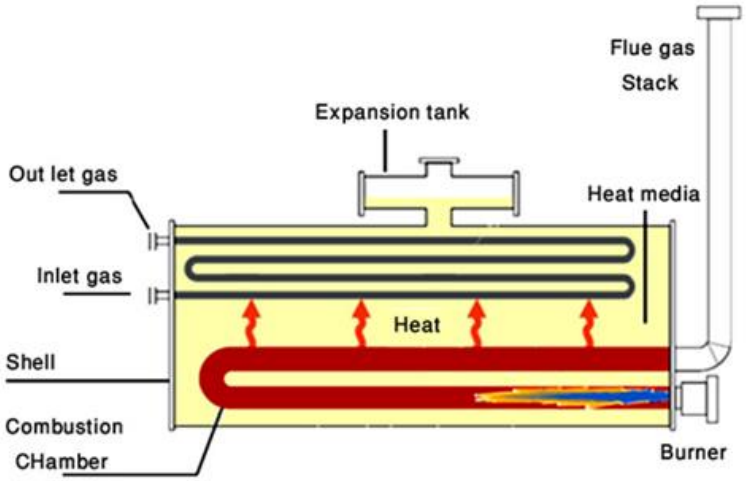

Figure 2.22 Scheme of the immersed heater [30].

CHAPTER 3

MATERIALS AND METHODS

The pressure of natural gas is reduced by using regulators at pressure reduction and measurement stations. Reducing the pressure of natural gas in the regulators reveals the problems mentioned in Section 2. Natural gas is usually heated before entering the regulator to prevent these undesired events at pressure reduction and measurement stations. Natural gas entering the station should be heated, especially in cold climates. The necessary energy is provided for heating the gas by burning natural gas in the heater. This amount of energy can be especially significant in cold climates.

The station where vortex tube application is available has a capacity of 600,000 Sm^3/h. This station works actively in cold weather conditions with intense gas usage for five months a year.

As an alternative to heaters, the vortex tube can provide the necessary heat without burning of natural gas. The inlet of the vortex tube is connected to the station gas line. The hot stream coming out from the hot outlet of the vortex tube combines with the stream coming out of the cold outlet. The combined stream is connected to the outlet line of the station. Theoretically, vortex tubes can be used as a pressure regulator since it has a design feature as a pressure reducing unit. However, since gas stations must operate with a precisely determined exit pressure, vortex cylinders should be used with pressure regulators.

Vortex tubes are used to support the heat process, and it is called vortex pilot gas heaters. The middle part of this device is a vortex tube. The heat energy of the hot gas is transferred to the pilot gas passing through the heat exchanger mounted on the walls of the vortex tube. Some of the heat flux produced is used to heat the pressure reduction inlet nozzles to prevent freezing.

3.1 Vortex Tube

Vortex tubes have a simple mechanism that works only with compressed gas, with no moving parts, except the control valve. This simple mechanism divides the high pressure gas stream tangentially entering the tube into two low-pressure streams, one is warmer than the inlet gas and the other colder than the inlet gas. Figure 3.1 shows a scheme of the operation and geometry of vortex tube [31].

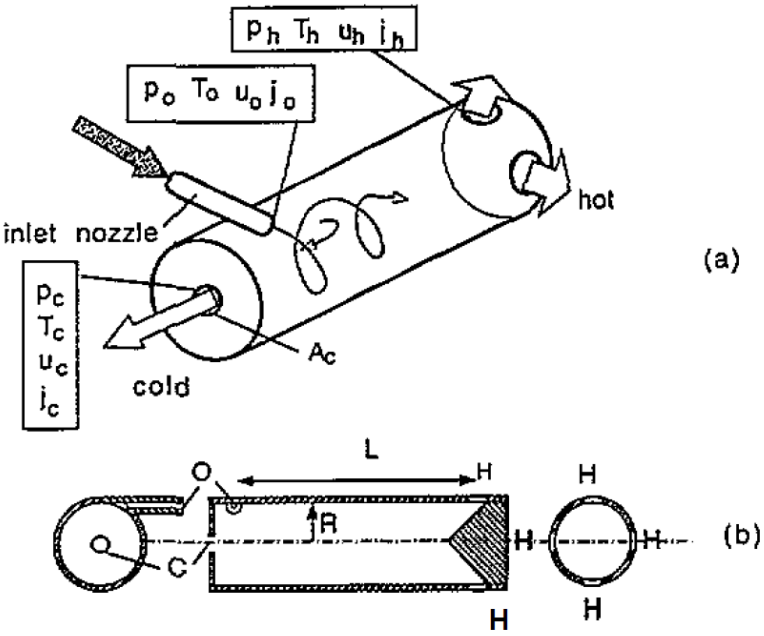

Figure 3.1 (a) Scheme of operation and parameter, (b) Geometry of vortex tube.

Vortex tubes were firstly discovered by Ranque in 1933 and developed by Hilsch in 1946 [19].

Vortex tubes have a wide usage area with the advantages of having a simple geometry, no moving parts, small and portable, low cost and maintenance, providing instant cold and hot air, long operating life, and adjustable temperature. The disadvantage is that it has low efficiency, noisy operation, and compressed gas requirement. Vortex tubes have a wide usage area with the thermal decomposition they create in heating and cooling applications. Very low temperatures can be achieved by cascade use with vortex tubes. It is used as an expansion engine in the liquefaction of gases. It is used

in the separation of heavy hydrocarbons from natural gas, gas separation applications such as CO_2 separation from natural gas and flue gas. It produces DC electric current with hot and cold air thermoelectric generator modules coming out of the vortex tube. It can be used in the drying process of gas in the gas industry. The basic elements of vortex tubes are body, inlet, and outlet orifices. The body of the vortex tube, which has a cylindrical shape, is usually made of steel due to its strength and resistance. Also, brass, perspex, plexiglass can be used as body material. The pressurized fluid enters the tube tangentially, passing through the inlet nozzles near the inlet of the tube. The function of the inlet nozzles is to allow the pressurized gas to enter the tube, and increase the fluid inlet velocity. The outlet orifice is an adjustable valve located in the hot outlet of the tube. By adjusting this valve, the hot flow rate can be increased or decreased so that the flow rate and temperature of the fluid coming out of the cold outlet can be adjusted [32].

Various researches have done on the working principle of the vortex tube. Some of these are below.

When the high pressure fluid is injected tangentially into the vortex tube over the inlet nozzle, a swirling flow occurs inside the tube chamber. As the gas swirls to the center of the tube, it expands and cools. Some part of the gas swirls to hot outlet as other part goes to the cold outlet directly in the chamber. The gas comes out at the lowest temperature from the cold outlet, and at the highest temperature from the hot outlet. Hot and cold flow temperatures obtained from the vortex tube mainly depend on the inlet pressure of the vortex tube. For example; in case of the gas is injected at a pressure of 6 bar, temperatures of 100 C can achieve in the hot gas outlet and -50 C in the cold gas outlet. Figure 3.2 shows this schematically [33].

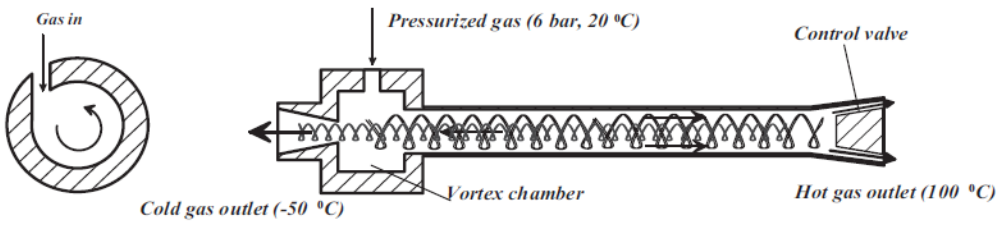

Figure 3.2 Schematic of the vortex tube [33].

The operation of a vortex tube is shown schematically in Figure 3.3. The compressed air tangentially enters the inlet nozzle (State p in the figure), and occurs an approximately axisymmetric vortex flow. When coming from point p to point i, the compressible flow expands and increase it acceleration. The gas entering the vortex tube applies pressure to the tube walls under influence of centrifugal force. The helical gas stream is directed to the hot outlet near the tube wall. From point i to point h, the gas heats up due to friction, especially near the tube wall where the velocity gradient is highest. Cold gas is formed by radial expansion towards the center of the vortex tube. As shown in the figure, cold gas flows to the cold gas outlet (point c) in a helical flow. Hot gas leaves the vortex tube at a higher temperature than the inlet gas, while cold gas leaves the vortex tube at a lower temperature [34].

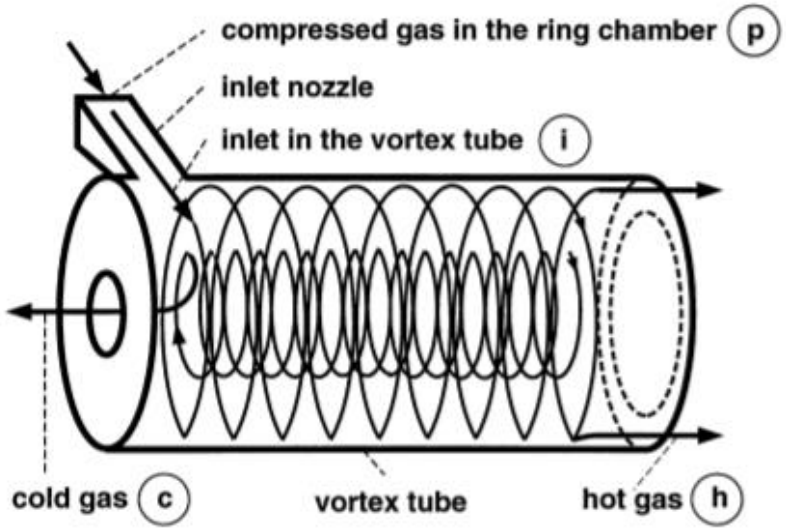

Figure 3.3 Helical stream lines of tube for hot and cold gas [34].

Vortex tubes are divided into two in terms of flow characteristics. First one is counter flow vortex tubes, and other is parallel flow vortex tubes. In counter flow vortex tubes (Figure 3.2 is also a schematic of it), strong eddy flow is formed inside the tube and the gas travels through the tube. Gas is divided into two parts as hot and cold. The hot gas around the tube passes through the hot gas outlet and leaves the vortex tube. The flow in the center of the tube turns in the opposite direction, leaving the orifice just behind the inlet and leaves the vortex tube. The main view of vortex tubes with parallel

flow is similar to the counter flow. Figure 3.4 shows a parallel flow in the vortex tube. The distinguishing features of these tubes are that the hot and cold stream outlets are on the same side of the tube. The end on the inlet side of the tube is closed. In parallel-flow vortex tubes, the cold stream exits the tube close to the center, while the hot stream leaves the tube circumferentially close to the tube wall.

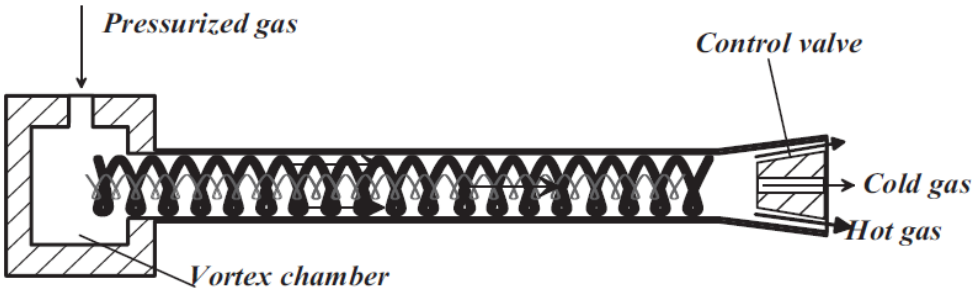

Figure 3.4 Parallel flow vortex tube.

3.2 Vortex Pilot Gas Heater

A vortex heater is utilized to transfer the heat flow of a vortex tube to separate gas flow in the system. For this, a slender tube plugged is mounted at the hot outlet of the vortex tube. The slender tube consists of fins attached to the outer part and a shell surrounding all of these. This is the outer wall of the generated heat exchanger. Gas flow from the pressure source is injected to the inlet end of the vortex tube. Vortex tube provides energy separation. Separate gas flow is connected to the inlet of the heat exchanger. Thus, this gas is removed from the heat exchanger by providing the gas entering the heat exchanger to heat. Figure 3.5 shows schematic design of vortex heater [35].

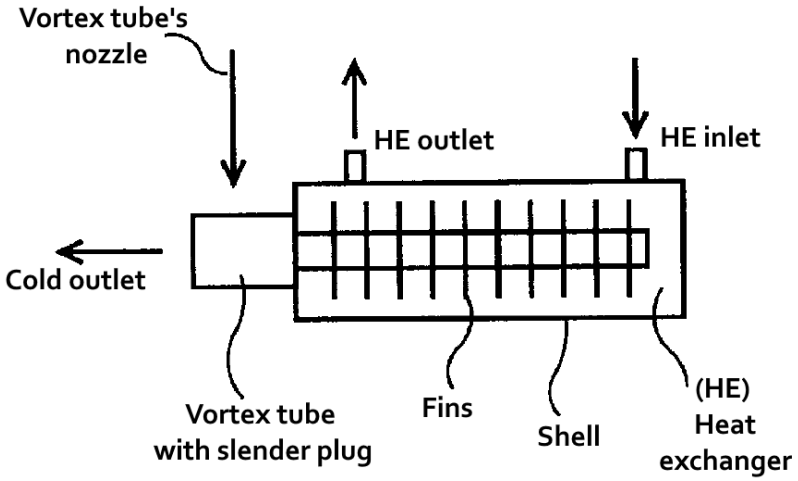

Figure 3.5 Vortex heater's schematic design [35].

The cooling efficiency of the vortex tube can be increased by providing heat transfer outside the vortex tube wall. This leads to a decrease in the actual temperature of the hot fraction. Accordingly, it leads to a decrease in the flow of heat directed from the vortex periphery to the vortex center (unlike the kinetic energy flow) relative to gas heat convection and conductivity. Thermal energy transferred outside the walls of the vortex tube can be used to heat a separate flow of gas or liquid. At this point, the vortex tube works as a heater. The best result can be achieved with the heat transfer approach, which has the largest temperature gradient in the vortex flow. In this case, the largest heat transfer is outside the walls of the vortex tube. Theoretically and experimentally, the vortex tube was found, which was completely closed with the throttle valve at the far end of the slender tube of the largest temperature gradient. In this mode of operation, the internal (cold) and external (hot) vortex layers of the vortex tube have the lowest and highest values of their absolute temperatures before mixing in the diaphragm discharge opening. In summary, heat transfer is provided outside the wall of the vortex tube, and this thermal energy is applied to heat the gas in the control pilot of gas pressure regulators [35].

The high pressure gas flow enters the gas pressure regulator and is monitored by the pilot control and exits with a desired lower pressure. In order to monitor the operation of regulators, the pilot's input is connected to the high pressure distribution line and its output is connected to the low pressure distribution line. Pilot gas pressure drops with

pilot gas throttle. The inlet of the vortex tube is connected to the high pressure distribution line and the outlet of the vortex is connected to the low pressure outlet of the gas distribution line. Since the vortex flow is small fraction (2-5%), it does not cause any distortion in low pressure line. The high pressure pilot gas flow enters the heat exchanger to receive thermal energy from the walls of the vortex tube and then returns to pilot control in a heated manner. Since the increase of gas temperature in the vortex heater is greater than the value of the Joule-Thomson effect, the conditions that cause the gas to freeze disappear in the pilot control. A shutoff valve was installed before the vortex heater inlet to respond to the low or zero transmitted gas flow rate demand. Fully closed or fully opened modes of this valve are operated and is monitored by the downstream pressure sensor. Figure 3.6 shows assembly of vortex pilot gas heater and its operation flow diagram [35].

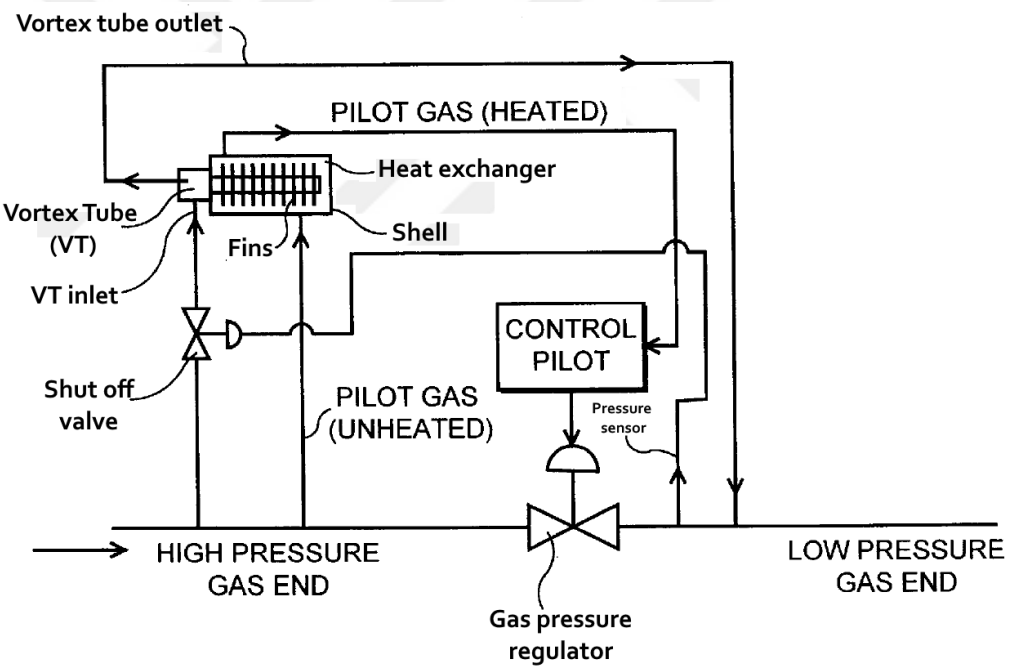

Figure 3.6 Flow diagram of vortex pilot gas heater [35].

Vortex Pilot Gas Heater can have a dual path and performs the same principles. The scheme of dual path vortex heater is shown Figure 3.7. Heat exchanger heats each pilot gas flow that consists of two separate chambers. So, it operates independently of two

pilot gases. Figure 3.8 shows two-stage pressure regulation with monitor and flow diagram [36].

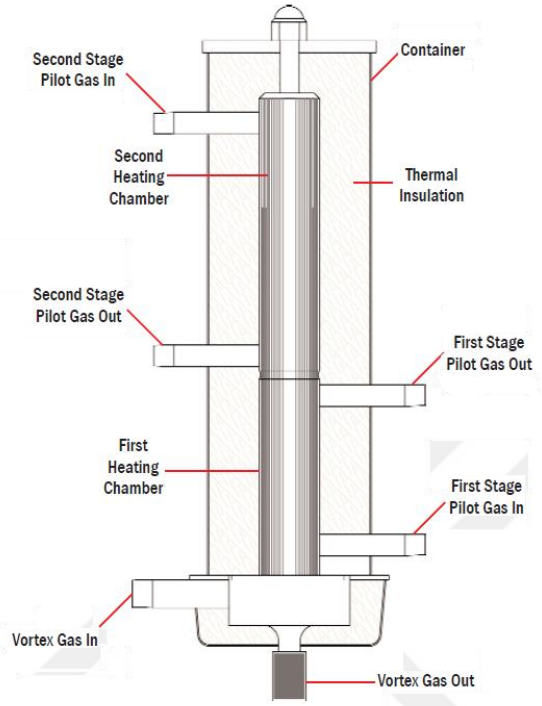

Figure 3.7 Dual path vortex heater [36].

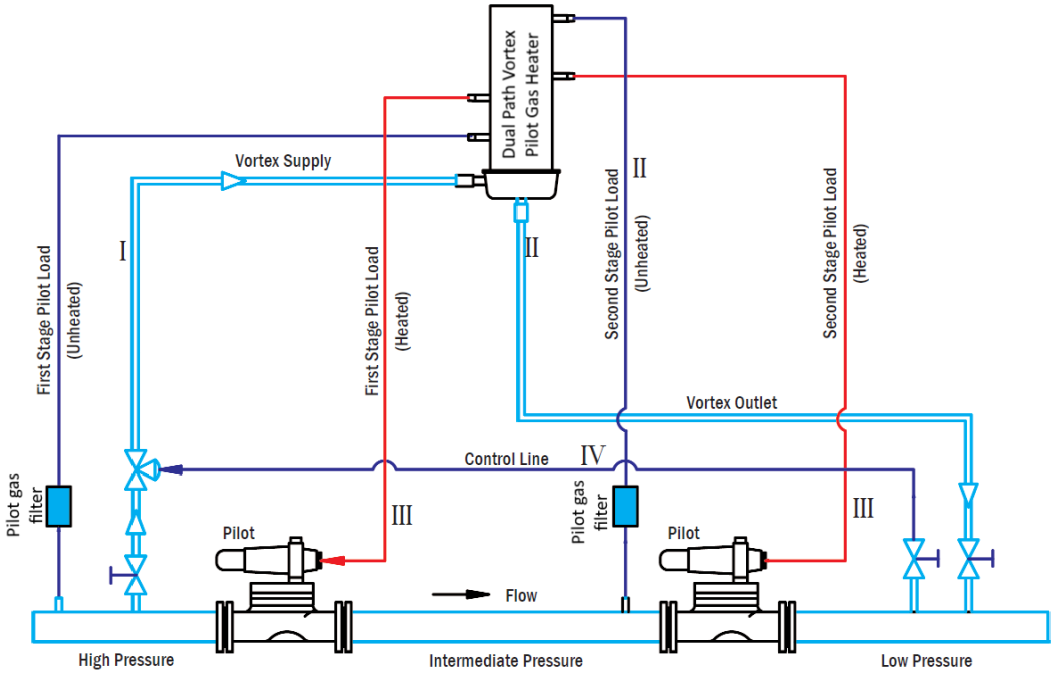

Figure 3.8 Two-stage pressure regulation with monitor and flow diagram [36].

3.3 Required Heat Duty and Fuel Consumption Analysis

The use of a vortex tube allows the heater outlet temperature to be reduced. Fuel consumption of heater has reduced by decreasing the amount of energy required for preheating. In order to determine this, the energy required to heat the gas must be calculated. Then, the amount of fuel consumed by using the thermal efficiency of the heater will be found with this energy need. In the current research, the available data are from the period when the vortex pilot gas heater was installed. With these data, the theoretical fuel consumption is compared with the actual data.

Vortex pilot gas heater allows the regulator outlet temperature to be reduced by up to 3 °C instead of 15 °C. Based on this information; it is assumed that there is no vortex pilot gas heater application. When the regulator outlet temperature is kept constant at 15 °C, the heater outlet temperature was determined before the pressure drop. The transition of the high-pressure gas to a lower-pressure medium causes a sudden temperature drop. As a practical approach, the information used is that the decrease in the temperature of the gas whose pressure is reduced by passing through a restriction element such as a valve or orifice can be taken as -0.5 °C in average at every 1 bar. The amount of heated gas, gas components and other properties are constant, the heater gas temperature was calculated approximately according to the known regulator input pressure, regulator output pressure and the regulator output temperature [21, 22].

In water bath indirect heater direct flame does not expose the natural gas. It is showed schematically in figure 3.9. The thermal energy is generated in the burner and is transferred the natural gas stream by water bath indirectly. When water bath heater selected as control volume, the fuel burned in the burner is input energy of the system that is thermal energy. Heat losses or wasted energies of the system stack (or flue gas) losses and surface (or radiation) losses [37].

$$Heater\ efficiency = [(input\ energy - wasted\ energy)/input\ energy]x100 \quad (3.1)$$

Input energy indicated by $\dot{Q}_{fuel}$ and it is calculated by the equation (1)

$$\dot{Q}_{\text{fuel}} = \dot{Q}_{\text{losses}} + \dot{Q}_{\text{NG}} + \dot{Q}_{\text{stored}} \tag{3.2}$$

The amount of fuel consumption and heat transfer depend on the difference between the inlet and outlet temperature of natural gas(ΔT) [37].

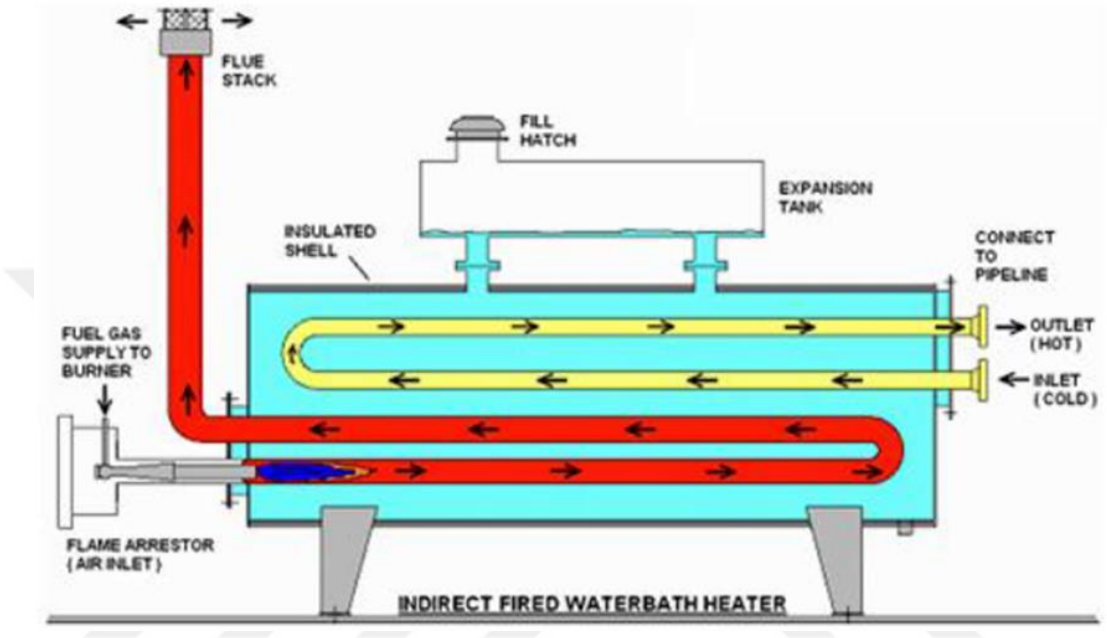

Figure 3.9 Schematic diagram of heater [37].

Combustion process in the burner of heater is supposed a steady state process at constant pressure. All gases are ideal. Natural gas is a mixture of multi complex component, and that include saturated hydrocarbons such as methane, ethane, propane, and butane and its isomers. It also contains a small amount of nitrogen, hydrogen sulfide, helium, argon, water vapor, and other components [38].

An example of natural gas analysis from the studied station is shown in table 3.1.

Table 3.1 Volumetric analysis of natural gas (in Ankara).

Components	Percent by volume (%)
Methane (CH_4)	963,409
Ethane (C_2H_6)	18,697
Propane (C_3H_8)	0,592
i-Butane (C_4H_{10})	0,0945
n-Butane (C_4H_{10})	0,0965
i-Pentane (C_5H_{12})	0,0203
n-Pentane (C_5H_{12})	0,0154
Nitrogen (N_2)	0,8184
Carbon dioxide (CO_2)	0,1407
Others	0,0116

According to the gas components mentioned in the table, the density of the gas is determined as 0.717 kg/m^3 and its lower heat value is 48,640.56 kcal/kgK. The constant pressure specific heat value of natural gas stream is a function of temperature. Equation 3.3 is used to find the specific heat of the gas mixture [39].

$$C_{P_{mix}} = \sum \mathrm{X_i x} C_{P_i} \tag{3.3}$$

The mass fraction of the component is represented X_i and C_{pi} is the specific heat in equation 3.3.

The specific heat of gas mixture is calculated as a temperature function in equation 3.4.

$$c_p\ (kj/kgK) = 1.16 + 0.11x10^{-3}T - 0.001x10^{-7}T^2 - 0.0002T^3 \tag{3.4}$$

where T varies from 250 K < T < 1200 K.

First law of thermodynamic is used with neglecting the potential and kinetic energies to determine $\dot{Q}_{NG.}$ The following equation 3.5 is used for required energy to heat the natural gas stream

$$\dot{Q}_{\mathrm{NG}} = \dot{m}_{\mathrm{NG}}(h_{out} - h_{in}) = \dot{m}_{\mathrm{NG}} \int_{T_{NG}}^{T_{NG}} C_{P_{NG}}\, dT \tag{3.5}$$

$\dot{m}_{NG}$ is natural gas mass flow rate in kg/s and h is natural gas enthalpy at inlet and outlet of heater in kj/kgK [38].

Thermal efficiency of heater is known from heater information label. Lower heating value is measured in the station daily. So, we can calculate the fuel consumption of heater according to following equation [40].

$$\dot{m}_f = \frac{\dot{Q}_{\mathrm{NG}}}{\eta_h x LHV} \tag{3.6}$$

LHV is lower heating value of fuel and η is efficiency of heater. It is taken from heater information label. Table 3.2 shows some properties of heater.

Table 3.2 Label information of heater.

Properties	**Values**
Operating pressure	25+75 kg/cm2
Operating temperature	5+31 °C
Desing temperature	90 °C
Net Duty	4419 Kw
Heating surface	Coil 215 m^2 - Water bath 106 m^2
Thermal efficiency	85%
Burner type	Pressure spray
Burner duty	5200 Kw
Blower flowrate	6000 Nmc/h

As a result of the calculations, January 2020, February 2020 and March 2020 are given as examples. There is %5.71 difference between the theoretically calculated fuel consumption and the actual value. Table 3.3 shows results of examples.

Tablo 3.3 Results of examples.

	January 2020	**February 2020**	**March 2020**
Heater inlet temperature (˚C)	13.16	10.8	11.05
Station inlet pressure (bar)	58.52	57.03	55.4
Heater outlet temperature (˚C)	23.44	22.5	22.06
Station outlet pressure (bar)	18.43	18.48	17.39
Station outlet temperature (˚C)	3.39	3.22	3.06
Heated gas flow rate (Sm^3/h)	275,149,262.00	228,207,301.00	156,911,800.00
Amount of fuel flow rate (Sm^3/h)	183,446.00	175,821.00	113,376.00
Theoretically calculated amount of fuel flow rate (Sm^3/h)	166,784.84	158,968.47	103,637.70
Theoretically calculated amount of fuel flow rate (no VPGH app.) (Sm^3/h)	359,973.76	323,442.32	217,689.18

3.4 Artificial Neural Network

Artificial neural networks (ANN) are created inspired by biological neural networks. These are mathematical models with learning ability that can be used to describe the complicated relationship between the inputs and outputs of a system. Artificial neural networks perform the learning process with the help of examples. It uses a calculation method with high error tolerance that can easily adapt to the environment, can work with incomplete information, and can decide in cases of uncertainties.

ANNs are successfully applied to the following topics, similar to the functional features of the human brain. These are learning, attribution, classification, generalization, prediction, feature determination, and optimization[41].

ANNs can work with numerical values and operate with them. For this reason, in our daily life, it is widely used in financial issues, engineering and medical science, production applications, fail detection, and analysis of these failures. ANNs are often used effectively in prediction, classification, data association, data interpretation, and data filtering[42].

3.4.1 Artificial nerve cells

Artificial nerve cells come together to form the artificial neural network. Artificial nerve cells basically consist of five parts.

Inputs: Inputs are information from an outside world to an artificial nerve cell. These are determined by the examples that the network wants to learn. The information can come to the artificial nerve cell from the outside world or from other cells.

Weights: It shows the importance of the information coming to an artificial cell and its effect on the cell. These are the coefficients that enable the learning process to take place. Weights can be large or small, which does not mean they are important or not important. The value of weight can be zero, and it can be the most important event for that network. Negative values mean not insignificant. Therefore, if it is plus or minus, it indicates that the effect is positive or negative. A zero indicates that there is no effect. Weights can be variable or fixed values.

Summing function: The summing function computes the net input to a cell. Different functions, such as minimum, maximum, or normalization algorithms are used to perform this process. The most common is to find the weighted sum. Here, each incoming input value is added by multiplying by its own weight. Thus, net input to the network is found.

Generally, the summing function is determined by trial and error. Not all process elements present in an artificial neural network have the same summing function. Each

process element can have a different summing function independently, or they can all have the same process element. Some process elements of the network may even have the same summing function in groups. Others can use different functions. This depends entirely on the designer's decision, based on her/his own foresight.

Activation function: The activation function determines the output that the cell will produce in response to this input by processing the net input to the cell. As in the summing function, different formulas are used to calculate the output as an activation function. Some models require that the derivative of this function is a receivable function. As in the summing function, in the activation function, not all process elements of the network need to use the same function. In the most suitable function for a problem, it is a situation that the designer can determine as a result of trials.

Activation functions limit the output value of the neuron in a neural network between the desired values. These values are usually between [0,1] or [-1,1]. Also, the activation function can be increased by applying a bias value to the artificial neural network. The bias value is the negative value of the threshold value.

The most used activation functions are described in detail below.

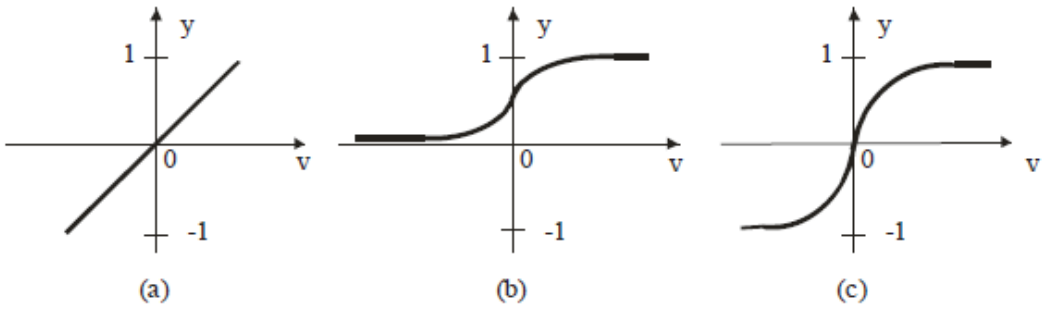

Figure 3.10 (a) Pureline activation function, (b) Sigmoid activation function, (c) Tangent Hyperbolic activation function [41].

Pureline Activation Function: The activation function can be selected linearly to solve linear problems. The output of the cell is calculated by multiplying the result from the summing function with a certain coefficient. The graph is shown in Figure 3.10a[41].

Sigmoid Activation Function: It is the most used activation function in artificial neural network applications. The function is continuous and can be derived. It generates a value between 0 and 1 for each of the input values. The graphic is shown in Figure 3.10b[41].

Tangent Hyperbolic Activation Function: One of the most used activation functions in artificial neural network applications is this function. It is similar to the sigmoid function. Output values are between -1 and 1. The graphic is shown in Figure 3.10c[41].

Output: Output is the unit of the activation function result sent to the outside world or other nerve cell. Although there may be another nerve entry at the exit of the nerve, more than one entry may come to the cells. Every cell must have an output. In this output, any amount of connection can be made to other cells.

3.4.2 Artificial Neural Network Models

Feed Forward Single Layer ANNs

The input layer is faces directly to the output layer in the simplest form of a single-layer network. A reverse orientation is not possible in this neural network. In other words, such networks are called feedforward networks. Since no calculations are made in the input layer in these networks, the output layer is shown as the single layer of the network[43].

Feed Forward Multilayer ANNs

If feed forward artificial neural networks have one or more hidden layers, such networks are called multi-layer artificial neural networks. In these networks, the calculation process takes place in hidden layers. The input layer of the network provides input signals to the second layer (first hidden layer). The signals generated by second layer are used as input for third layer, and this flow continues in the rest of the network. Typically, neurons in all layers of the network have only the output signals of the previous layer as their input. The output signals of the neurons of the

network's output layer constitute the general response of the neurons of the network's input (first) layer[43].

3.4.3 Learning Process

Learning process is a multi-parameter, complex, and mathematically difficult operation. The learning rules used today are simplified or expressed in different formats.

Backpropagation algorithm (BP)

It is the most common and most widely used teaching algorithm in applications. It is the most preferred teaching algorithm since it is easy to understand and to prove mathematically. This algorithm is named backpropagation because it tries to reduce errors back to the output. In backpropagation algorithms, the calculation consists of two parts as forward pass and backward pass.

The forward pass starts with this calculation method showing each sample in the training data set from the input layer to the network. The input data is sent to the layer between the input and the hidden layer without any changes. Here, the summing function is calculated for each artificial nerve cell in the hidden layer. By adding the result of the summing function with the threshold value, the net input of the artificial nerve cell in the hidden layer is calculated. In order to generate a signal as in biological nerve cells, each artificial nerve cell normalizes their net inputs with activation functions and can generate an output value for the cell. This output value creates the input values of the artificial nerve cells in the next layer. The calculation continues until the exit of the network. The advanced calculation process of the network of values in the output layer is completed[44].

In the backward pass, the output values produced by the network for the input data presented to the network are compared with the expected output values of the network. The difference between them is considered an error. The aim is to minimize this error. In the backward pass, this error is distributed to the weight values of the network and the error is reduced in the next iteration.

All errors must be summed up to find the total error of the output layer. Since some error values will be negative, the squares of the weights are calculated to prevent the sum from being zero, and the root of the result is taken. The error value calculated at the network output should be distributed to all artificial nerve cells to reduce the total error. So weights need to be changed.

When changing the weights between the hidden layer and the output layer, only the error of an artificial nerve cell in the output layer is calculated for each weight. The weights between the input layer and the hidden layer have a share in the occurrence of total error. Therefore, the error of all artificial nerve cells is taken into account when changing the weights between the input layer and the hidden layer[44][43].

Levenberg – Marquardt Method (LMM)

The Levenberg-Marquardt (LM) algorithm is an iterative approach that determines the minimum of a multivariable function that is proposed as the sum of squares of nonlinear real-valued functions. Today, it has become a standard technique for widely accepted nonlinear least squares problems in a wide range of disciplines. The steepest descent is considered a combination and the Gauss-Newton method. When the predicted result is far from the experimental result, the algorithm works like a steepest landing method: make sure it is slow, but convergent, and if the predicted result is experimental, it behaves like the Gauss-Newton method[45].

3.4.4 ANN Modelling

ANN modeling was made on the data of the station for the years 2016-2019. While selecting the data, the main values affecting fuel consumption have been selected. The purpose of this is to provide facilities for stations with different input values in determining the savings that the vortex tube application will promise on the amount of fuel consumption. These values are the values that can be followed up and easily accessed in other A type stations.

Heater inlet temperature (˚C), station inlet pressure (bar), station outlet pressure (bar), heated gas amount (Sm^3/h) and lower heating value of gas (kj/kg.K) are the input

values determined in this developed ANN model. As the output value, the theoretical fuel consumption amount (Sm^3/h) after the vortex tube application was specified.

The training was carried out on the data of 2016-2019 of a station in Ankara. 580 days of data for these years were used in training the network. 121 days of data for 2020 were used to test the network. The data has been arranged in order to reach more accurate results in the artificial neural network and turned into numerical data that the network can understand.

The following steps were followed after the data was determined:

Step 1: Determining the type of network,

Step 2: Determining the learning algorithm,

Step 3: Determining the number of hidden layers and neurons,

Step 4: Determining the activation function and creating the mathematical model,

Step 5: Examining the success of the output parameter values,

Feed forward back propagation algorithm was used in the system creation. Levenberg-Marquardt (LM) learning algorithm was used in the training of the network. According to the input values, the output values calculated by the network are compared with the actual output values. The difference between network output and actual output has been calculated as an error. MSE (Mean Squared Error) was used as the error performance function of the network during training.

There is no clear rule for determining the activation function of ANN while creating the system model. Therefore, depending on the system behavior, the activation function to be used in the hidden layer and the output layer was obtained by trial and error and it was determined according to the minimum error rate. In the created model, the least error rate was found with the tangent hyperbolic activation function. The architecture of the artificial neural network to be used in this study is shown in Figure 3.11.

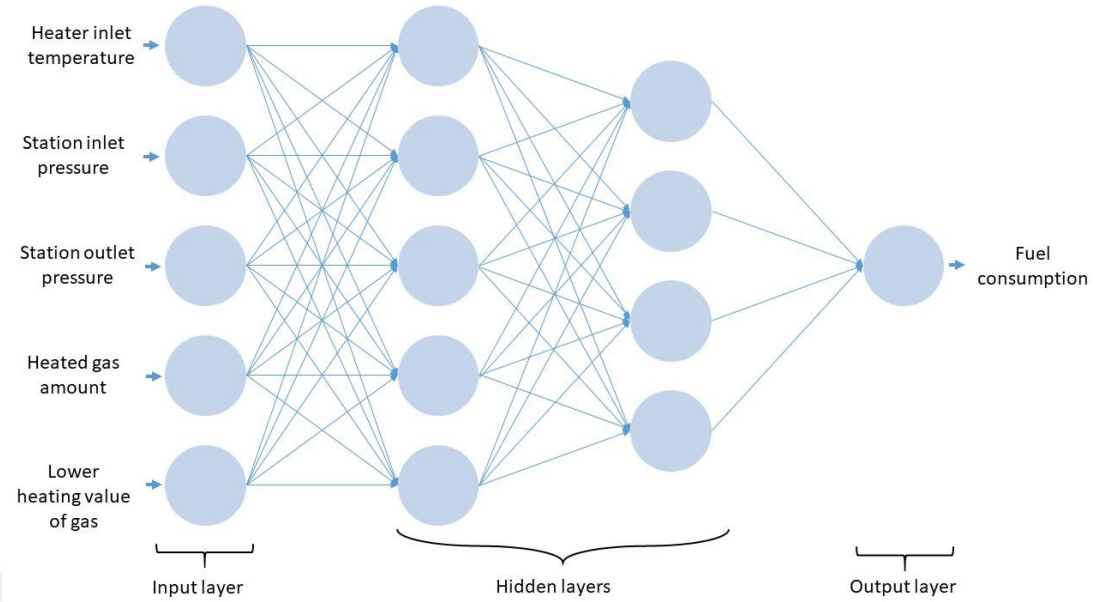

Figure 3.11 Architecture of the artificial neural network.

System modeling was done with MatLab 2016b nntool. After various trials, the most successful R value was found to be 0.98. The network model created is shown in Figure 3.12. Here, the network consisting of 5 and 4 neurons with 2 hidden layer rows is bent with LM learning algorithm. The training error function is MSE and has been trained with 5000 epoch values and maximum 5000 error control. Training results are given graphically in figure 3.13.

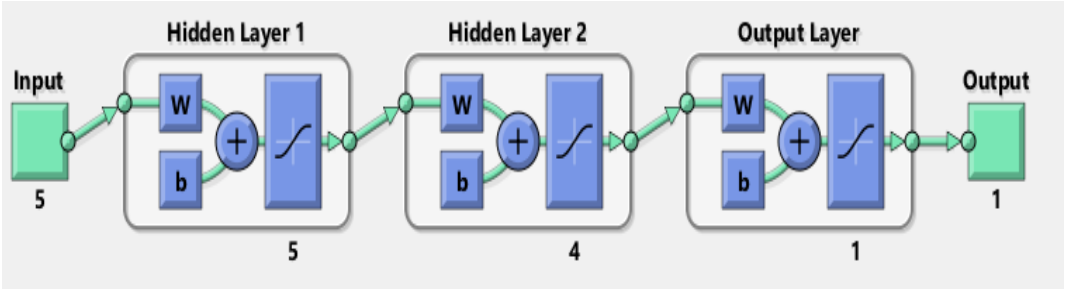

Figure 3.12 Network model.

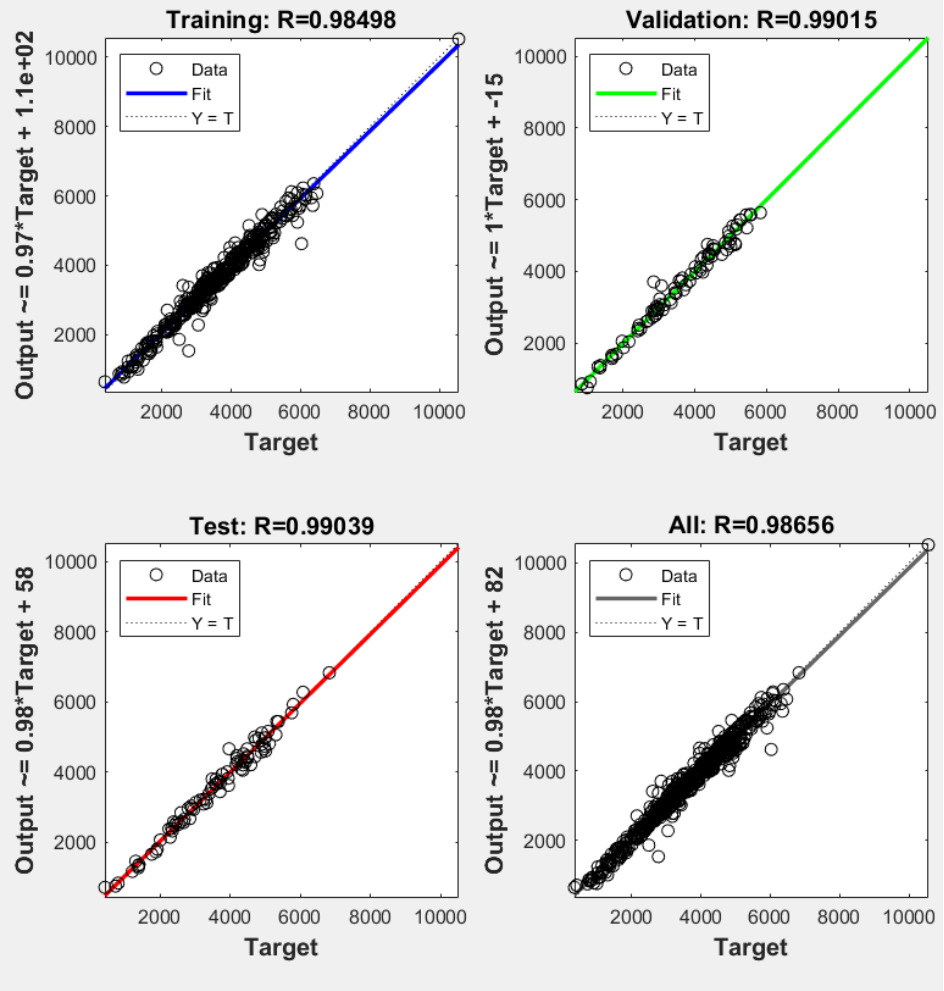

Figure 3.13 Results of training.

While modeling the system, network type, activation function, learning algorithm, hidden layer number, and neuron numbers were determined as a result of various experiments. All of the pieces of training were completed with 5000 epoch values and maximum 5000 error checks. Some examples of trials are shown in table 3.4.

Table 3.4 Some examples of trial.

# Train	# Hidden layer	# Neuron	Learning function	Error function	Network type	R
1	1	8	LM	MSE	Feed-forward backprop	10
2	2	5 - 4	GDX	MSE	Feed-forward backprop	12
3	2	5 - 4	SCG	MSE	Feed-forward backprop	22

Table 3.4 (Continued) Some examples of trial.

# Train	# Hidden layer	# Neuron	Learning function	Error function	Network type	R
4	1	10	SCG	MSREG	Feed-forward backprop	87
5	1	5	GDX	MSE	Feed-forward backprop	90
7	1	5	SCG	MSE	Cascade-backprop	93
8	1	10	LM	MSE	Feed-forward backprop	93
9	1	3	GDX	MSE	Feed-forward backprop	94
10	1	8	GDX	MSREG	Feed-forward backprop	94
11	1	8	SCG	MSREG	Feed-forward backprop	94
12	2	5 - 1	LM	MSE	Feed-forward backprop	95
13	2	5 - 4	LM	MSE	Cascade-backprop	96
14	1	5	LM	MSE	Feed-forward backprop	96
15	1	8	GDX	MSE	Feed-forward backprop	96
16	1	5	GDX	MSREG	Feed-forward backprop	96
17	1	5	SCG	MSE	Feed-forward backprop	96
18	2	4 - 2	LM	MSE	Feed-forward backprop	96
19	1	8	LM	MSE	Cascade-backprop	97
20	1	6	LM	MSE	Feed-forward backprop	97
21	1	4	LM	MSE	Feed-forward backprop	97
22	1	3	LM	MSE	Feed-forward backprop	97
23	1	2	LM	MSE	Feed-forward backprop	97
24	1	10	LM	MSE	Feed-forward backprop	97
25	2	5 - 4	LM	MSE	Feed-forward backprop	98

A comparison was made with statistical methods to check the accuracy of training and test results of the created ANN model. Absolute fraction of variance (R^2), Root mean square error (RMSE) and Mean error percentage (MEP) values were found to compare

both training outputs and test outputs with real values. R^2 with equation 3.7, RMSE with equation 3.8, and MEP with equation 3.9 were calculated.

$$RMSE = \left((1/p) \sum_{\mathrm{j}} \left| t_j - o_j \right|^2 \right)^{1/2} \tag{3.7}$$

$$R^2 = 1 - \left[\frac{\sum_{\mathrm{j}} \left(t_j - o_j \right)^2}{\sum_{\mathrm{j}} \left(o_j \right)^2} \right] \tag{3.8}$$

$$MEP = \frac{\sum_{\mathrm{j}} \left(\frac{t_j - o_j}{t_j} x100 \right)}{p} \tag{3.9}$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results

4.1.1 Fuel Consumption

There is a vortex pilot gas heater application at the station mentioned in this study. The amount of heat required for heating the natural gas at the station was calculated and the fuel consumption was calculated using the efficiency of the heater. Accordingly, the calculated fuel consumption and actual fuel consumption data were compared. The comparisons are given in the table 4.1. This difference varies by month.

Table 4.1 Comparison of fuel consumptions.

Date	Heated gas flow rate (Sm^3/h)	Amount of fuel flow rate (Sm^3/h)	Theoretically calculated amount of fuel flow rate (Sm^3/h)	Theoretically calculated amount of fuel flow rate (no VPGH app.) (Sm^3/h)
January 2016	229,426,496.00	164,989.00	147,800.05	323,370.34
February 2016	134,859,983.00	131,162.00	114,706.28	222,359.37
March 2016	30,899,616.00	30,809.00	25,994.47	50,464.37
April 2016	35,583,492.00	35,150.00	31,584.23	59,898.85
Novomber 2016	90,845,158.00	39,852.00	45,392.52	102,698.11
December 2016	257,848,494.00	145,738.00	151,200.80	312,418.12
January 2017	215,789,523.00	152,369.00	136,023.06	300,104.02
February 2017	200,936,737.00	148,015.00	134,473.69	272,691.92
March 2017	139,998,881.00	144,476.00	122,957.74	229,825.99
April 2017	41,359,808.00	36,223.00	33,385.42	63,801.42
Novomber 2017	167,299,585.00	90,720.00	90,447.82	210,907.61
December 2017	131,024,556.00	67,083.00	81,241.58	175,428.01
January 2018	182,466,800.00	127,016.00	123,615.34	260,472.71
February 2018	168,935,184.00	114,794.00	130,199.53	258,891.21
March 2018	144,616,996.00	133,507.00	125,953.25	233,079.02

Table 4.1 (Continued) Comparison of fuel consumptions.

Date	Heated gas flow rate (Sm^3/h)	Amount of fuel flow rate (Sm^3/h)	Theoretically calculated amount of fuel flow rate (Sm^3/h)	Theoretically calculated amount of fuel flow rate (no VPGH app.) (Sm^3/h)
April 2018	44,812,620.00	39,588.00	35,780.57	69,679.24
October 2018	12,294,428.00	5,639.00	6,320.02	14,162.07
December 2018	206,645,648.00	110,346.81	119,196.14	266,824.74
January 2019	258,504,416.00	199,334.00	187,200.95	379,733.60
February 2019	190,610,809.00	143,080.00	132,169.58	274,291.88
March 2019	173,779,456.00	144,737.00	132,825.28	263,430.55
April 2019	121,169,670.00	104,978.00	99,567.24	191,185.52
Novomber 2019	132,332,613.00	61,600.00	55,468.13	147,842.72
December 2019	244,126,548.00	144,815.00	125,153.84	300,971.37
January 2020	275,149,262.00	183,446.00	166,783.84	359,972.76
February 2020	228,207,301.00	175,821.00	158,968.47	323,442.32
March 2020	156,911,800.00	113,376.00	103,637.70	217,689.18
April 2020	98,994,202.00	72,098.00	67,904.55	140,324.43
Total	4,315,430,082.00	3,060.761.81	2,885,952.09	6,025,961.46

The fuel consumption data in the table are summarized in the figure 4.1.

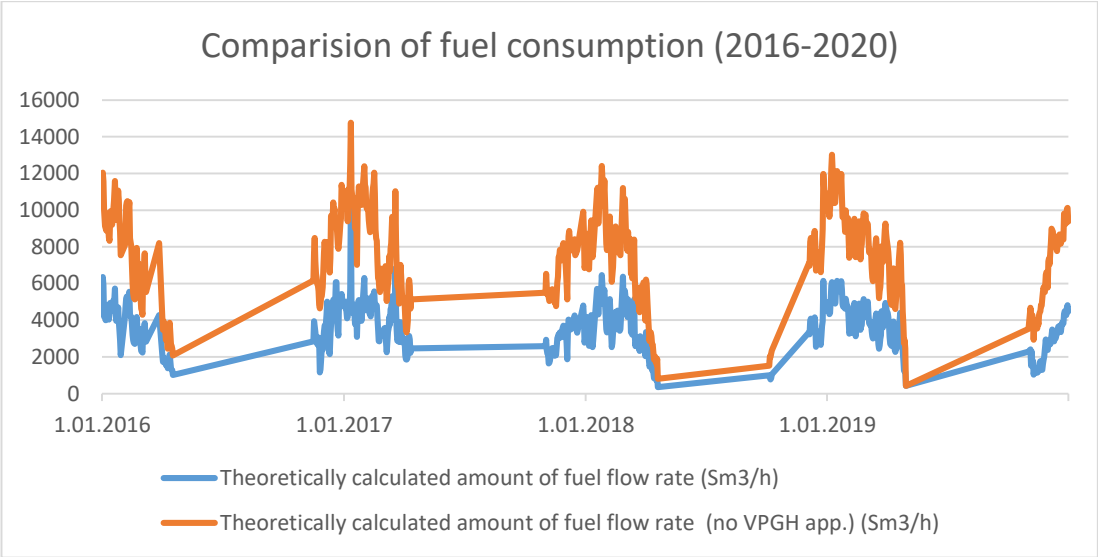

Figure 4.1 Comparison of fuel consumptions.

Fuel consumption was recalculated by assuming that there was no vortex pilot gas heater application at the station. Here it is aimed to show the how affects the vortex tube to fuel consumption. Monthly recoveries are shown in the table 4.2. The comparison here was made according to the theoretical calculation.

Table 4.2 Comparison of monthly fuel consumption between 2016-2020.

Date	Theoretically calculated amount of fuel flow rate (Sm^3/h)	Theoretically calculated amount of fuel flow rate (no VPGH app.) (Sm^3/h)	Real and theoretical fuel consumption comparasion (%)	VPGH and no VPGH app. fuel consumption comparasion (%)
January 2016	147,800.05	323,370.34	-10.42	54.29
February 2016	114,706.28	222,359.37	-12.55	48.41
March 2016	25,994.47	50,464.37	-15.63	48.49
April 2016	31,584.23	59,898.85	-10.14	47.27
Novomber 2016	45,392.52	102,698.11	13.9	55.8
December 2016	151,200.80	312,418.12	3.75	51.6
January 2017	136,023.06	300,104.02	-10.73	54.67
February 2017	134,473.69	272,691.92	-9.15	50.69
March 2017	122,957.74	229,825.99	-14.89	46.5
April 2017	33,385.42	63,801.42	-7.83	47.67
Novomber 2017	90,447.82	210,907.61	-0.3	57.11
December 2017	81,241.58	175,428.01	21.11	53.69
January 2018	123,615.34	260,472.71	-2.68	52.54
February 2018	130,199.53	258,891.21	13.42	49.71
March 2018	125,953.25	233,079.02	-5.66	45.96
April 2018	35,780.57	69,679.24	-9.62	48.65
October 2018	6,320.02	14,162.07	12.08	55.37
December 2018	119,196.14	266,824.74	8.02	55.33
January 2019	187,200.95	379,733.60	-6.09	50.7
February 2019	132,169.58	274,291.88	-7.63	51.81
March 2019	132,825.28	263,430.55	-8.23	49.58
April 2019	99,567.24	191,185.52	-5.15	47.92
Novomber 2019	55,468.13	147,842.72	-9.95	62.48

Table 4.2 (Continued) Comparison of monthly fuel consumption between 2016-2020

Date	Theoretically calculated amount of fuel flow rate (Sm^3/h)	Theoretically calculated amount of fuel flow rate (no VPGH app.) (Sm^3/h)	Real and theoretical fuel consumption comparasion (%)	VPGH and no VPGH app. fuel consumption comparasion (%)
December 2019	125,153.84	300,971.37	-13.58	58.42
January 2020	166,783.84	359,972.76	-9.08	53.67
February 2020	158,968.47	323,442.32	-9,59	50.85
March 2020	103,637.70	217,689.18	-8.59	52.39
April 2020	67,904.55	140,324.43	-5.82	51.61
Total	2,885,952.09	6,025,961.46	-5.71	52.11

Monthly fuel consumption values between 2016-2020 are in table 4.2. The contribution of the vortex tube to fuel consumption can be clearly seen in figure 4.2.

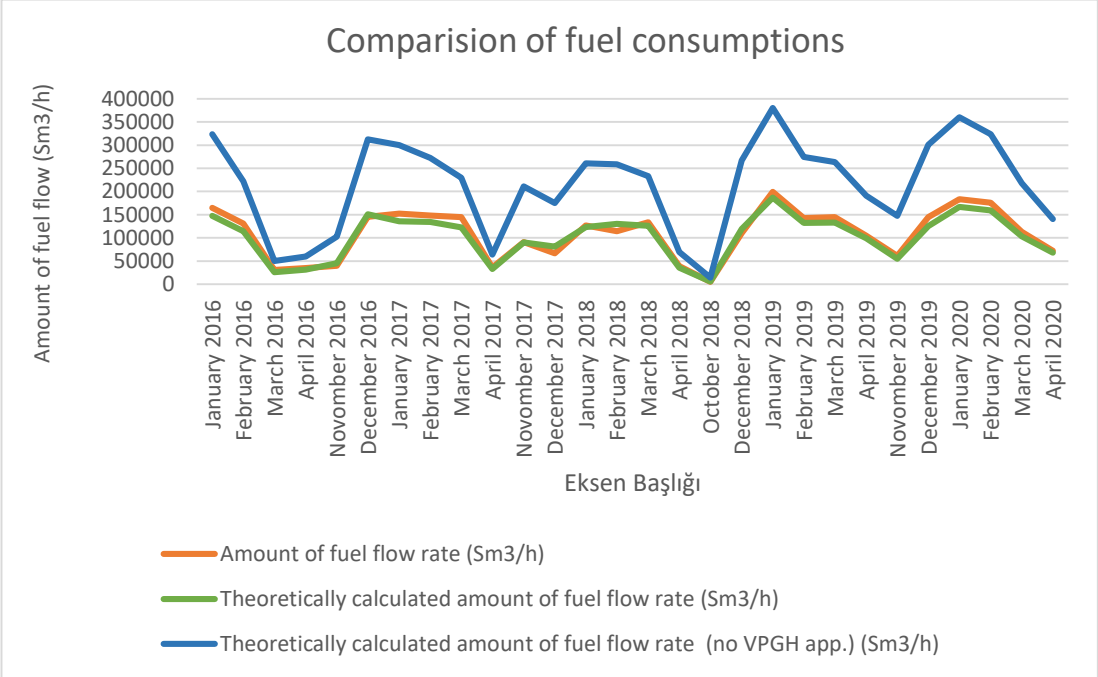

Figure 4.2 Comparison of fuel consumptions.

The amount of heated gas and the amount of consumed gas are directly proportional. The figure 4.3 shows the relationship between the amount of heated gas and fuel consumption by months.

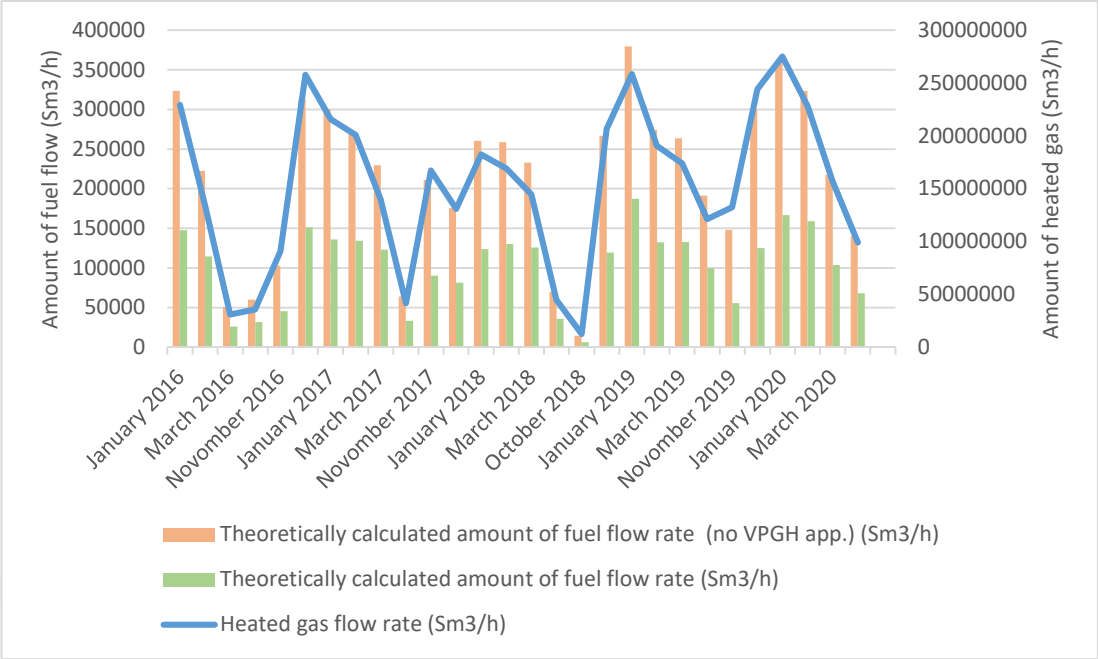

Figure 4.3 The relationship between the amount of heated gas and fuel consumption by months.

The difference in monthly fuel consumption between the case of no vortex tube application and the case of vortex tube application was compared in order to reveal the economic effect of vortex tube on energy gain in the station within the scope of the research. The economic gain of the vortex tube application was calculated over the average monthly m^3 sales price of the gas. Table 4.3 shows the saved amount of fuel consumption and the economic gain. The total economic gain is 4,227,492.18 TL and total saved fuel is 3,140,009.38 Sm^3/h according to the total amount of 4,315,430,082.00 Sm^3/h heated gas flow rate.

Table 4.3 Economic gain and saved amount of fuel (monthly).

Date	Heated gas flow rate (Sm3/h)	VPGH and no VPGH app. fuel consumption comparasion (%)	Sales price of fuel (TL/ m3)	Saved amount of fuel (Sm3/h)	Economic gain (TL)
January 2016	229,426,496.00	54.29	1.13	175,570.29	198,394.40
February 2016	134,859,983.00	48.41	1.13	107,653.09	121,648.00
March 2016	30,899,616.00	48.49	1.13	24,469.90	27,650.98
April 2016	35,583,492.00	47.27	1.13	28,314.62	31,995.52
Novomber 2016	90,845,158.00	55.8	1.03	57,305.59	59,024.75

Table 4.3 (Continued) Economic gain and saved amount of fuel (monthly).

Date	Heated gas flow rate (Sm3/h)	VPGH and no VPGH app. fuel consumption comparasion (%)	Sales price of fuel (TL/ m3)	Saved amount of fuel (Sm3/h)	Economic gain (TL)
December 2016	257,848,494.00	51.6	1.05	161,217.32	169,278.20
January 2017	215,789,523.00	54.67	1.07	164,080.97	175,566.60
February 2017	200,936,737.00	50.69	1.1	138,218.23	152,040.10
March 2017	139,998,881.00	46.5	1.11	106,868.25	118,623.80
April 2017	41,359,808.00	47.67	1.11	30,416.00	33,761.76
Novomber 2017	167,299,585.00	57.11	1.05	120459.79	126,482.80
December 2017	131,024,556.00	53.69	1.09	94,186.43	102,663.20
January 2018	182,466,800.00	52.54	1.12	136,857.37	153,280.30
February 2018	168,935,184.00	49.71	1.13	128,691.68	145,421.60
March 2018	144,616,996.00	45.96	1.12	107,125.78	119,980.90
April 2018	44,812,620.00	48.65	1.11	33,898.67	37,627.53
October 2018	12,294,428.00	55.37	1.09	7,842.05	8,547.84
December 2018	206,645,648.00	55.33	1.46	147,628.60	215,537.80
January 2019	258,504,416.00	50.7	1.46	192,532.65	281,097.70
February 2019	190,610,809.00	51.81	1.36	142,122.29	193,286.30
March 2019	173,779,456.00	49.58	1.37	130,605.28	178,929.20
April 2019	121,169,670.00	47.92	1.35	91,618.28	123,684.70
Novomber 2019	132,332,613.00	62.48	1.73	92,374.59	159,808.00
December 2019	244,126,548.00	58.42	1.77	175,817.53	311,197.00
January 2020	275,149,262.00	53.67	1.79	193,188.92	345,808.20
February 2020	228,207,301.00	50.85	1.8	164,473.85	296,052.90
March 2020	156,911,800.00	52.39	1.82	114,051.48	207,573.70
April 2020	98,994,202.00	51.61	1.83	72,419.88	132,528.40

The amount of heated gas by years, the amount of saved fuel, and economic gain is summarized in the table 4.4.

Table 4.4 Economic gain and saved amount of fuel (yearly)

Date	Heated gas flow rate (Sm^3/h)	Saved amount of fuel (Sm^3/h)	Economic gain (TL)
2016	779,463,239.00	554,530.80	607,991.86
2017	896,409,090.00	654,229.68	709,138.20
2018	759,771,676.00	562,044.15	680,395.84
2019	1,120,523,512.00	825,070.61	1,248,002.95
2020	759,262,565.00	544,134.13	981,963.16

Since there are three pressure reduction lines in the current station, the vortex pilot gas heater is also three pieces. The approximate cost of one vortex pilot gas heater application is 106,294 TL, and the total cost is 106,294X3 = 318,882 TL. Considering the achieved economic gain, it is seen that the vortex tube application has covered its cost within three months.

4.1.2 ANNs Model Results

580 days of data for the years 2016-2019 were used as training data. The network consisting of 5 and 4 neurons with 2 hidden layers has been trained with LM learning algorithm. After learning the network, training output values and actual output values were compared. The comparison is shown in the figure 4.4.

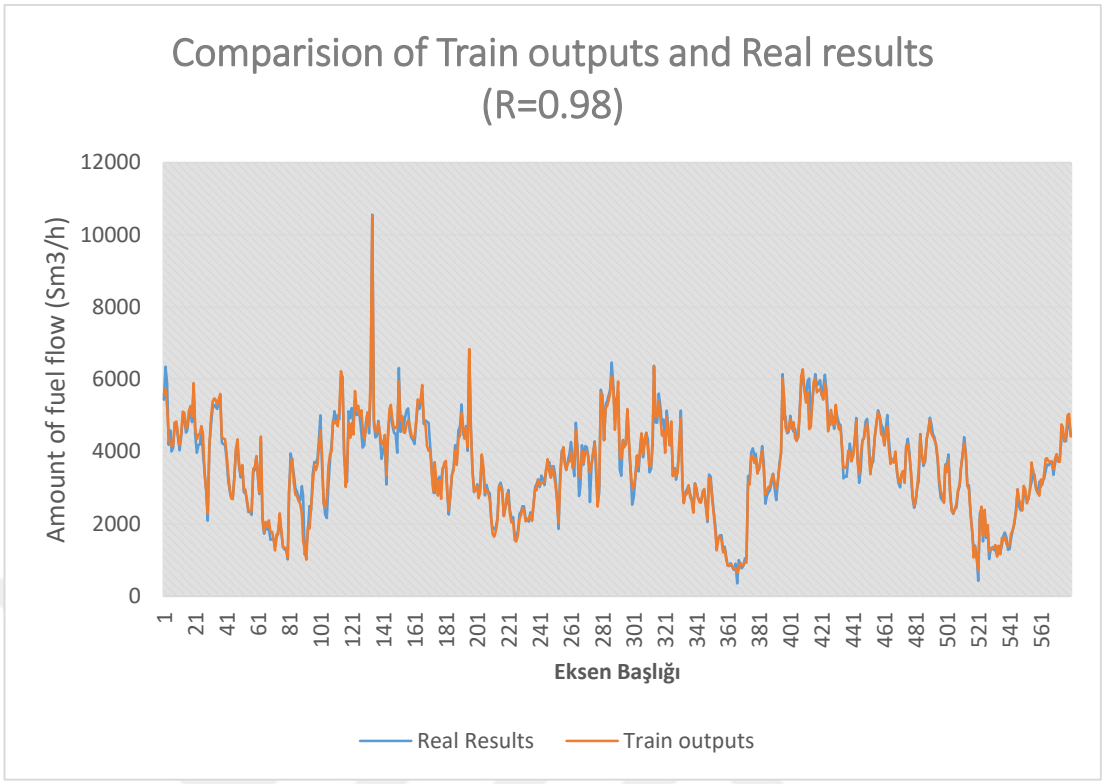

Figure 4.4 Comparison of train outputs and real results.

After the training, it was tested with 121 days of data from 2020. Test results are compared with real results. It was seen in figure 4.5.

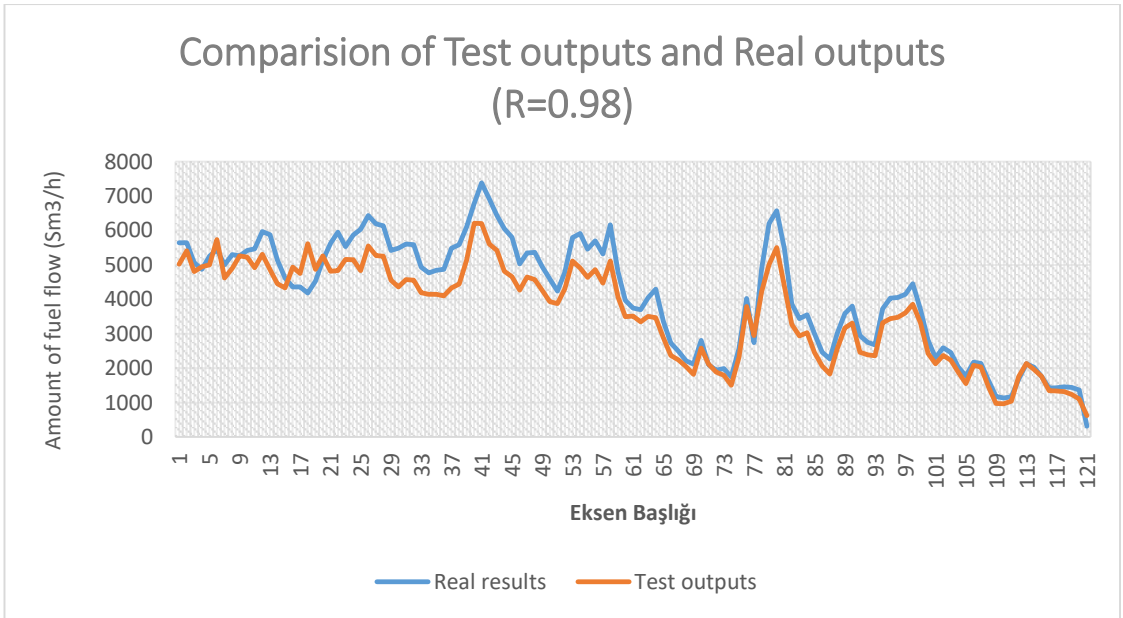

Figure 4.5 Comparison of test outputs and real results.

The accuracy of the training and test results of the created network was checked by statistical methods. The results of the comparison of the training and test results of the network with their actual values are in Table 4.5.

Table 4.5 Statistical performance of network.

	Absolute Fraction of Variance (R^2)	**Root Mean Square Error (RMSE)**	**Mean Error Percentage (MEP %)**
Training results	0.98	0.025	4.56
Test results	0.97	0.063	13.05

4.2 Discussion

In this study, the positive effect of the vortex tube, which was emphasized in many studies on station efficiency and energy saving, on station costs was theoretically proved. According to the results of the heat analysis, it was calculated that 52.11 percent saving was achieved when the vortex tube was used. In addition, this saving was supported by the results of modeled ANN calculations and aimed to guide other stations in application.

In the literature review conducted on this subject, similar research was found by Yılmaz et al. (2007) in Erzurum RMS-A station. According to 2007 data, the researchers stated that the fuel consumption for heating was 700,612 Sm^3/h, and this amount would be saved if the vortex tube was used. Kibritçi (2014) also stated that the use of vortex tube will save energy. The researcher emphasized that, although the investment cost is high, the operation and maintenance costs are very low, and the use of tubes will save energy with low costs. Shaıkhutdınov (1999) again drew attention to energy saving. He stated that this can be achieved by reducing the need for preheating of the gas by using the vortex tube. Köse (2014) similarly explained the effect of tube use on energy saving. He also stated that the cold outlet of the tube can be used in various cooling functions. Based on all these researches, it can be said that the use of vortex tubes has an effect on energy saving and therefore it can be benefited in terms of energy saving in the natural gas sector.

The results obtained from the network were also checked by statistical methods. There are R^2=0.98, MEP %=4.56 and RMS=0.025 for the training results, and R^2=0.97, MEP %=13.05 and RMS =0.063 for the training results. These values show that it is statistically significant and consistent. The results obtained are interrelated and it is proved that there is no significant difference between the data.

CHAPTER 5

CONCLUSION

In this study, the advantages and effects of vortex tube use in natural gas pressure reduction and measuring stations are investigated. For this, primarily information was given about natural gas properties, production, and consumption. A research was conducted on energy recovery at stations, and information was given about researches on the use of vortex tubes. Natural gas pressure reduction and measurement station equipment were introduced within the scope of the study. In particular, the effects of the pressure drop and the temperature decrease during the pressure drop were be emphasized. At this point, the preheating requirement is explained, and how this was done at the selected station was mentioned. General features of vortex tube and vortex pilot gas heater were described.

Afterwards, a station with vortex tube pilot gas heater was selected in Ankara, and calculations were made based on the station's data for 2016-2019. In the calculation, the standard values taken daily from the station were used. These are gas component percentages, thermal values of the gas, inlet and outlet temperature, inlet and outlet pressure and gas amount passing through the station. Here, the temperature of the gas after heating was determined from the station outlet temperature and basic drop rate of the gas. While determining the specific heat value of the gas, the function has been established according to the temperature change under constant pressure. The gases used was considered ideal. Accordingly, preheating fuel consumption before and after vortex tube usage was calculated and consumption amounts were compared. As a result of the comparison, the positive effect of vortex tube use on the amount of fuel consumption was observed. When all the data were examined, it was seen that the total difference was 5.71 percent.

When the vortex tube was used, the total fuel consumption in the specified four years was found to be 2,388,657 Sm^3/h. In the assumption that there is no vortex tube application, it was calculated as 4,984,532 Sm^3/h. In this study, it is seen that a total of 51.86 percent saving is achieved by using only vortex tube at the station.

There is a 5.71 % difference between the theoretically calculated fuel consumption and the current fuel consumption. The main reason for this difference is that there is not enough data to calculate heat losses. As another reason, operational problems such as failure of the heater in the station, cold weather conditions, sudden malfunctions can be shown. When all data were examined, it was seen that it reduced fuel consumption by 52.11. percent. The main reason of this contribution is that it provides the opportunity to reduce the station outlet temperature to 3 °C when the vortex tube is used.

When the energy gain of the vortex tube at the station is examined economically, it is seen that it has gained 4,227,492.01 TL according to the current data between 2016-2020. The vortex pilot gas heater, with an approximate installation and device cost of 318,882 TL, paid off its own cost in approximately 3 months.

In this study, artificial neural network modeling was also performed. For this, the network was trained with the data of 2016-2019. It was determined as feed forward back propagation as a network algorithm. The number of hidden layers of the network was determined as 2 according to the results of trial and error. 5 neurons were selected in the first hidden layer, and 4 neurons were selected in the second hidden layer. Tangent hyperbolic activation function was used in hidden layers and output layer. The training of the model with the data for 2016-2019 was completed using the Levenberg-Marquardt (LM) algorithm. The most successful result was R value of 0.98. It was tested with a four-month data of the year 2020 with the network trained according to these values. When the results of the test and the available data are compared, the results are close to each other. This reveals the validity of the modeled ANN. This is another proof of the efficiency of vortex tube application on fuel consumption. In addition, when any station adds the specified data as input to the network, it can reach the amount of fuel it will consume when the vortex tube is used and the amount of fuel when there is no vortex tube application. Thus, this ANN also provides resources for fuel consumption efficiency and comparison that they will reach other stations in the form of vortex tube applications.

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APPENDIX

Appendix A – Example of ANN data

Appendix A - Example of ANN data

Table A.1 Example of training data.

Date	Heater inlet temperature (°C)	Station inlet pressure (bar)	Station outlet pressure (bar)	Heated gas amount (Sm^3/h)	Lower heating value (kJ/kg.K)	Theoretical fuel consumption (Sm^3/h)
6.01.2016	12.07	57.13	17.38	7492256	48646.75	4002.34
12.01.2016	12.17	67.02	17.44	5705824	48624.28	4409.47
20.01.2016	11.19	62.94	17.38	8227776	48296.27	5726.52
5.02.2016	10.8	67.54	17.35	5661568	48519.51	4721.19
13.02.2016	10.9	63.73	17.34	5679104	48097.98	4201.99
25.02.2016	10.21	60.39	43907	5057440	47720.63	3546.65
26.02.2016	10.41	61.57	17.37	3976416	47698.19	2867.22
29.02.2016	10.35	59.6	17.36	3393856	48295.78	2323.68
6.03.2016	10.33	59.07	17.34	4823424	48478.5	3294
3.12.2016	14.45	57.27	17.87	7318462	48519.48	3687.54
8.12.2016	13.82	47.76	17.79	8272288	49020.13	2668.15
11.12.2016	14.19	54.56	44091	7335488	48929.54	3069.62
19.12.2016	13.24	52.92	17.57	9359744	48892.27	6071.6
22.12.2016	12.93	46.86	17.87	9360192	48555.64	3425.53
29.12.2016	12.67	62.29	17.03	8358720	49036.69	5008.07
4.01.2017	12.38	54.2	17.76	9907667	48517.7	4508.41
7.01.2017	12.47	59.73	17.96	8300288	48743.93	4797.09
14.01.2017	11.92	56.23	17.9	8986880	48388.82	4429.42
19.01.2017	11.96	58.95	17.99	7767552	48398.83	4340.84
27.01.2017	11.05	52.72	17.75	9159040	48975.89	3962.47
4.02.2017	11.37	56.2	17.85	8404224	48898	4924.54
9.02.2017	11.05	61.03	17.67	6510656	48692.38	4319.76
10.02.2017	10.75	59.58	17.65	6704192	48375.96	4203.12
13.02.2017	10.16	57.76	17.59	8517632	48428.53	5177.9
23.02.2017	10.07	43.13	17.69	6162260	48988.44	2850.67
4.03.2017	9.37	62.49	17.64	4663296	48026.04	3567.21
8.03.2017	9.52	63.71	17.68	3980672	48583.7	3362.8
12.03.2017	9.58	64.17	17.61	5214336	48528.18	4584.05
22.03.2017	10.21	57.39	17.66	4531200	48399.25	2879.11
3.04.2017	10.28	61.18	17.6	2893376	48163.87	2071.94
8.04.2017	10.28	59.91	17.2	4278144	48272.34	3048.93
4.11.2017	16.34	57.87	17.29	5330810	47934.89	2159.83
7.11.2017	16.45	53.67	17.32	5680068	48094.86	1674.88
11.11.2017	16.42	62.15	17.24	5081260	48248.94	2487.13
21.11.2017	15.7	61.49	17.08	6497636	48160.6	3234.17
2.12.2017	15.66	64.49	17.44	5558848	48994.3	3283.56
8.12.2017	15.23	60.39	17.24	7280448	49008.26	3635.63
15.12.2017	15.06	65.28	17.56	6707412	49016.93	4269.73
29.12.2017	14.01	60.94	16.69	7261000	49011.16	4103.14
1.01.2018	14.41	63.73	17.49	6736120	48168.32	4176.24
4.01.2018	13.9	61.58	17.43	7046536	47830.93	4127.42
9.01.2018	13.68	60.69	16.62	7584928	47960.33	4284.04

Table A.1 (Continued) Example of training data.

Date	Heater inlet temperature (°C)	Station inlet pressure (bar)	Station outlet pressure (bar)	Heated gas amount (Sm^3/h)	Lower heating value (kJ/kg.K)	Theoretical fuel consumption (Sm^3/h)
23.01.2018	12.89	65.15	17.65	7769584	47999.3	5573.9
26.01.2018	12.66	63.16	17.65	8746608	48175.69	5832.25
2.02.2018	12.73	55.55	17.53	7001216	49030.45	3329.75
7.02.2018	12.22	63.96	17.63	6120832	48216.45	4205.12
11.02.2018	12.37	59.53	17.56	5561056	48970	3301.56
18.02.2018	12	65.09	17.53	6109296	48533.87	4521.46
5.03.2018	12.17	63.58	17.46	5702208	48811.94	4167.37
9.03.2018	12.07	65.02	10.34	5257120	48765.51	4642.33
12.03.2018	12.22	64.17	16.85	4486240	48538.5	3222.14
20.03.2018	12	66.62	16.93	3733696	48732.16	3050.25
24.03.2018	11.51	64.75	17.4	4028352	48270.09	3126.74
30.03.2018	12.23	61.89	17.43	4474560	48119.11	2941.95
2.04.2018	11.94	65.06	17.4	4346656	48201.89	3359.56
5.10.2018	17.01	61.38	16.85	1410300	48756.55	997.63
8.10.2018	17.84	61.05	16.98	2161120	49045.76	841.98
6.12.2018	15.85	65.88	17.26	6626816	48448.15	3985.74
11.12.2018	15.43	60.07	17.41	7334432	48452.44	3488.93
15.12.2018	15.18	53.7	17.47	7100160	49022.02	2554.82
22.12.2018	14.29	54.94	17.53	6452220	48589.56	2657.79
26.12.2018	14.04	60.87	11.81	8710848	48616.4	6146.79
28.12.2018	13.43	58.41	17.5	8948064	48565.08	4969.61
1.01.2019	13.75	59.51	17.59	8882720	48057.57	4691.71
3.01.2019	13.47	57.8	17.57	8560768	48571.48	4628.41
6.01.2019	13.25	60.37	17.62	9014624	48535.28	5121.43
12.01.2019	12.59	59.43	17.63	8436864	48687.88	6025.18
14.01.2019	13.3	64.45	17.66	8228544	48188.17	5417.7
18.01.2019	12.82	62.44	17.6	9062240	48440.58	5879.64
2.02.2019	11.57	58.03	17.71	6796544	48639.85	4063.58
5.02.2019	11.84	58.49	17.74	6096224	48424.27	3301.72
7.02.2019	11.4	57.97	17.69	6664768	48349.93	4220.98
12.02.2019	10.59	54.47	17.7	6554560	47932.9	3919.1
15.02.2019	10.91	56.26	17.68	7390080	48073.81	4300.52
21.02.2019	10.99	56.6	17.74	6381952	47946.55	3645.85
1.03.2019	11.09	55.25	17.68	7500928	48514.36	4177.78
5.03.2019	11.15	57.27	17.72	6176064	48532.04	3841.24
16.03.2019	10.99	61.48	17.69	6132352	49063.27	4358.99
18.03.2019	11.32	61.39	17.74	5089600	48390.06	3367.74
8.11.2019	16.89	61.48	12.42	3676510	47084.63	1759.63
11.11.2019	16.64	58.35	17.19	3640240	46883.4	1352.62
19.11.2019	15.38	53.87	18.85	4892519	47470.01	1758.17
21.11.2019	16.5	52.41	18.78	5906409	48795.08	1285.5
2.12.2019	14.78	56.28	18.72	7298015	48307.45	2794.45
5.12.2019	15.31	56.65	18.57	8256395	48111.16	2994.68
7.12.2019	15.3	56.37	18.48	8975670	48122.87	3497.24
31.12.2019	14.62	61.51	18.46	8080702	48657.05	4467.38

Table A.2 Example of test data

Date	Heater inlet temperature (°C)	Station inlet pressure (bar)	Station outlet pressure (bar)	Heated gas amount (Sm^3/h)	Lower heating value (kJ/kg.K)	Theoretical fuel consumption (Sm^3/h)
1.01.2020	14.75	64.83	18.49	8137955.00	48873.59	5640.12
2.01.2020	14.26	62.47	18.42	8794812.00	48938.53	5641.15
5.01.2020	14.29	60.51	18.44	8714702.00	48955.32	5255.24
7.01.2020	14.06	58.25	18.40	8697226.00	48545.77	5000.98
12.01.2020	13.98	64.14	18.46	8626583.00	48433.38	5964.97
13.01.2020	13.37	60.67	18.41	8772155.00	48612.34	5875.97
16.01.2020	12.92	53.74	18.44	8809804.00	48853.88	4359.11
18.01.2020	12.80	52.14	18.44	8877438.00	49043.29	4185.14
19.01.2020	13.11	55.56	18.45	8996326.00	48739.95	4529.10
20.01.2020	12.69	55.25	18.40	9589166.00	48655.98	5131.19
21.01.2020	12.66	55.76	18.41	9422387.00	48444.67	5627.17
22.01.2020	12.17	57.09	18.42	9431213.00	48482.68	5948.66
23.01.2020	12.19	54.75	18.41	9653032.00	48818.08	5529.81
25.01.2020	12.35	58.50	18.49	9087286.00	48684.16	6034.59
26.01.2020	12.91	64.19	18.54	8608502.00	48710.97	6431.76
31.01.2020	11.89	57.37	18.45	8649738.00	48842.39	5601.14
1.02.2020	12.06	59.04	18.48	8203494.00	48989.24	5586.22
2.02.2020	11.84	58.05	18.55	7504738.00	48980.38	4931.64
4.02.2020	11.68	57.58	18.54	7298501.00	47382.95	4845.77
6.02.2020	11.28	56.39	18.51	7897830.00	48242.01	5484.73
7.02.2020	11.02	54.81	18.45	8482207.00	47790.74	5584.80
11.02.2020	10.80	55.75	18.37	9969124.00	47600.72	6914.47
12.02.2020	10.87	57.22	18.42	9239406.00	47562.44	6434.27
14.02.2020	10.59	54.68	18.51	8515029.00	47038.99	5802.76
16.02.2020	10.76	57.86	18.57	7726035.00	47784.21	5348.99
19.02.2020	10.37	54.10	18.58	7106087.00	47524.67	4586.86
20.02.2020	10.49	54.72	18.60	6928844.00	47423.91	4235.90
24.02.2020	10.30	58.49	18.58	7103330.00	46858.60	5458.41
25.02.2020	10.50	59.54	18.46	7230766.00	46826.39	5702.49
29.02.2020	10.19	51.37	18.30	6711013.00	47039.81	3971.51
1.03.2020	10.69	53.78	18.32	6496001.00	47259.32	3742.61
3.03.2020	11.77	61.88	18.35	5322272.00	46887.25	4039.88
4.03.2020	11.57	63.63	18.32	4931080.00	46880.88	4296.02
6.03.2020	10.86	51.19	17.93	4824761.00	47070.40	2732.01
13.03.2020	11.51	54.86	17.07	3420364.00	47646.46	1989.19
14.03.2020	11.34	54.79	17.07	2820999.00	48641.25	1742.37

Table A.2 (Continued) Example of test data

Date	Heater inlet temperature (˚C)	Station inlet pressure (bar)	Station outlet pressure (bar)	Heated gas amount (Sm^3/h)	Lower heating value (kJ/kg.K)	Theoretical fuel consumption (Sm^3/h)
16.03.2020	9.99	50.65	16.95	6799457.00	48467.73	4027.85
19.03.2020	10.95	57.71	16.94	8260027.00	48098.62	6198.72
21.03.2020	10.99	61.53	17.31	6311138.00	48947.94	5468.31
22.03.2020	10.91	59.64	17.38	4915203.00	48535.05	3867.54
26.03.2020	10.91	56.37	17.40	3654965.00	47047.30	2458.65
27.03.2020	10.89	54.91	17.40	3504933.00	47017.67	2266.21
28.03.2020	10.70	54.12	17.35	4642540.00	47028.46	3007.57
29.03.2020	11.13	56.76	17.32	5336612.00	47069.22	3585.72
31.03.2020	11.40	55.86	17.37	4417053.00	46956.91	2940.89
1.04.2020	11.25	53.32	17.36	4607036.00	46900.01	2750.11
2.04.2020	11.37	53.20	17.37	4584211.00	46980.97	2675.41
3.04.2020	11.70	57.00	17.30	5718495.00	46998.12	3721.77
4.04.2020	12.15	63.99	17.37	4793000.00	48295.65	4029.93
7.04.2020	11.41	65.91	17.37	4794023.00	48887.90	4454.20
8.04.2020	11.09	63.47	17.38	4366979.00	48898.31	3703.39
9.04.2020	10.91	57.11	17.39	3879871.00	48920.26	2801.41
11.04.2020	11.53	61.95	17.45	3275801.00	48921.55	2589.70
13.04.2020	11.01	57.21	17.42	2989899.00	49101.88	2033.77
14.04.2020	11.30	56.45	17.45	2670740.00	49098.45	1772.67
17.04.2020	11.46	57.73	17.45	2456435.00	49095.43	1629.86
18.04.2020	11.49	56.46	17.48	1813754.00	49100.23	1175.01
19.04.2020	11.72	56.51	17.48	1808718.00	49097.73	1129.23
21.04.2020	10.99	54.01	17.41	3130939.00	49096.41	1678.32
22.04.2020	10.68	52.65	17.39	3833539.00	49090.12	2125.90
24.04.2020	11.17	52.98	17.44	3267431.00	49094.23	1759.44
25.04.2020	11.55	53.15	17.46	2698169.00	49096.84	1419.13
26.04.2020	11.74	54.41	17.46	2616983.00	49097.52	1426.40
28.04.2020	11.86	55.49	17.47	2399632.00	49098.40	1441.15