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Back-up the Natural Gas Combustion System of Bar Rolling Mill Annealing Furnace with LPG

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by

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Date: 10.09.2023

Back-up the Natural Gas Combustion System of Bar Rolling Mill Annealing Furnace with LPG

Abstract

In recent years, due to cost and supply issues, Liquefied Petroleum Gas (LPG) has been planned as an alternative to natural gas used in the combustion process of the annealing furnace. Direct utilization of LPG in the system is not possible due to differences in its calorific value and relative density. To use pure LPG, all orifices and burner nozzles in the furnace annealing system need to be replaced. The required revisions in the annealing furnace result in production and labor losses. For these reasons, calculations of the Wobbe index, which is the substitutability parameter between gases, have been performed. The Wobbe index is a measure of the heat input to a device at a specific pressure through a certain opening and is proportional to the lower heating value and relative density of the gas. Analytical values of the mixture of natural gas and LPG, as well as their lower heating values and the required amount of oxygen for complete combustion, have been calculated. The calorific value and density of LPG are higher than that of natural gas. To equalize the Wobbe index, a mixture of LPG and air is required. In the mixture calculations, a 45,5% air and 54,5% LPG composition ratio has been determined, and there is no need for any changes in the air fan flow rate for complete combustion. An LPG-air mixer with a capacity of 4000 Nm^3/h has been designed. The designed mixer consists of a pressure regulator, vortex flowmeter, flow control valve, static mixer, pneumatic actuated valve, gas analyzer, manometer, and thermometer equipment. This equipment is controlled by a PLC system. The mixer has been manufactured and commissioned. The nominal operating oxygen values in the flue gas are captured within the range of $1\% < O_2 < 6\%$ using the LPG-air mixer. The system is backed up to operate by simply opening and closing the valve without requiring any shutdowns.

Keywords: LPG-air Mixer, Bar Rolling Annealing Furnace, Fuel Replacement, Combustion

Çubuk Haddehanesi Tav Fırınının Doğal Gaz Yanma Sisteminin LPG ile Yedeklenmesi

Öz

Hadde tav fırınında yanma prosesinde kullanılan doğal gaz son yıllarda maliyet ve tedarik problemleri sebebiyle alternatif olarak LPG kullanımı planlanmıştır. LPG’nin kalorifik değeri ve bağıl yoğunluk farklarından dolayı sistemde direkt kullanılamamaktadır. Saf LPG kullanımı için fırın tav sisteminde tüm orifislerin ve brülör namlularının değişmesi gerekmektedir. Tav fırınında yapılması gereken revizyonlar üretim ve iş gücü kaybına neden olmaktadır. Bu sebeplerle gazların birbirlerine ikame edilebilirlik parametresi olan Wobbe endeksi hesaplamaları yapılmıştır. Wobbe endeksi gaz alt ısıl değeri, bağıl yoğunluğu ile orantılıdır ve belirli bir açıklıktan belirli bir basınçta bir cihaza verilecek ısı girdisinin ölçüsüdür. Doğal gazın ve LPG’nin karışım analiz değerleri ile alt ısıl değerleri ve tam yanma için gerekli oksijen miktarları hesaplanmıştır. LPG’nin kalorifik değeri ve yoğunluğu doğal gazdan yüksektir. Wobbe endeksini eşitlemek için LPG ve hava karışımı gerekmektedir. Yapılan karışım hesaplamalarında %46,5 Hava ve %54,5 LPG karışım oranı belirlenmiştir ayrıca tam yanmanın oluşabilmesi için hava fanı debisinde herhangi bir değişikliğe ihtiyaç yoktur. 4000 Nm^3/h kapasiteli LPG-hava karıştırıcı tasarlanmıştır. Tasarlanan karıştırıcı; basınç regülatörü, vorteks debimetre, akış kontrol valfi, statik mikser, pnömotik aktüatörlü vana, gaz analizörü, manometre, termometre ekipmanlarından oluşmaktadır. Bu ekipmanlar PLC sistemi ile kontrol edilmektedir. Karıştırıcı imalatı yapılmış ve devreye alınmıştır. Baca gazı içindeki nominal çalışma hacimsel oksijen değerleri $\%1<O_2<\%6$ aralığı LPG-Hava Karıştırıcı ile yakalanmıştır. Sistem hiçbir duruşa ihtiyaç duymadan, sadece vana açıp, kapatarak çalışacak şekilde yedeklenmiştir.

Anahtar Kelimeler: LPG-Hava Karıştırıcı, Çubuk Hadde Fırını, Yakıt Değişimi, Yanma

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List of Abbreviations

UEL	Upper Explosive Limit
LEL	Lower Explosive Limit
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
LPG	Liquefied Petroleum Gas
FT	Flow Transmitter
FCV	Flow Control Valve
R	Regulator
PT	Pressure Transmitter
TT	Thermal Transmitter
S	Shutoff Valve
LNG	Liquefied Natural Gas
SNG	Synthetic Natural Gas
EPDK	Energy Market Regulatory Authority

List of Symbols

$\dot{M}$	Mass Flow Rate (kg/h)
v	Fluid velocity (m/s)
$\dot{V}$	Normal Volume Flow Rate (Nm^3/h)
R_u	Universal Gas Constant (kj/kmol ºK)
R	Gas Constant (kj/kg ºK)
$\overline{V}$	Molar Volume (Nm^3/kmol)
$\overline{M}$	Molar Mass (kg/kmol)
H_U	Lower Heat Value (kcal/Nm^3)
ρ	Density (kg/Nm^3)
$\dot{Q}$	Volume Flow Rate (m^3/s)
A	Pipe Section Area (m^2)
D	Pipe diameter (m)
r_X	Volumetric Ratio of Molecules in the Mixture
$(H_u)_{C_xH_y}$	Lower Calorific Value of Hydrocarbon in the Mixture(kcal/Nm^3)
μ	Dynamic Viscosity (Pa. s)
d	Orifice Diameter (mm)
q_m	Mass Flow Rate (kg/s)
Δp	Differential Pressure (Pa)
Re	Reynolds Number
β	d/D Ratio
X_{NG}	Natural Gas

Chapter 1

Introduction

Natural gas is widely used in industrial facilities, businesses, and households across all regions of our country. It is the most preferred fossil fuel in Turkey due to its low emissions, ease of distribution and operation, user comfort, and low-cost maintenance.

However, as is well known, our country is also an importer of fossil fuels. While the supply of natural gas has been diversified, especially in recent years, supply-related disruptions due to supplier issues, international political factors affecting supply or price policy variability have posed challenges for industrial establishments in our country. Examples include the decrease in gas supply attributed to faults in gas imported from Iran in 2020 and 2023, the stability of LPG prices while natural gas prices surged during the Ukraine-Russia war, and problems in imports [1][2].

For industrial facilities that are set up to use natural gas, interruptions in natural gas supply or the high cost of natural gas procurement can significantly increase the costs of industrial facilities in our country, making them unable to compete with their foreign counterparts, and even leading to production stoppages. For this reason, industrial establishments, especially those in the iron and steel sector, have been seeking alternative fuels to natural gas.

LPG (Liquefied Petroleum Gas) is one of the petroleum products that can be stored in liquid form and used in the gas phase, with a high calorific value. It is a good alternative for industrial establishments. In our country, the production of LPG in petroleum refineries, its storage, and its transportation by tanker ships from many different countries have diversified its supply. Additionally, infrastructure such as storage is available in our country thanks to its long-term use as fuel in rural areas and vehicles.

In our country, LPG-air mixers are already being used in some sectors such as glass and ceramics. These mixers are imported from the Far East or European countries. Although offers have been received from relevant companies, the feasibility was not deemed suitable due to price and delivery time reasons.

This study aims to determine the working principle of the reheat furnace using natural gas in the Habaş Iron and Steel facilities, to extract the necessary criteria for replacing natural gas with LPG, to perform calculations, to design the LPG-air mixer system, to manufacture it, and to observe the results.

Chapter 2

Literature Research

Natural gas is used in various sectors across our country, including industry, power plants, households, the service sector, transportation, and all regions. According to EPDK (Energy Market Regulatory Authority) data, 99.31% of this consumption is imported, while 0.69% is domestically produced [3]. Such widespread and intensive consumption has made natural gas indispensable. However, occasional supply and price issues have prompted major industrial enterprises to seek alternatives.

Solid fuels like coal cannot be used directly in reheating furnaces at steel mills, and liquid fuels such as fuel oil and diesel create solid particles, soot, and ash in the furnaces, reducing furnace efficiency. This situation increases maintenance periods and reduces production quantities. The transition to alternative fuels and every fuel change will lead to labor and production losses."

Table 2.1: Comparison of methane, ethane, propane, butane properties [4][5]

	Chemical Formula	Boiling Point (ºC) 1 atm	Density $\rho, kg/m^3$	H_U (Kcal/Nm^3)	[UEL]	$[LEL]$
Methane	CH_4	-161,5	0,7157	8785,32	5,0	15,0
Ethane	C_2H_6	-88	1,3416	15574,56	3,0	12,4
Propane	C_3H_8	-42,1	1,9674	22267,16	2,1	9,5
Butane	C_4H_{10}	-0,5	2,5932	28909,04	1,8	8,4

Natural gas contains over 95% methane gas. As seen in Table 2.1, methane gas has a lower calorific value compared to other hydrocarbons. Its low boiling point enables it to remain in gaseous form even at high pressures. For combustion, it needs to mix volumetrically with air in the range of 5-15%.

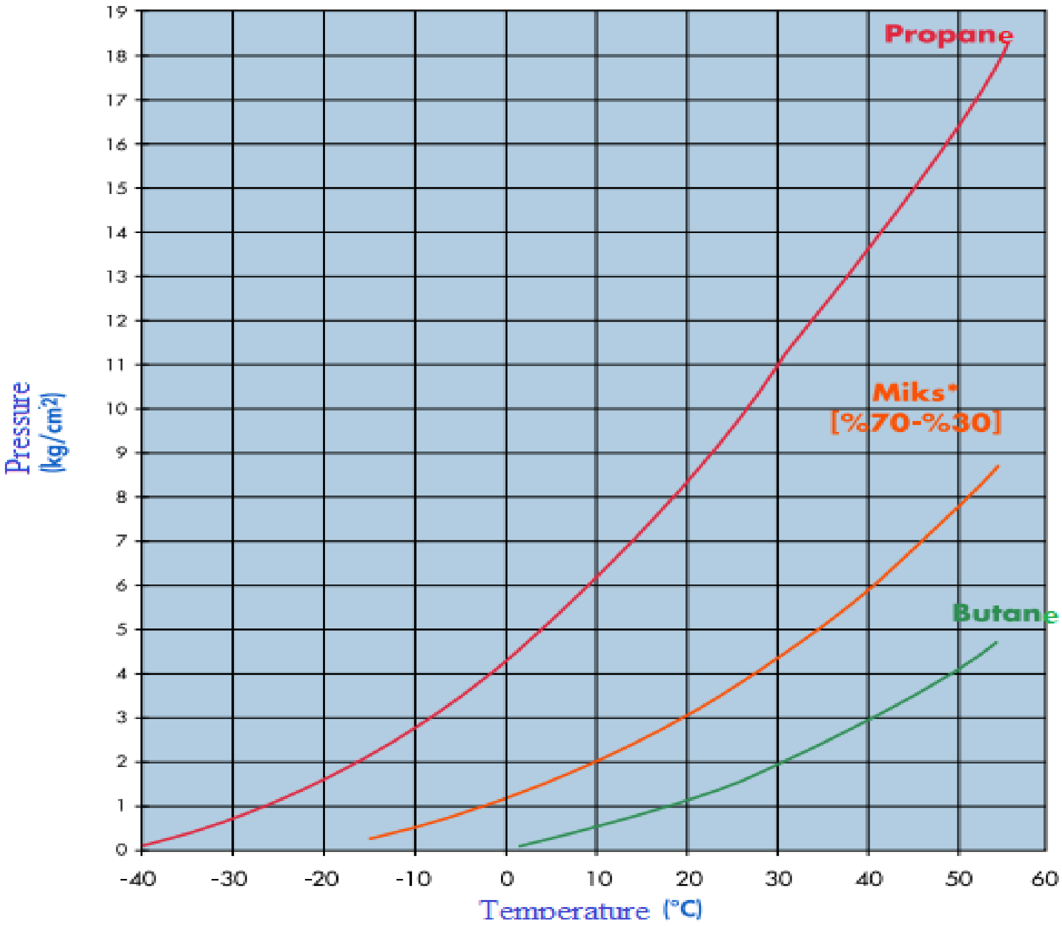

Figure 2.1: LPG (70% butane -30% propane) pressure temperature graph [6]

In our country, LPG is composed of 30% propane and 70% butane. This mixture has a calorific value approximately three times that of natural gas. However, this ratio varies seasonally due to the low condensation temperature of butane (-0.5°C at 1 atm pressure). As illustrated in Figure 2.1, in systems where LPG is intended to be used in the gas phase, careful attention should be paid to the pressure-temperature graph of LPG. Critical temperatures should be determined at process operating pressures, and measures such as insulation or accompanying lines should be taken. The flammability range of LPG with air is 1.8-9.5% volumetrically.

In literature research on fuel interchangeability or blending, studies by Caillat and col. [7] and [8] in reheating furnaces involved continuous mixtures of coke gas, blast furnace gas (a mixture of CH_4, CO_2, CO, N_2, H_2), and oxygen furnace gases. Parameters such as flame stability, calorific value, Wobbe index, and combustion air requirement were determined. Reducing the Wobbe index value in mixtures decreased combustion efficiency. Furthermore, studies conducted for the industry [9], [10] aimed at stabilizing the compensation changes in natural gas supplied from different sources. These studies involved adding LPG or air to control calorific value, fix the Wobbe index, control combustion air, and monitor flue gas O_2 concentration parameters. In another study [11], in the process of enriching CH_4 gas obtained from waste with LNG and LPG, it was stated that when the Wobbe index values of the mixtures were equal, flame temperatures had similar profiles. However, only when their calorific values were equal, as the CH_4 ratio decreased, flame temperature decreased. Vicek and col. [12] and other studies [13] involved making mixtures of coke gas and natural gas in an industrial furnace while only preserving the calorific value of the mixture. However, changes in the gas mixture ratio led to increased consumption. Among these reasons, the decrease in the Wobbe index value was indicated. Additionally, other parameters such as combustion temperature, flame stability, calorific value, and flue gas quantity were mentioned as important factors for combustion efficiency in industrial furnaces. In another study [14], research focused on the mixability, interchangeability, flame stability, and emissions of LNG and LPG gases for a condensation boiler. Burners did not burn efficiently below a certain Wobbe index value. For fuels with equal relative density values, increasing the Wobbe index value resulted in similar flame height behavior at a constant combustion air flow rate. When the Wobbe index was equal but the relative density was high, the CO concentration increased. This was attributed to incomplete combustion, and an increase in the combustion air flow rate was necessary. Lin [15] conducted an experimental study on fuel interchangeability for premixed burners, mixing nitrogen (N_2), hydrogen (H_2), and butane (C_4H_{10}) in various ratios. It was stated that the Wobbe index and lower calorific value parameters provided the most efficient results for burner combustion. The common method used for fuel interchangeability or burner performance in the above-mentioned articles was the

Wobbe index. Both residential and industrial burners achieved fuel interchangeability by equalizing the Wobbe index values. In Chen and col.'s study [16], it was noted that an increase in gas Wobbe index led to a higher probability of more yellow flames, and gases with similar Wobbe index values exhibited similar flame characteristics. These studies utilized LPG, LNG, natural gas, coke gas, blast furnace gas, and biogas obtained from waste. Parameters such as flame stability, flame length, calorific value, and flue gas emission rates were also evaluated.

In situations where natural gas composition changes, similar studies were conducted for all of Europe by Wood and Mokhatab [17], for Germany [18], and for the Netherlands [19]. These studies aimed to supply gas from different sources to the natural gas transmission lines provided by countries. However, as these gas compositions change, their calorific values also change. However, heat values provide not only energy content but also information about burner performance. The point of interest for end-users is burner performance to optimize their combustion equipment. The internationally accepted method for evaluating burner performance is the Wobbe index. Many international gas markets have established interchangeability parameters to protect end-users, with the most common reference being the Wobbe index.

In studies by Ferguson and colleagues [20][21], as natural gas demand increased for gas turbines, alternative fuels such as coal-derived synthesis gas, LNG, and hydrogen were investigated as combustion fuels. However, studies conducted on a laboratory scale using the Rijke tube showed that the Wobbe index was insufficient for gas turbine combustion analysis. In Xiang's study [22], the Wobbe index was used for fuel interchangeability in an internal combustion engine. However, it was deemed insufficient for characterizing engine performance, necessitating the use of simulation for accurate performance predictions. In Park's study [23], the effect of methane concentration variation on the combustion process in an internal combustion engine was examined. It was found that the Wobbe index and upper calorific value parameters were also insufficient. The Maximum Combustion Potential (MCP) parameter was used. Kalimstra's study [24] showed that the power capacity of an engine with a fixed Wobbe index could change by up to 6% depending on fuel compensation. These studies collectively demonstrate that the Wobbe index parameter alone may not yield effective results for fuel interchangeability in all devices.

In a study by Hull and colleagues [25], differences in fuel calorific values necessitated a reduction in fuel quantity in burners. A reduction in fuel volume required adjustments to the orifices controlling fuel flow and the replacement of all nozzles. In another study [26], it was stated that a furnace operating with natural gas could work with an LPG-air mixture without the need for modifications or shutdowns, thus eliminating the need to change orifices and nozzles in the process. A study by the American Gas Association (AGA) [27] demonstrated that when devices were regulated with gas flow orifices and the benefit of the Wobbe index, all gas mixtures with the same Wobbe number would provide an equal amount of heat input for a specific orifice. This study also showed that when Wobbe numbers were equalized, an equal amount of heat input could be provided without changing orifices and nozzles.

In a study by Ericson and col. [28], the Wobbe index value was monitored with a tolerance of ±5% by following the lower calorific value and relative density using gas chromatography for gas turbine feed. Another study [29] noted that in fuel mixtures of natural gas and LPG-air with equalized Wobbe indices, the required amount of air for the combustion process remained unchanged. Moreover, it was stated that if the difference in the Wobbe index values of the two fuels was less than ±5%, the equipment could operate without significant efficiency loss. In a study by Masebinu and col. [30], it was found that if the Wobbe indices of two fuels were the same, the energy output would also be the same for a specific pressure and valve setting. Generally, changes of up to ±5% were allowed because such changes would not be noticed by the consumer. These studies demonstrated that the instantaneous changes in Wobbe values due to the mixture of hydrocarbons in the fuel could be tolerated by the system up to a certain limit.

Literature research has investigated the essential parameters for the utilization of an LPG-air mixture instead of natural gas. It has been understood that in internal combustion engines and gas turbines, only the Wobbe index is not sufficient as the primary parameter, and these processes are much more sensitive. However, in residential equipment and industrial furnace burner designs, parameters such as the Wobbe index, flame length, calorific value, flue gas mixture, and flue gas temperature have been observed to be used. Furthermore, it has been observed that there is no need for equipment changes, such as orifices and nozzles, on industrial furnaces, which will facilitate operation and prevent product loss. It has been observed that industrial furnace burners behave like natural gas in the combustion process when the Wobbe indices of the LPG-air mixture are equal. The mixture ratio varies in the range of 45% air - 55% LPG to 50% air - 50% LPG, depending on the butane-propane ratios. These ratios are far from the combustion limits of LPG, which are in the range of 1.5%- 9.5%. Therefore, when necessary, precautions are taken, this should not pose a problem. Additionally, as the saturation pressure increases, the risk of liquefaction of the mixture decreases.

In order to substitute natural gas with an LPG-air mixture, the following criteria have been established:

Equal Heat Input: The heat input should be maintained at an equal level for both systems. This ensures that the energy requirements of the system remain consistent during the substitution.

No Modification to the System: The substitution should be possible without making any alterations to the existing system. This criterion ensures that the transition can be achieved seamlessly without significant changes or disruptions.

Consistency in Flame Length for Burners and Heat Transfer Method in Furnaces: The flame length in burners and the heat transfer method in furnaces should remain the same. This consistency ensures that the combustion process and heat transfer within the system remain unchanged, maintaining performance and efficiency.

Steady Flue Gas O_2 Value: The oxygen (O_2) value in the flue gas should remain constant. This criterion is crucial for the continuity of production and operability, as fluctuations in oxygen levels can impact the combustion process and product quality.

Based on these criteria, it has been determined that substituting natural gas with an LPG-air mixture is an appropriate method for ensuring production continuity and operability, provided that these conditions are met.

Chapter 3

Reheating Furnace

In a steel mill, liquid phase steel transitions to the solid phase through a continuous casting machine, yielding semi-finished steel billets. Various process applications are required in the bar rolling mill to shape and impart mechanical properties to these billets for them to become final products.

The rolling process involves subjecting steel to plastic deformation. Rolling can be carried out in two forms: hot and cold. The focus of this thesis is on hot rolling in the rolling mill. Hot rolling involves elevating the temperature of the steel above its recrystallization temperature, which is above 1000°C. This process leads to the reshaping of the steel through plastic deformation while simultaneously reducing its strength values. Unlike cold rolling, hot rolling allows for significant dimensional changes. For instance, it is possible to obtain Ø8 mm construction steel from a 150x150x12000 mm steel billet through hot rolling.

To facilitate the reshaping of semi-finished steel billets, they need to be uniformly heated above the recrystallization temperature. This heating process is carried out in the reheating furnace of the rolling mill.

The bar rolling mill's reheating furnace operates on a continuous feed basis using a traveling beam system and has a capacity of 180 tons per hour. Natural gas is used as the combustion fuel for this continuous feed furnace. Steel billets measuring 150x150x12000 mm are heated to a temperature of 1100°C in this furnace.

The reheating furnace consumes 6000 Nm^3/h of natural gas. A radial-type air fan generates an airflow of 63000 Nm^3/h at a pressure of 80 mbar gage. The combustion system comprises 8 zones and 79 burners, all of which are of the forced-draught type.

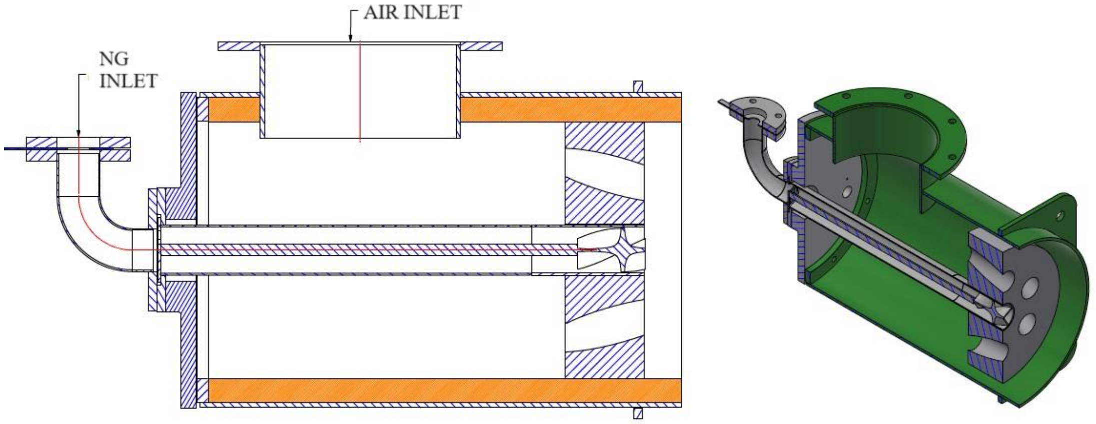

Figure 3.1: Furnace burner cross-sectional image (Used with company permission)

The natural gas supplied at a pressure of 5 bar gage undergoes pressure reduction through a regulator to reach a pressure level of 80 mbar gage. The natural gas distribution system is structured with an array of 8 distinct zones. These zone pipelines are strategically located to feed groups of burners situated along the side wall, front wall, and roof of the furnace. In total, there are 79 burners, each categorized into 4 different thermal power types.

Each individual burner is further supplied with air through dedicated air collectors, with the system being divided into 8 zones mirroring the burner distribution. The furnace's control system, which operates via a PLC (Programmable Logic Controller), governs each zone through actuated butterfly valves. Additionally, the consumption of fuel is meticulously monitored using orifice flow meters.

Within the burners themselves, appropriately sized orifices and nozzles are employed to maintain a consistent fuel flow rate and fixed airflow velocity. This meticulous control ensures the stability of the flame length during operation.

Chapter 4

Methodology

4.1 Wobbe Index

In a combustion system, the heat release rate is one of the most crucial parameters, and dissimilar volumetric gas flows for different gases result in varying heat release rates. Furthermore, in most systems, the gas flow rate typically varies along with density because it is supplied through a fixed orifice or nozzle. For instance, a gas with a decreased flow rate should possess a higher calorific value to achieve comparable heat release rates within the combustion system. Under the same pressure conditions, equal heat release rates are obtained by equalizing the Wobbe indices of fuels without altering the dimensions of the orifices and nozzles.

$$\text{Wobbe index}=\frac{Lower\ Heating\ Value}{\sqrt{Specific\ Gravity}}\,\frac{kcal}{Nm^3} \tag{4.1}$$

The Wobbe Index is the ratio of the lower heating value of a fuel to the relative density of the fuel. Its unit is the same as that of the lower heating value. Since calculations are typically conducted in kcal/Nm^3, the Wobbe Index is also calculated in kcal/Nm^3.

Calorific value, on the other hand, represents the amount of energy contained in one unit of fuel, also known as its heat content. It is calculated in two forms: the lower heating value and the higher heating value. The higher heating value accounts for the energy obtained from the condensation of water vapor produced during the combustion process. However, in the reheating furnace, there is no system to condense water vapor. Consequently, all fuel calculations are conducted using the lower heating value.

Relative density refers to the ratio of the density of a gas at reference conditions to the density of air at the same temperature and pressure. It is a parameter that influences the flow rate of the gas. A gas with a higher relative density will result in a reduced flow rate through the burner's orifice, nozzle, and turbulator.

4.2 Calculation of Wobbe Indices and Mixture Ratios of LPG-air Mixture and Natural Gas

The properties of hydrocarbons found in the natural gas and LPG mixture are presented in Table 4.1. Their molar volumes are provided in Normal cubic meters (Nm^3) under standard conditions of 0°C temperature and 101.325 kPa pressure. In the calculations, the values for I-butane and n-butane are considered to be identical.

Table 4.1: Comparison of the molar mass, density, molar volume, and lower heating value data of natural gas and LPG Mixtures [4][32]

	$\overline{M}$ (kg/kmol)	ρ(kg/m³)	$\overline{V}$(Nm³/kmol)	H_U(kcal/Nm³)
Methane (CH_4)	16,043	0,7157	22,4158	8510,0
Ethane(C_2H_6)	30,070	1,3416	22,4135	15574,56
Propane(C_3H_8)	44,077	1,9674	22,4036	22267,16
Butane(C_4H_{10})	58,124	2,5932	22,4140	28909,04

Each hydrocarbon is multiplied by its mixing ratio, and the sum of these values yields the lower calorific value [4].

$$H_o = \left[r_{CH_4}(H_u)_{CH_4}\right] + \left[r_{C_2H_6}(H_u)_{C_2H_6}\right] + \left[r_{C_3H_8}(H_u)_{C_3H_8}\right] + \left[r_{C_4H_{10}}(H_u)_{C_4H_{10}}\right] \tag{4.2}$$

The density calculation formula involves the mass molar value of each mixture molecule being divided by the volumetric molar value and then multiplied by the volumetric percentage within the entire fuel. When all calculated values are summed, the density of the mixture gas at reference conditions is determined.

$$\rho \quad = r_{CH_4}\frac{\overline{M}_{CH_4}}{\overline{V}_{CH_4}} + r_{C_2H_6}\frac{\overline{M}_{C_2H_6}}{\overline{V}_{C_2H_6}} + r_{C_3H_8}\frac{\overline{M}_{C_3H_8}}{\overline{V}_{C_3H_8}} + r_{C_4H_{10}}\frac{\overline{M}_{C_4H_{10}}}{\overline{V}_{C_4H_{10}}} + r_{CO_2}\frac{\overline{M}_{CO_2}}{\overline{V}_{CO_2}} + r_{N_2}\frac{\overline{M}_{N_2}}{\overline{V}_{N_2}} \tag{4.3}$$

The company possesses a natural gas combined-cycle power plant and employs a chromatograph device. Since natural gas is supplied through the same pipeline, the mixture of natural gas can be measured instantaneously. Analysis values for LPG are obtainable from the supplier firm for all shipments. The mixture values of natural gas and LPG are presented in Table 4.2.

Table 4.2: Analysis ratios of natural gas and LPG mixtures (Used with company permission)

	Formula	Natural Gas	LPG
Methane	CH_4	%93,9	%0,036
Ethane	C_2H_6	%3,5	%1,25
Propane	C_3H_8	%1,1	%35,094
Butane	C_4H_{10}	%0,2	%62,597
Carbon dioxide	CO_2	%0,3	-
Nitrogen	N_2	%0,7	-

According to Table 4.2, the calculations for natural gas's lower calorific value, density, and Wobbe index are as follows;

$$H_{U_{NG}} = [0{,}939 \times 8785{,}32] + [0{,}035 \times 15574{,}56] + [0{,}011 \times 22267{,}16] + [0{,}002 \times 28909{,}04]$$

$$H_{U_{NG}} = 9086{,}574 \frac{kcal}{Nm^3}$$

$$\rho_{NG} = 0{,}939 \frac{16{,}043}{22{,}4158} + 0{,}035 \frac{30{,}070}{22{,}4135} + 0{,}011 \frac{44{,}077}{22{,}4036} + 0{,}002 \frac{58{,}124}{22{,}4140} + 0{,}003 \frac{44{,}0098}{22{,}413616} + 0{,}007 \frac{28{,}0134}{22{,}413739}$$

$$\rho_{NG} = 0{,}7605 \frac{kg}{Nm^3}$$

The Wobbe index of natural gas is calculated as follows:

$$W_{NG} = \frac{9086{,}57 \frac{kcal}{Nm^3}}{\sqrt{\frac{0{,}7605 \frac{kg}{Nm^3}}{1{,}2866 \frac{kg}{Nm^3}}}} = 11818{,}77 \frac{kcal}{Nm^3}$$

Calculations for the lower heating value, density, and Wobbe index of LPG based on Table 4.2 are as follows:

$$H_{U_{LPG}} = [0{,}0036 \times 8785{,}32] + [0{,}0125 \times 15574{,}56] + [0{,}35094 \times 22267{,}16] + [0{,}62597 \times 28909{,}04]$$

$$H_{U_{lpg}} = 26136{,}94 \frac{kcal}{Nm^3}$$

$$\rho_{LPG} = 0{,}036 \frac{16{,}0426}{22{,}417256} + 0{,}0125 \frac{30{,}0694}{22{,}413391} + 0{,}35094 \frac{44{,}0962}{22{,}413635} + 0{,}62597 \frac{58{,}1230}{22{,}412490}$$

$$\rho_{LPG} = 2{,}3563 \frac{kg}{Nm^3}$$

The composition of air consists of approximately 78.05% Nitrogen (N_2), 20.95% Oxygen (O_2), 0.04% Carbon Dioxide (CO_2), and 0.96% other gases.

$$\rho_{air} = r_{N_2}\frac{\overline{M}_{N_2}}{\overline{V}_{N_2}} + r_{O_2}\frac{\overline{M}_{O_2}}{\overline{V}_{O_2}} + r_{CO_2}\frac{\overline{M}_{CO_2}}{\overline{V}_{CO_2}} \tag{4.4}$$

$$\rho_{air} = 0{,}7805\frac{28{,}134}{22{,}413739} + 0{,}2095\frac{31{,}9988}{22{,}413391} + 0{,}004\frac{44{,}0098}{22{,}413616}$$

$$\rho_{air} = 1{,}2866\frac{kg}{Nm^3}$$

The density value of the LPG-air mixture, consisting of 54.5% LPG and 45.5% air

$$\rho_{LPG+air} = r_{LPG}\rho_{LPG} + r_{air}\rho_{air} \tag{4.5}$$

$$\rho_{LPG+air} = 0{,}545 \times 2{,}3563 + 0{,}455 \times 1{,}2866$$

$$\rho_{LPG+air} = 1{,}8696\frac{kg}{Nm^3}$$

The Wobbe value of the LPG-air mixture, consisting of 54.5% LPG and 45.5% air

$$W_{LPG+air} = \frac{14244{,}63\frac{kcal}{Nm^3}}{\sqrt{\frac{1{,}8696\frac{kg}{Nm^3}}{1{,}2866\frac{kg}{Nm^3}}}} = 11816{,}77\frac{kcal}{Nm^3}$$

The standard lower heating value of natural gas is 8250 kcal/Nm^3. The total thermal capacity of the reheating furnace in the rolling mill is as follows

8250 kcal/Nm^3*6000 Nm^3/h=49500000 kcal/h

The maximum consumption values for the existing LPG-air mixture and natural gas are as follows

$$V_{LPG+air} = \frac{49500000kcal}{14130{,}55\frac{kcal}{Nm^3}} = 3503{,}05 \text{ Nm}^3/\text{h}$$

$$V_{LPG}=V_{LPG+air}\times r_{LPG}=3503{,}05\times 0{,}545=1909{,}16\ \mathrm{Nm^3/h}$$

$$V_{air}=V_{LPG+air}\times r_{air}=3503{,}05\times 0{,}455=1593{,}89\ \mathrm{Nm^3/h}$$

$$V_{Natural\ gas}=\frac{49500000kcal}{9086{,}574\frac{kcal}{Nm^3}}=5447{,}6\ \mathrm{Nm^3/h}$$

The furnace annealing process is monitored based on the furnace temperature value. Therefore, any variation in the maximum fuel consumption volume is attributable to changes in the lower calorific values of the fuels.

4.3 Calculation of Natural Gas and LPG Combustion Air Volume

The molar volume values for calculations are determined in Nm³/h units using the ideal gas equation under standard conditions (P=101.325 kPa, T=0°C). The volume calculations are performed for complete combustion. When hydrocarbons are burned, water vapor and carbon dioxide are produced. In cases of incomplete or partial combustion, carbon is emitted from the stack as two different molecules, carbon dioxide and carbon monoxide.

Methane $CH_4 + 2\,O_2 \rightarrow CO_2 + 2H_2O$

Ethane $C_2H_6 + 7/2\,O_2 \rightarrow 2CO_2 + 3H_2O$

Propane $C_3H_8 + 5\,O_2 \rightarrow 3CO_2 + 4H_2O$

Butane $C_4H_{10} + 13/2\,O_2 \rightarrow 4CO_2 + 5H_2O$

$$O_{2minDG}=\left(2\frac{r_{CH_4}}{\overline{V}_{CH_4}}+\frac{7}{2}\frac{r_{C_2H_6}}{\overline{V}_{C_2H_6}}+5\frac{r_{C_3H_8}}{\overline{V}_{C_3H_8}}+\frac{13}{2}\frac{r_{C_4H_{10}}}{\overline{V}_{C_4H_{10}}}\right)\overline{V}_{O_2} \qquad (4.4)$$

$$O_{2minDG}=\left(2\frac{0{,}939}{22{,}417256}+\frac{7}{2}\frac{0{,}035}{22{,}413232}+5\frac{0{,}011}{22{,}413635}+\frac{13}{2}\frac{0{,}002}{22{,}412490}\right)22{,}413391$$

$$O_{2minDG} = 2{,}0682\frac{Nm^3{}_{O_2}}{Nm^3{}_{fuel}}$$

$$L_{minair} = \frac{O_{2min}}{0{,}2095} = \frac{2{,}0682}{0{,}2095} = 9{,}87\frac{Nm^3air}{Nm^3{}_{fuel}}$$

$$O_{2minDG} = \left(2\frac{0{,}00036}{22{,}417256} + \frac{7}{2}\frac{0{,}0125}{22{,}413232} + 5\frac{0{,}35094}{22{,}413635} + \frac{13}{2}\frac{0{,}62597}{22{,}412490}\right)22{,}413391$$

$$O_{2minLPG} = 5{,}86812\frac{Nm^3{}_{O_2}}{Nm^3{}_{fuel}}$$

$$L_{minair} = \frac{O_{2min}}{0{,}2095} = \frac{2{,}86812}{0{,}2095} = 28{,}01\frac{Nm^3air}{Nm^3{}_{fuel}}$$

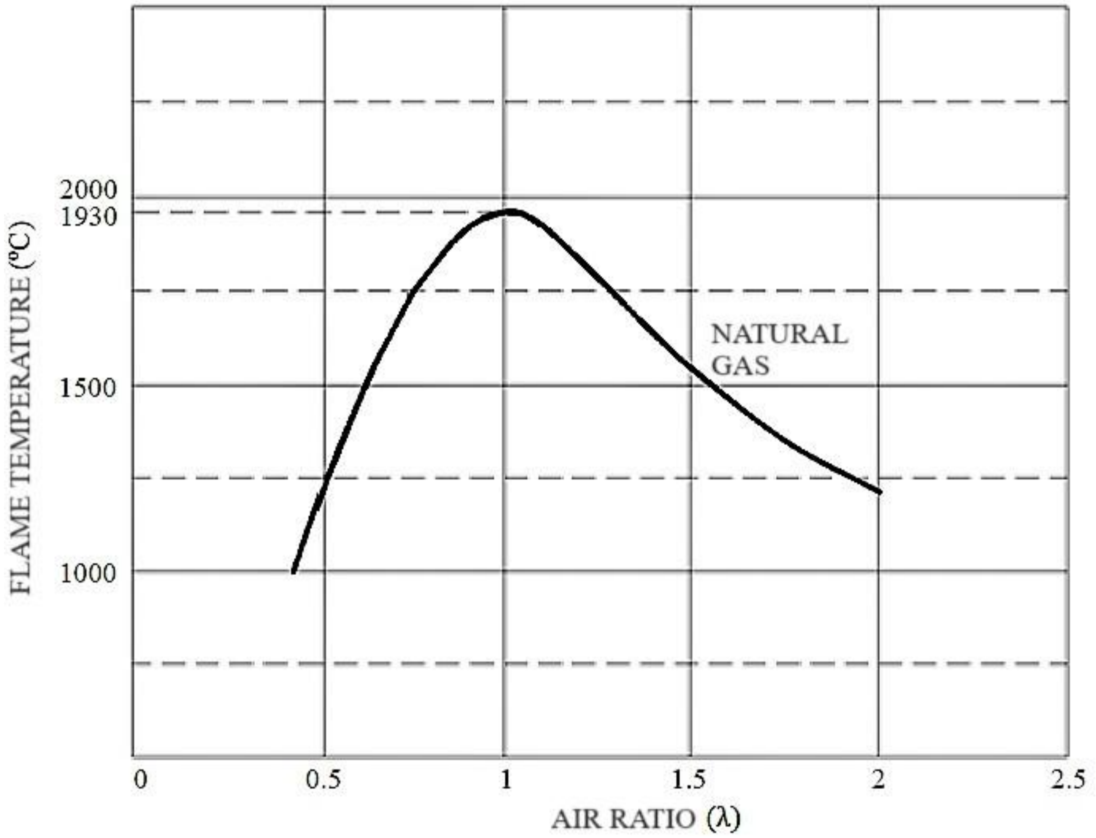

Figure 4.1: Natural gas air ratio (λ)- flame temperature graph [33]

In theory, the desired complete combustion fuel is achieved by mixing fuel with air in stoichiometric proportions. However, more air is always supplied than the theoretical requirement. As observed in Figure 4.2, providing combustion air in stoichiometric proportions results in oxygen and carbon monoxide exiting the stack in approximately equal volumes. The ratio of the actual air flow rate given to burn a unit amount of fuel to the stoichiometric air flow rate is known as the air excess factor (λ). Optimal combustion, as shown in Figure 4.1, occurs when the air excess factor (λ) is greater than 1 but close to 1.

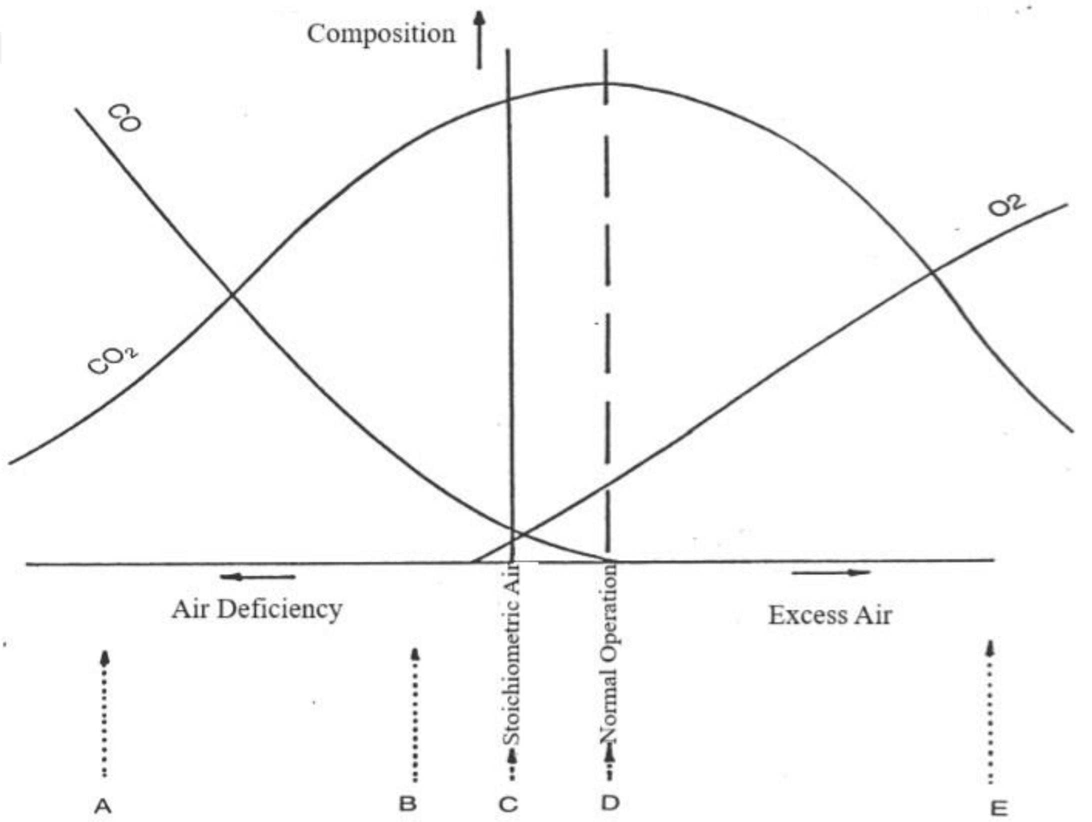

Figure 4.2: Flue gas composition- air-fuel ratio [34][35]

If these ratios are multiplied by fuel volumes;

$$\dot{V}_{Naturalgascomcustionair=}53767{,}8\ \mathrm{Nm^3/h}$$

$$\dot{V}_{Mixcombustionair=}53475{,}6\ \mathrm{Nm^3/h}$$

As calculated, the combustion air flow rates are close, and the existing air fan can provide up to 15% more flow. There is no need for a replacement of the air fan.

4.4 Orifice Calculations

The reheating furnace consists of 8 zones, with flow rates measured using orifice flow meters in each zone. For example, flow rate calculations and orifice meter sizing will be performed for a selected zone using LPG-air fuel, following the ISO 5167-1:2003 [36] iteration method. Calculations will be conducted for natural gas, LPG, and LPG-air mixtures in the chosen zone. In this selected zone, the maximum flow rate on an 8'' sch 40 pipe is measured using an orifice flow meter, with a maximum differential pressure of 1400 Pa. Table 4.3 provides flow rates for equal calorific value natural gas, LPG, and LPG-air mixture. The calorific values are calculated as 8250 Kcal/m³ for natural gas and 26000 Kcal/m³ for LPG. Volumetrically, LPG consists of 70% butane and 30% propane, while the LPG-air mixture comprises 48% air, 36% butane, and 16% propane. The density and dynamic viscosity values at 30ºC temperature and 80 mbar gage pressure in Table 4.3 represent upper pressure surface values. These values have been obtained from the ABB company's product selection assistant online program.

Table 4.3: Information on natural gas, LPG, and LPG-air mixtures [37]

	Natural gas	LPG	LPG-air
μ (Pa. s)	0,00001114	0,000007853	0,00001296
ρ (Kg/m^3)	0,809996	2,445313	1,872126
D (m)	0,202722	0,202722	0,202722
$q_m(kg/s)$	0,2592	0,248	0,366
Δp (Pa)	1400	1400	1400

$$\Re e_D = \frac{4q_m}{\pi\mu D} \tag{4.6}$$

$$A_2 = \frac{\mu\Re e_D}{D\sqrt{2\Delta p\rho}} \tag{4.7}$$

The iteration equation takes into account the discharge coefficient (C) value, which is set at 0.604 for natural gas and LPG-air mixture, and 0.602 for LPG. The expansibility factor (ε) is assumed to be 1 [36].

$$\frac{C\varepsilon\beta^2}{\sqrt{1-\beta^4}}=A_2 \tag{4.8}$$

The accuracy criterion has been set with a value of n = 6.

$$\left|\frac{A_2 - X_2 C\varepsilon}{A_2}\right| < 1 \times 10^{-n} \tag{4.9}$$

Calculation of orifice diameter (d):

$$d = D\left(\frac{X_2^2}{1 + X_2^2}\right)^{0,25} \tag{4.10}$$

$$\beta = \frac{d}{D}$$

The orifice diameter (d) has been calculated as follows:

For natural gas, the calculated orifice diameter (d) is 105.08 mm.

For LPG, the orifice diameter (d) is calculated as 79.15 mm.

For the LPG-air mixture, the orifice diameter (d) is calculated as 101.56 mm.

The current operating orifice diameter is 102.85 mm.

$$C=0{,}5959+0{,}312\beta^{2{,}1}-0{,}1840\beta^{8}+\frac{0{,}09\beta^{4}}{[D(1-\beta^{4})]}-\frac{0{,}0337\beta^{3}}{D}+\frac{91{,}71\beta^{2{,}5}}{\Re e^{0{,}75}} \tag{4.11}$$

Using the iteration method, the orifice diameter (d) has been calculated within an approximate tolerance range of about 2%. The discharge coefficient C (4.11) formula was reevaluated with β and Re [38]. In the iterative process, it was observed that the calculated values are close to the current orifice diameter of 102.85 mm. Based on these results, it is necessary to change the orifice plate for the use of LPG. However, for natural gas and LPG-air mixture fuels, the orifice diameter falls within the tolerance range. Therefore, there will be no change in the orifice plate.

4.5 Pipe Diameter Calculations

The mixture ratios were calculated as 54.5% LPG and 45.5% air based on the existing analysis values. However, any changes in the mixture ratios for natural gas and LPG will alter the Wobbe index and the LPG-air mixture ratio. Therefore, for pipe diameter calculations, a 2100 Nm^3 capacity pipe will be selected for the air pipeline, a 2100 Nm^3 capacity pipe for the LPG pipeline, and a 4000 Nm^3 capacity pipe for the LPG-air pipeline.

To calculate the pipe diameters, it is necessary to determine the actual flow rates from the Nm^3/h values. The Gas constant values for LPG and LPG-air mixture are calculated by dividing the universal gas constant value by the molar masses of the fuel mixtures [39].

$$P\dot{V}=\dot{M}RT \tag{4.12}$$

$$R=\frac{R_u}{\overline{M}} \tag{4.13}$$

The pipe diameter is calculated by relating the actual volume to the maximum velocity of the fuels, which is 25 m/s.

$$\dot{Q} = v \times A \tag{4.14}$$

For the pipe diameter calculation for an air consumption of 2100 Nm³/h, it is necessary to determine the actual flow rate of air under real conditions, which includes a temperature of 30°C and a pressure of 2 bar gage.

$$2100Nm^3 = \frac{\dot{M}_{air} 0{,}2870 \frac{kj}{kgK} 273{,}15K}{101{,}325kPa}$$

$$\dot{M}_{air}\text{=2714,27 kg/h}$$

$$\dot{V}_{airreel} = \frac{2714{,}27kg 0{,}2870 \frac{kj}{kgK} 303{,}15K}{303{,}975kPa}$$

$$\dot{Q}_{airreel} = 776{,}88 \frac{m^3}{h} \frac{1}{3600} \frac{h}{s}$$

$$\dot{Q}_{airreel}\text{=0,2158m}^3\text{/s}$$

$$A = \frac{Q\, m^3/s}{Vm/s}$$

$$\frac{\pi D^2}{4} = \frac{0{,}2158m^{\,3}/s}{25\, m/s}$$

D=0,105 m, DN100 pipe diameter is suitable.

For the calculation of the pipe diameter for a consumption of 2100 Nm³/h of LPG, it is necessary to determine the real volume of LPG under standard conditions with a temperature of 35°C and a pressure of 2 bar gage.

$$R_{LPG} = \frac{R_u}{\overline{M}} = \frac{8{,}3143}{(44{,}097 * 0{,}35 + 58{,}123 * 0{,}63 + 30{,}069 * 0{,}013)}$$

$$R_{lpg} = 0{,}1585$$

$$2100Nm^3 = \frac{\dot{M}_{LPG} 0{,}1585 \frac{kj}{kgK} 273{,}15K}{101{,}325kPa}$$

$\dot{M}_{LPG}$=4914,8kg/h

$$\dot{V}_{LPG} = \frac{4914{,}8kg 0{,}1585\frac{kj}{kgK}308{,}15K}{303{,}975kPa}$$

$$\dot{Q}_{LPG} = 789{,}69\frac{m^3}{h}\frac{1}{3600}\frac{h}{s}$$

$\dot{Q}_{LPG}$=0,2194m³/s

$$A = \frac{Q\, m^3/s}{Vm/s}$$

$$\frac{\pi D^2}{4} = \frac{0{,}2194m^3/s}{25\, m/s}$$

D=0,106 m, DN100 pipe diameter is suitable.

To calculate the pipe diameter for a consumption of 4000 Nm³/h of LPG, it is necessary to determine the real volume of LPG under standard conditions with a temperature of 30°C and a pressure of 2 bar gage.

$$R_{LPG+air} =$$

$$\frac{8{,}3143}{(28{,}97 * 0{,}455 + 44{,}097 * 0{,}545 * 0{,}35 + 58{,}12 * 0{,}545 * 0{,}63)}$$

$R_{LPG+air}$ =0,1991

$$4000N\, m^3/h = \frac{\dot{M}_{LPG+air} 0{,}1991\frac{kj}{kgK}273{,}15K}{101{,}325kPa}$$

$\dot{M}_{LPG+air}$ = 7452,54kg/h

$$\dot{V}_{LPG+air} = \frac{7452{,}54kg 0{,}1991\frac{kj}{kgK}303{,}15K}{303{,}975kPa}$$

$$\dot{Q}_{LPG+air} = 1479{,}77\frac{m^3}{h}\frac{1}{3600}\frac{h}{s}$$

$$\dot{Q}_{LPG+air}=0{,}411\,\mathrm{m}^3/\mathrm{s}$$

$$A=\frac{Q\,m^3/s}{Vm/s}$$

$$\frac{\pi D^2}{4}=\frac{0{,}411m^{\,3}/s}{25\,m/s}$$

D=0,145 m DN150 pipe diameter is suitable.

Chapter 5

LPG-air Mixer

Following the Wobbe index calculations, a volumetric mixer was designed for the determined ratios of the mixture. Figure 5.1 displays the LPG-air mixer. Since the factory houses a natural gas combined-cycle power plant, the natural gas mixture analysis values can be monitored in real-time. The factory is supplied with LPG through tanker trucks, and the LPG mixture analysis values for each tanker are collected. Given that the Wobbe index can vary due to mixture ratios, the system has been designed to accommodate variable flow rates. All flow calculations in the mixture are performed in Nm^3 with reference to standard conditions, at a temperature of 0°C (273 ºK) and a pressure of 1013.25 mbar (1 atm). Flow control valves adjust the flow rates by monitoring the volumes with air and LPG flowmeters at constant pressure as they enter the mixer. A static mixer in the mixing chamber ensures a homogeneous mixture. A combined air-LPG flowmeter controls the total flow, and a gas analyzer monitors hydrocarbons and the air-to-fuel mixture ratio.

LPG storage tanks and the vaporization station currently supply pure LPG in the gas phase to the steel mill and other units. From here, gaseous LPG is provided at a fixed pressure of 2.1 bar gage and a temperature of 35°C. Both LPG and air are filtered with 30-micron cartridge filters before entering the mixer.

The piping for LPG and air has been designed to ensure a maximum velocity of 25 m/s. Carbon steel of seamless construction, rated as SCH 40, has been used for all pipes, elbows, Ts, reductions, and other connection components within the facility. All joints are welded connections. Flanged partition valves have been employed throughout the facility, utilizing spherical-type designs to ensure maximum sealing. The instruments selected for the facility are ATEX and Ex proof compliant. Pressure ratings are set at PN 40.

Figure 5.1: LPG-air mixer photos (Used with company permission)

5.1 Instruments

5.1.1 Regulator

Pressure adjustments are being made for the gases. In the LPG line where a constant pressure is supplied to the mixer, a regulator has not been employed. In the air line, the pressure is reduced from 5 bar gage to 2 bar gage. It's important to note that as the pressure differential between the inlet and outlet of regulators decreases, their flow permeability also decreases. These factors have been taken into account in the selection of regulators.

5.1.2 Flowmeter

Vortex flow meters measure velocity and, subsequently, flow rate through the counting of frequencies using an internal sensor. The frequencies measured are directly proportional to the flow rate. Pressure and temperature data directly affect the density in the measurement of mass flow rates of gas fluids. For situations where pressure and temperature values are variable, a compensated model has been preferred. Flow measurements are conducted in units of Nm^3/h, compensating for the changing density. Gas measurements are performed with a precision of ±1.0% in the air and LPG lines, ranging from 142.6 Nm^3/h to 2250 Nm^3/h, and in the LPG-air mixture line, ranging from 404.4 Nm^3/h to 12010 Nm^3/h. There are three flowmeters in the setup, for air, LPG, and LPG-air mixture lines.

5.1.3 Flow Control Valve

Flow control valves are employed to determine process variables such as pressure, flow rate, and differential pressure, with the aim of maintaining them at a set value for gases. A globe-type steel casting control valve has been selected for this purpose. The positioner operates with a precision of 0.1%. The safety position is normally closed. It operates within a temperature range of -10°C to +220°C. The sealing class is Class IV, and it is equipped with CrNiMo bellows. It is connected to the PLC system via a 4-20mA control signal. There are two flow control valves in the setup, for the air and LPG lines.

5.1.4 Actuated Valve

İt is a ball valve actuated by a single-acting pneumatic actuator, serving as a safety element in the system. The selection of a single-acting pneumatic actuator is crucial. It overcomes the opposing spring force with the entry of air to enable flow, and it provides complete sealing in emergency situations and during power outages. It is typically of the normally closed type. There are three actuated valves in the setup, for the LPG, air, and LPG-air mixture lines.

5.1.5 Static Mixer

A static mixer was fabricated with the aim of achieving a homogeneous mixture of air and LPG with low pressure drop by altering the flow directions of these gases along the length of the mixing section. It was constructed from 5 mm thick, 350 mm long Ansi-304 quality stainless-steel sheet, with an inner diameter matching the pipe's width.

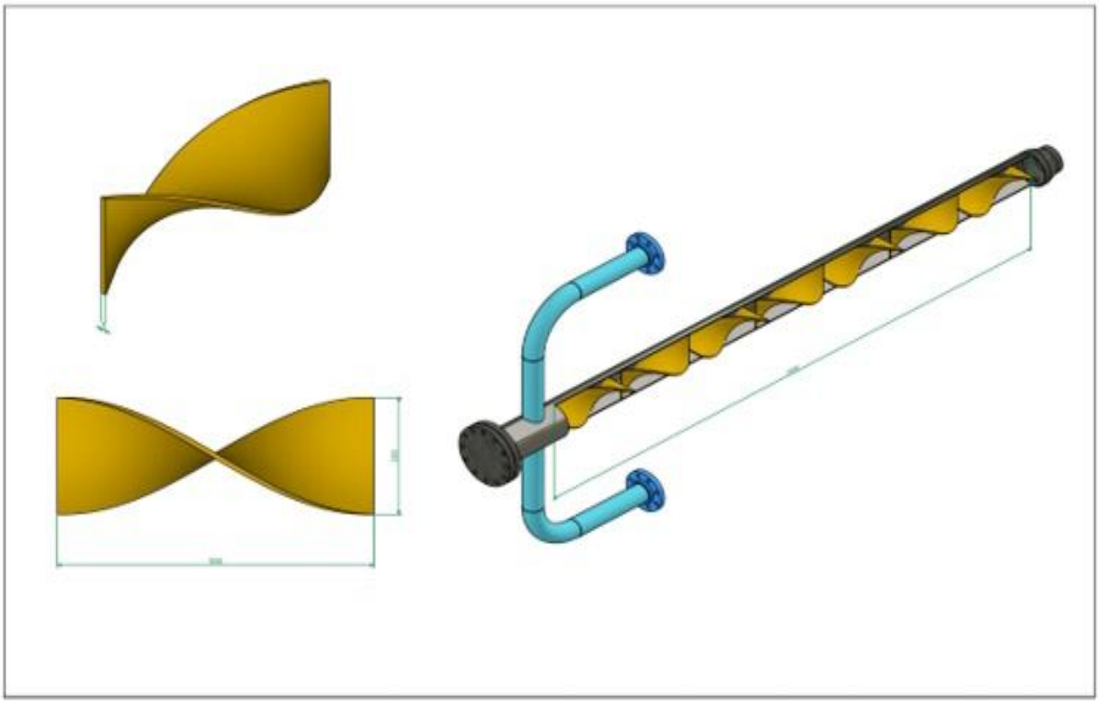

Figure 5.2: Static mixer and its assembly (Used with company permission)

As depicted in Figure 5.2, seven fixed mixing zones were established by bending the stainless-steel sheet in a 360º configuration, with the first zone following a clockwise direction and the second zone in the opposite direction, promoting homogeneous mixing by acting as a turbulator in the laminar flow region.

5.1.6 Gas Analyzer

Measurement is conducted using an adjustable filter spectroscopy method, which provides readings for hydrocarbons in the air as a percentage. Connection to the device is established from the mixing line via a pilot line.

5.1.7 Pressure Transmitter

This instrument on the pipeline measures the relative and absolute pressure of gases. It is connected to the PLC system via a 4-20mA control signal. The input pressures of the mixer, pressures after regulation, and the mixture pressure are transmitted to the PLC system.

5.1.8 Temperature Transmitter

This instrument on the pipeline measures the temperature of gases. It is connected to the PLC system via a 4-20mA control signal. The input temperatures of the mixer, temperatures after regulation, and the mixture temperature are transmitted to the PLC system. In case of malfunctions, thermowells are installed for replacement without stopping the system.

5.1.9 Manometer and Thermometer

The pressures and temperatures on the pipeline are utilized for visual monitoring by the operator.

5.2 LPG-air Mixer Process

The LPG-air mixer is designed to achieve homogeneous mixing in the mixing zone by adjusting the pressures and flows in the air and LPG lines using instruments. The mixed gas line is then connected to the existing natural gas line (Figure 5.3).

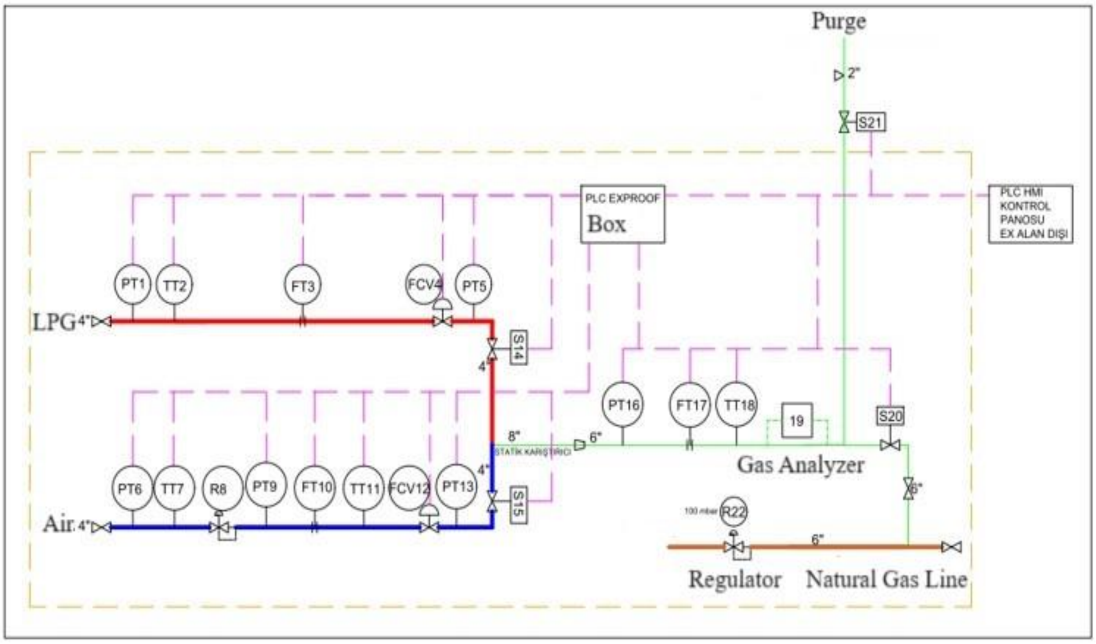

Figure 5.3: LPG-air mixer piping and instrumentation diagram (Used with company permission)

The input to the mixer includes LPG in the gas phase with an average pressure of 2.1 bar gage and a temperature of 35°C, and air with an average pressure of 5 bar gage and a temperature of 25°C. The air pressure is regulated to 2.2 bar gage using a regulator. Initially, LPG is primarily mixed. Pressure at the mixing zone reaches 2 bar gage. In the furnace line, it is reduced to 80 mbar gage using a regulator before being supplied to the furnace burners. The furnace line consists of a total of 79 burners of 4 different sizes, which are divided into 8 different zones.

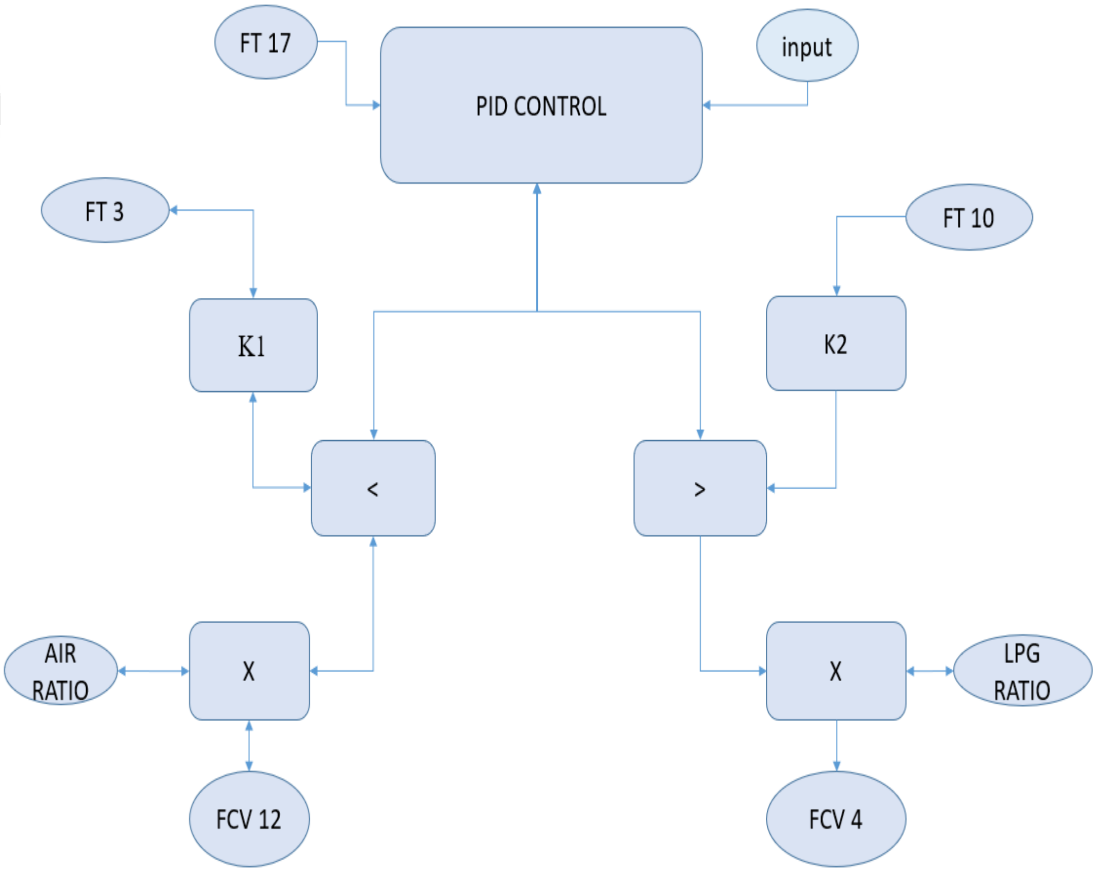

Figure 5.4: LPG-air mixer PID control scheme (Used with company permission)

Figure 5.4 provides the PID control scheme for the LPG-air mixer. The instrument codes are given in Figure 5.3. In summary, the system starts by inputting the calculated LPG-air mixture ratio and the reference LPG-air production value into FT17 flowmeter.

The PID control system adjusts the flows with FCV4-coded LPG flow control valve and FCV12-coded air flow control valves.

For the LPG FCV4 flow control valve, the value from FT17 mixture flow meter is compared with the value from FT10 air flow meter, multiplied by the K2 coefficient. The larger value is accepted as the reference value. This value is then multiplied by the LPG ratio and sent as a command to FCV4.

For the air FCV12 flow control valve, the value from FT1 mixture flow meter is compared with the value from FT3 LPG flow meter, multiplied by the K1 coefficient. The smaller value is accepted as the reference value. This value is then multiplied by the air ratio and sent as a command to FCV12.

The aim here is to keep the air-to-fuel mixture ratio below the LPG-air mixture set value while increasing or decreasing the flow, ensuring it never approaches combustion values.

Figure 5.5: LPG-air mixer PID interface (Used with company permission)

Figure 5.5 represents the interface of the mixer. Air flow, LPG flow, mixture flow, flow control valve opening ratios, mixture ratio, all temperature and pressure values can be simultaneously monitored and controlled. The operator can access all information in real-time.

Safety measures for safe operation are as follows:

In the LPG-air mixture, the air ratio is the most critical parameter to monitor. The mixture flow meter and gas analyzer are used to monitor the mixture ratio. If the air ratio exceeds 75% in either of these instruments, the system will be shut down.

Pressure and temperature data obtained from pressure and temperature transmitters are compared with the pressure-temperature graph for LPG and LPG-air mixture. If the system enters a region where liquefaction is a risk, it will be shut down.

If a gas leak is detected by the gas detector, the system will be shut down. In the event of a leak, LPG will settle due to its higher relative density, while natural gas will rise. This fact should be considered when positioning gas alarms. Additionally, if an operator anticipates a risk, the system can be shut down using an emergency stop button.

Chapter 6

LPG-air Mixer Performance

When natural gas is used as a combustion fuel in the fixed annealing mode, the volumetric ratio of oxygen (O_2) gas in the flue gas is considered within the range of 0.5% to 1.5% as a reference (Figure 6.1).

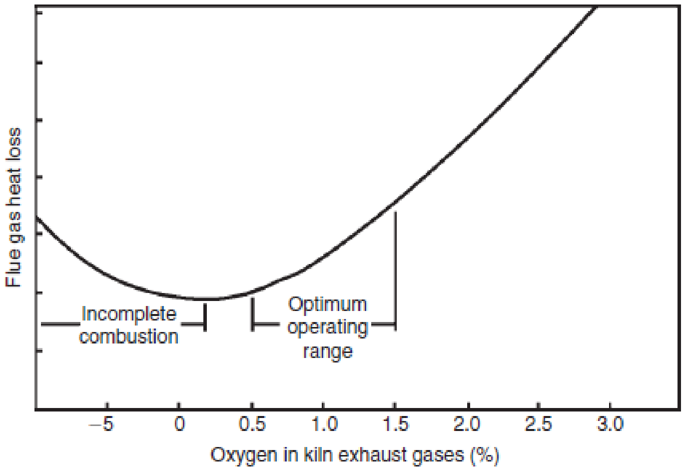

Figure 6.1: Effect of flue gas oxygen(O_2) ratio on heat losses [31]

The volume of oxygen (O_2) should not exceed 1.5% of the flue gas volume. Excess combustion air in the annealing furnace implies that a portion of the energy is used to heat this excess volume, leading to efficiency losses. The volume of oxygen (O_2) should not fall below 0.5% of the flue gas volume. Insufficient combustion air in the annealing furnace results in incomplete combustion and increased carbon monoxide (CO) formation, causing efficiency losses.

In the steel annealing process of the rolling mill furnace, there are variations such as shutdowns and hot charges in the natural gas production line. Therefore, the furnace operates within the range of $1 < \text{oxygen } (O_2) < 6$. These values have been achieved with the LPG-air mixer (Figure 6.2).

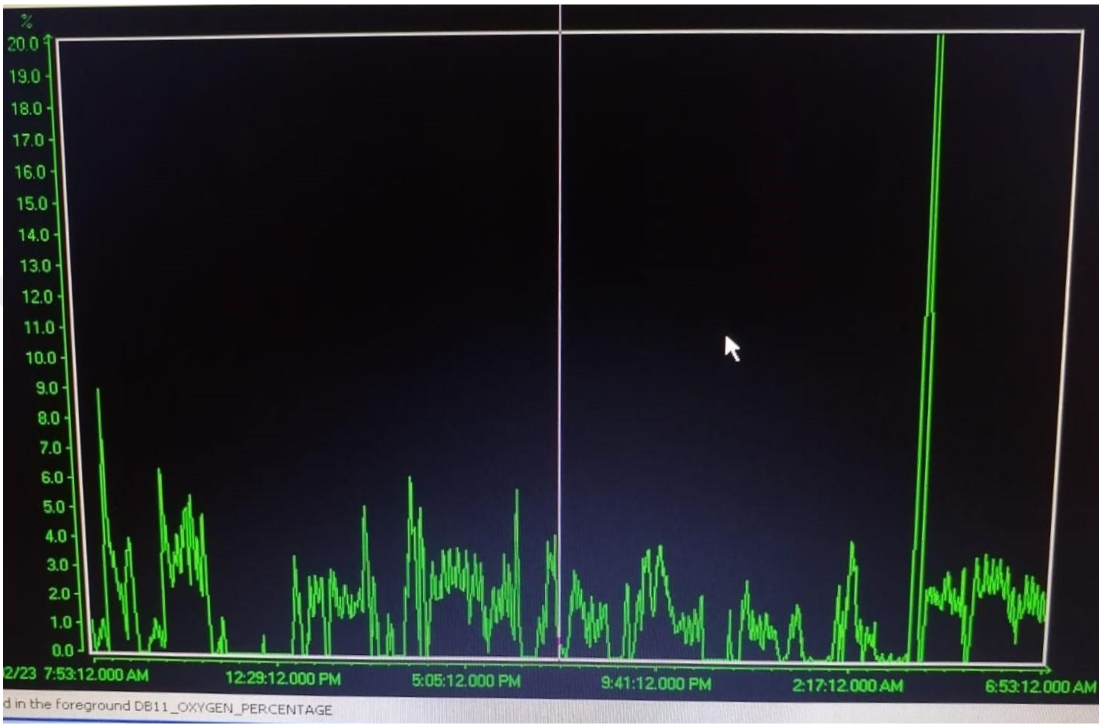

Figure 6.2: Flue gas oxygen(O_2) ratio (Used with company permission)

The LPG-air mixing system has been in operation for approximately 3 months. During this period, it has been operated interchangeably with natural gas based on fluctuations in LPG and natural gas prices or supply sources. When these changes occur, the natural gas line valve is closed, and the LPG-air mixture line valve is opened, allowing the annealing process to continue. There has been no production loss during these transitions.

In this process, to reach a temperature of 1200°C from ambient temperature for the billet iron, the calorific value of the natural gas consumed is 290 Mcal/ton. Size variations, breakdowns, and other stoppages have resulted in monthly fluctuations of

±10,000 kcal. In this three-month period, the daily calorific value for LPG has ranged from a maximum of 303 Mcal/ton to a minimum of 282 Mcal/ton. Volumetrically, the hourly LPG consumption compared to natural gas consumption has been 0.312.

Figure 6.3: LPG fuel burner combustion (Used with company permission)

In the operation with the LPG-air mixer, no difference in flame lengths in the burners was observed (Figure 6.3). During the mixer studies, in the other rolling mill within the factory campus with a capacity of 90 tons per hour and 8 old-style walking beam burners, burner orifices and barrels were replaced, and an LPG conversion was performed.

Figure 6.4: Samples of burner front accumulation (Used with company permission)

It operated for approximately three months in two different rolling mills. Formation at the burner tip, as seen in Figure 6.4, was detected during maintenance shutdown. An analysis of this formation revealed 82% carbon, 12% sulfur, and various amounts of iron and aluminum elements. No such formation was observed in the rolling mill where the LPG conversion with the mixer was performed.

Chapter 7

Conclusions

In the reheating furnace, the average natural gas thermal consumption was achieved with a tolerance of +1% using the LPG-air mixture. The LPG-air mixer was not imported but produced at 30% of its cost. The basic requirement for using LPG instead of natural gas is the equalization of the Wobbe index values. As discussed in the literature review, although the Wobbe index may not be sufficient for internal combustion engines and gas turbines, it was found to be applicable for the reheating furnace in the steel mill. If only the calorific values had been equalized, the fuel flow rate would have decreased, and the possibility of flame flashback would have remained without changing the orifices and nozzles. For this reason, both the calorific values and the Wobbe indices have been equalized.

Using LPG in a mixture has more advantages than using it in its pure form. Fuel can be changed directly without requiring orifice and nozzle replacement. It does not cause production and labor losses. The dew point of the mixture is below the dew temperature of pure LPG, reducing the risk of liquefaction. A solid formation containing carbon and sulfur has been observed at the burner tip of the reheating furnace running on LPG, but not in the reheating furnace running on LPG-air mixture. The system operated with the LPG-air mixer can operate more efficiently.

The combustion air flow rate remains unchanged. The existing air fan is used. For complete combustion during reheating, adjustments can be made to the air flaps in the air flows during reheating changes. An LPG-priority mixture flow diagram should be made in the mixer. The mixture ratio should not approach the LEL and UEL limits. Since the LPG butane-propane mixture ratios change, the ability to change the LPG-air mixture ratio will increase efficiency.

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