LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

LUT School of Energy Technology

Degree Programme of Bioenergy

Master's thesis

Review of gas burners used in small capacity heat plants and assessment of their environmental impact

Ivan Kaling

Examiners: Professor, Ph.D. Esa Vakkilainen, Docent, Ph.D. Juha Kaikko

Supervisor: Professor, Ph.D. Esa Vakkilainen

Lappeenranta, 2019

ABSTRACT

Lappeenranta University of Technology

School of Energy System

Degree Program in Bioenergy

Ivan Kaling

Review of gas burners used in small capacity heat plants and assessment of their environmental impact

Master's Thesis

2019

67 pages, 5 tables, 34 figures and 1 appendices

Examiners: Professor D.Sc. Esa Vakkilainen, Docent, Ph.D. Juha Kaikko

Supervisors: Professor D.Sc. Esa Vakkilainen

Keywords: heat plant, gas burner, environmental impact, emission

This master's thesis on gas burners used in small capacity heat plants and assessment of their environmental impact at first, describes the global energy consumption of natural gas, second, introduces gas combustion technologies and the classification of burners and their use in modern conditions.

The experience of operating heat engineering equipment was presented with the example of the company SUE ”TEK SPb”, which provides heat to the majority of consumers in St. Petersburg, Russia. To reduce specific emissions of nitrogen oxides and mono- and carbon dioxide, the company is introducing new highly efficient equipment.

After the modernization of the old thermal heat plants, the environmental impact was significantly reduced due to lower specific consumption of natural gas. Natural gas consumption was reduced by 21%. However, the use of the methodology used in Russia to report emissions from heat plants is not applicable to the comparative analysis of heat plants due to the absence of specific parameters.

ACKNOWLEDGMENT

I would like to thank Lappeenranta University of Technology for providing an unforgettable experience that turned my life upside down.

First of all, I want to thank my supervisors Professor Ph.D. Esa Vakkilainen and Docent Ph.D. Juha Kaikko for quick and practical advice that helped me not to stray from the chosen path and to reach an excellent final result. I discovered new aspects of scientific work that have become very close and clear to me.

A special thank goes to the company SUE ”TEK SPb” for the information provided for the analysis.

I also would like to thank D.Sc. (Tech.) Ivan Deviatkin. Thanks to your unindifference to science and impeccable methods of teaching new skills; my experience of writing a thesis was instructive, fascinating and unforgettable.

Finally, I am very grateful to my family, especially to my beloved wife and our daughter. Your unshakable faith in me, round the clock support, care and love inspired me to write the thesis. You are my life compass, which shows the surest and happiest way.

Table of contents

Abbreviations

ANSI - American national standards institute

AMS - Automation and management systems

BCM - Billion cubic meters

CHP - Cogeneration heat and power plants

CO - Carbon monoxide

CO_2 - Carbon dioxide

FGR - Flue gas recirculation

GTI - Gas Technology Institute,

GWP - Global warming potential

IR - Infrared or Radiant

IHEA - International Health Economics Association

IEA - International Energy Agency

LNG - Liquefied natural gas

LCA - Life cycle assessment

MPa - a unit of pressure, megapascal

MP - Multi-port

NO_x - Nitrogen oxide

NO_2 - Nitrogen dioxide

N_2 - Nitrogen gas

PJ - Unit of work, energy and quantity of heat

RI - Return intake

SCADA - Supervisory control and data acquisition

SCR - Selective catalytic reduction

SNCR - Selective non-catalytic reduction

TTAI – Think walled heat exchanging apparatus intensified

TOE - Tonne of oil equivalent

VOC - Volatile organic compounds

1 Introduction

The global energy consumption has been constantly growing throughout the human history (IEA, 2018b) due to rapid population growth, urbanization, and industrialization, to name the main reasons. Natural gas has been one the most reliable energy sources. A new record on the natural gas production was set in 2017 of 3 768 Billion cubic meters (Bcm) (IEA, 2018a). On the country level, the most significant increase in the extraction of 49,8 Bcm out of the total increase of 132 Bcm in 2017 was due on behalf of Russia.

Despite the fact that one-third of natural gas extracted in Russia is exported (IEA, 2015), a significant share of it still remains within the country for domestic consumption. Figure 1 shows that 58% of natural gas consumed in the domestic Russian market is transformed into energy with 44% used in cogeneration heat and power (CHP) plants. While the use of natural gas in heat plants accounts for 12% of the domestic natural gas consumption in Russia, this value equals to 2 034 PJ, which is nearly as much as the consumption of natural gas in Germany (2 403 PJ), a country which consumes the most of natural gas in Europe.

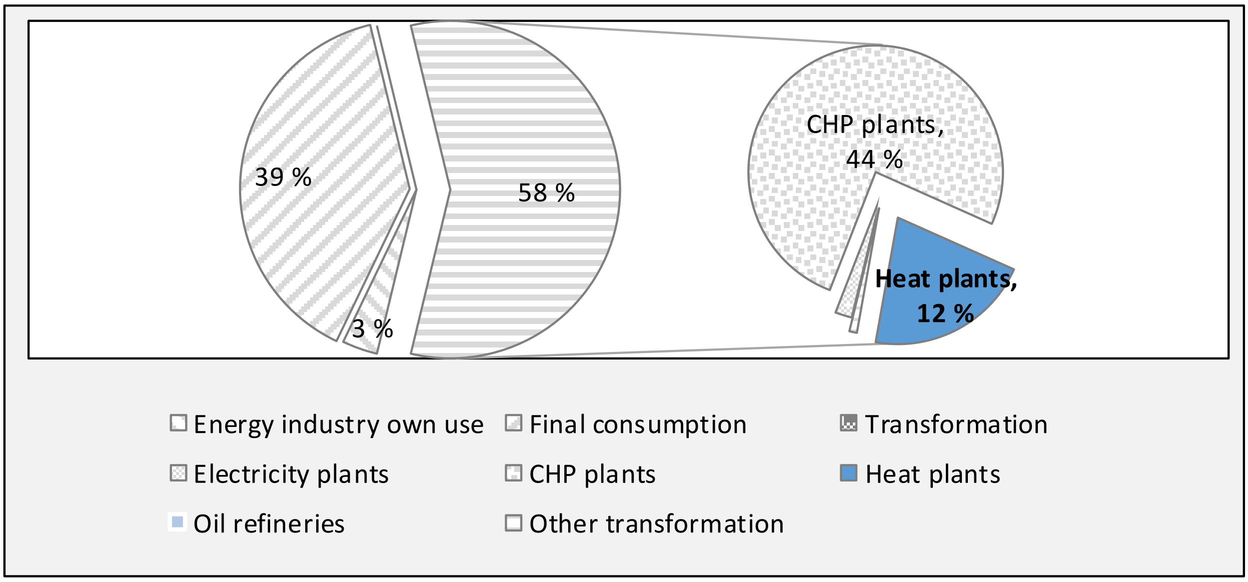


Figure 1: Distribution of natural gas consumed across the Russian market in 2015 (IEA, 2015).

Gas burners with small capacity represent a viable solution for district heating in densely populated areas, such as St. Petersburg, Russia, where CHP plants cannot be located close enough to the dwellers, which would result in substantial heat losses in the district heating systems. Furthermore, modern equipment allows for a significant increase in the heat generation efficiencies. All of these led to a significant expansion of the marker of gas burners in Russia. A large variety of technological solutions available on the market dictates the need for an extensive literature review of gas burners applied. In this study, a review of technological solutions applied in St.Petersburg will be presented.

Finally, the reduction of global warming potential (GWP), which is also referred to as climate change or carbon footprint, associated with the gradual renewal of gas burners in St. Petersburg will be calculated using life cycle assessment (LCA) methodology. The reference situation studied considered district heat generation using old burners run on natural gas or even coal. Furthermore, a possible reduction of the environmental impact due to the upcoming equipment update is estimated.

2 Energy use in Russia

Globally, Russia is one of the largest producers and exporters of oil, natural gas and other crude fuels and resources. Because of substantial known reserves, Russian economy is strongly tied to exports of hydrocarbons to its neighbours, which is once more proven by active projects of natural gas export to China and Europe. As much as 36% of Russian budget in 2016 originated from the income from oil and natural gas exports. Russia was the largest producer of crude oil in 2016 producing more than 10 mil. barrels of liquid hydrocarbons per day. Also, the production of natural gas in Russia toped the world statistics. (Finance, 2017)

Regarding exports, Russia's one of the main markets is Europe, which naturally has only limited resources of crude fuels. Therefore, there is a dual dependency between Europe and Russia: Europe needs gas, while Russia needs markets. Yet, this situation changes slowly with the recent contact on imports of gas from the USA to Poland for the next 20 years. This step was in the light of Europe's strong dependency on Russian imports, which accounted for nearly 70% of natural gas imports.

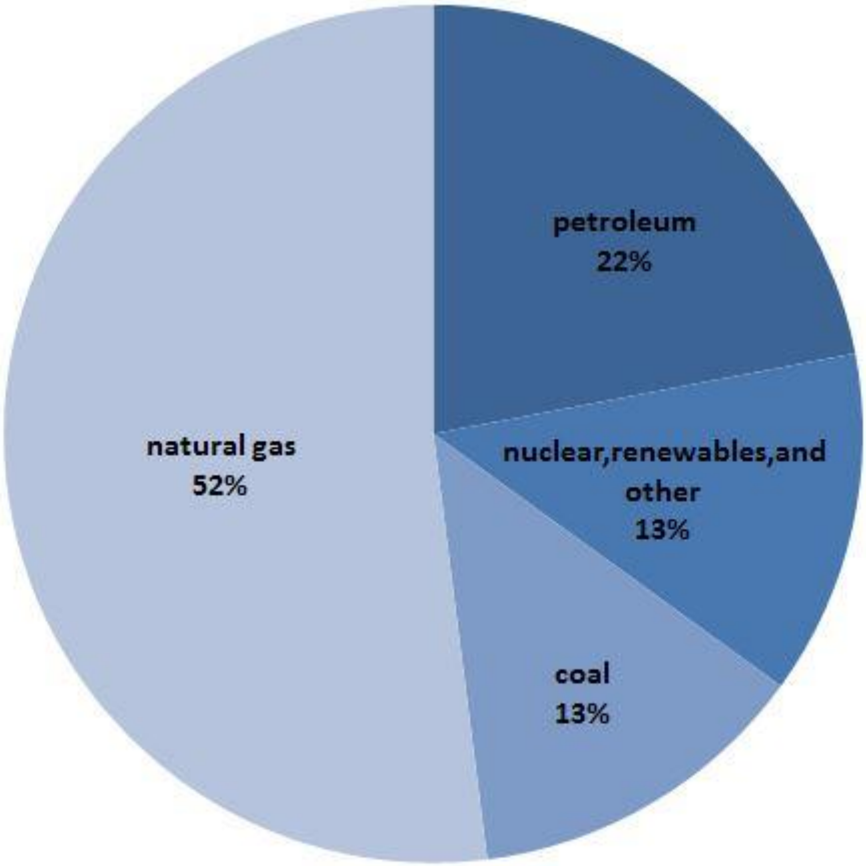


Figure 2: Russia`s primary consumption of energy carriers in 2016 (U.S. Energy Information Administration 2017)

Since the beginning of this century, consumption of natural gas in Europe has not been growing, but even sometimes decreasing. In the light of it, Russia has focused on diversification of natural gas markets to Asia which face a fast economic growth. This was also promoted by the sanctions from USA and EU which were imposed in 2014 due to the questionable situation in Crimea. All of it resulted in bilateral agreements between Russia and China on natural gas exports.

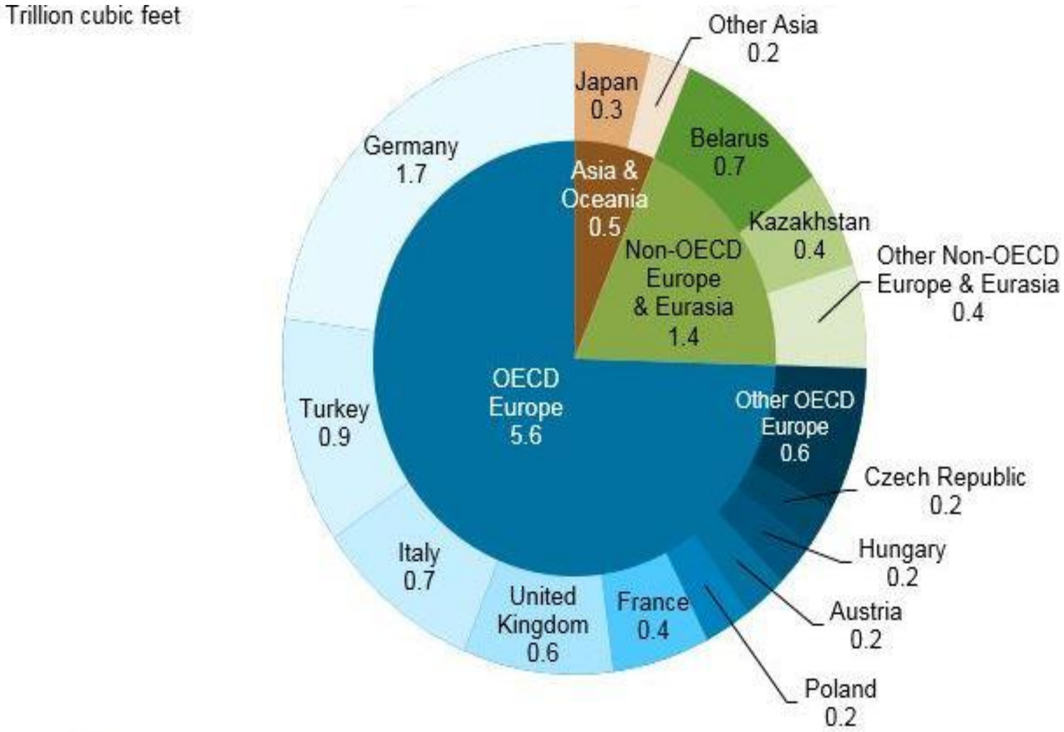


Figure 3: Exports of natural gas from Russia by destination (U.S. Energy Information Administration, 2017)

Russian energy sector relies on the consumption of natural gas, which accounts for 52% of the primary energy consumed in the country as shown in Figure 2. Other key sources of energy are petroleum oil and its products accounting for 22% and coal, which still accounts for 13% of all energy consumed. Finally, having the world's fifth largest installed capacity of nuclear and a developed system of hydropower on Russia's main rivers, those sources account for the remaining 13% of energy consumption.

Russia's known reserves are the largest in the world. According to the information in Figure 4, Russia's reserves are around 1600 trillion cubic feet. As such, they account for a fourth of the global reserves. Naturally, natural gas extraction is located in Siberia, where the reserves are. Some of the largest extraction places belong to a state-backed company - Gasprom. Those are located in Bovanenkovo, Medvezhye, Yamburg, Urengo, and Zapolyarnoye. Altogether, they accounted for two thirds of all natural gas production in Russia in 2016. Strong position of Gazprom on the market is also determined by its monopoly on pipeline gas exports.

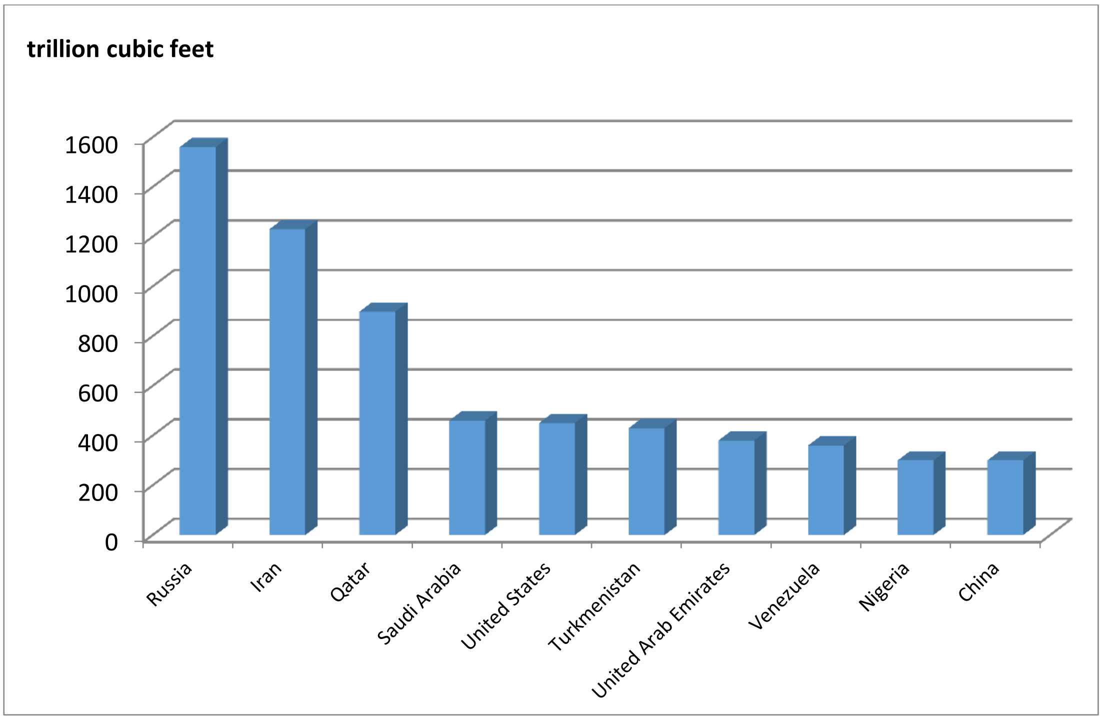


Figure 4: Estimated proved natural gas reserves in 2017 (Oil & Gas Journal).

Table 1. Key producers of natural gas in Russia, 2016 (U.S. Energy Information Administration).

Company	Tcf
Gazprom	14.8
Novatek	2.4
Rosneft	2.4
Kukoil	0.7
Surgutneftegaz	0.3
PSA operators	1.0
Others	1.0
Total	22.6

To make a working natural gas market, several Ministries and the President himself lead the policy. First of all, the Ministry of Natural Resources and Environment decided on the permits for natural gas extraction. Also, the Ministry controls the extraction process and its compliance with the license agreements. Finally, it control the production process in terms of emissions and their environmental impacts. Then, when the natural gas is exported, the Ministry of Energy comes into play by developing general energy polices. Taxation of natural gas production and exports is handled by the Ministry of Finance. And finally, because exports of natural gas are monopolized, the Federal Antimonopoly Service regulates those issues related to exports.

3 Review of gas boilers

Gas boilers represent only one part of integral heating systems which is shown in the Figure 5. The total heating system is composed of four main parts: i) boiler or burner combination, which is needed to actually produce heat, ii) piping with pumps and valves, which is needed to distribute the heat generated, iii) radiators and convectors, which are needed to produce the heat to customer, and iv) control_equipment, such as outside temperature control and room thermostat, which is needed for controlling the system and temperature of the water.

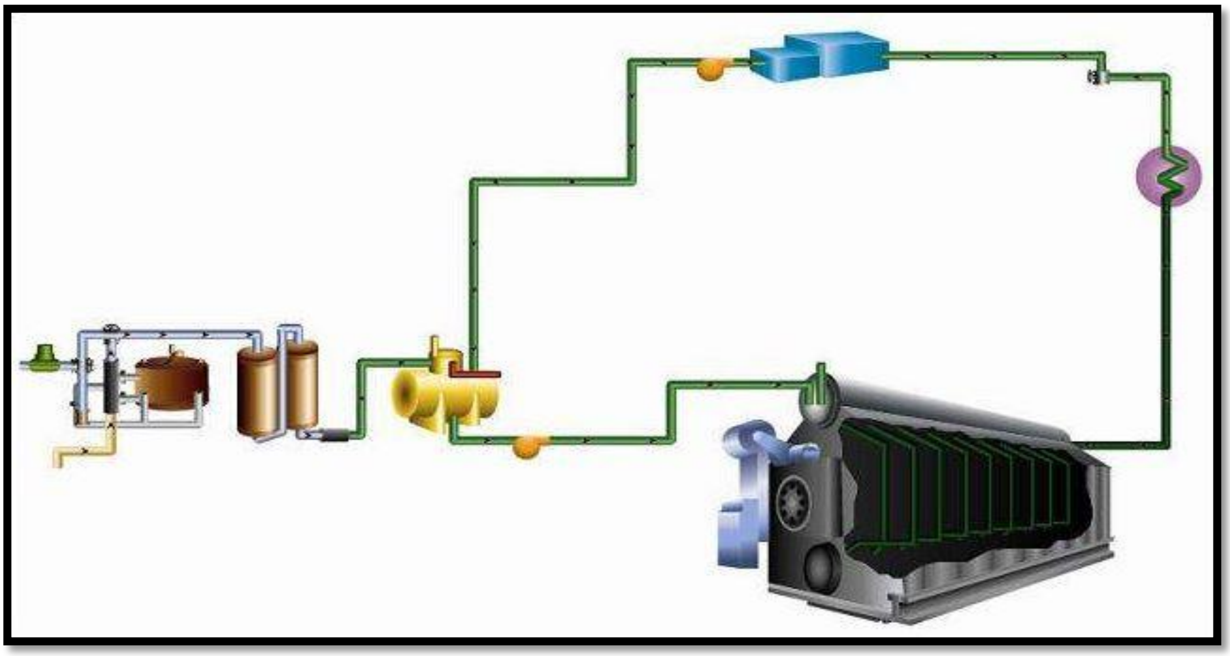


Figure 5: Parts of a Heating System (Industrial Wiki, n.d.).

Different types of boilers manufactured by different manufacturers are available on the market. Such variety is driven by the wide range of applications of the boilers. The boilers have undergone substantial improvement in their thermal efficiencies and the new models are actively replacing old and inefficient ones. Boilers can be broadly classified as fire tube (also often referred to as shell-tube) and water tube boilers. Apart from the constructional differences, boilers can be ranked low pressure boilers and high pressure boilers. High-pressure boilers are designed to proceed under pressure above 1 bar. In another way, boilers can be classified based on the product which can be steam or just hot water. Boilers for hot water are not even considered boilers. However, due to a number of similarities with a steam boiler, it is often called "a hot water boiler". Hot water boilers which are usually operate at temperatures above 110 °C and pressure above 11 bar are referred to as high temperature hot water boilers. If hot water boilers are referred to as low temperature hot water boilers when they work at temperature under 110 °C and pressure under 11 bar.

Boilers are also distinguished by the way of their production: casted boilers are named cast iron boilers and fabricated boilers - steel boilers. Casted boilers can be made of iron, brass, bronze, or other alloys. In fabricated boilers, steel, brass or copper can be used, while steel is the most spread.

Also, boilers are differentiated by their capacity. The principle of size definition is given in the thesis. The most optimal size of a boiler should provide enough heat for the most cold period. Furthermore, many boilers were oversized on purpose by tens of percent to ensure their safe and reliable application, so-called “safety margin”. Today boilers are usually not oversized because all the calculations can be done with high precision. and also it is not favored because of the global trend on energy saving. In the aggregate of the above factors, it becomes possible to have smaller radiators, which entails a reduction in the cost of installing the boiler and operating costs. The power of the pump and circulating water that flows through pipes of the adequately size determined the amount of radiators that must be installed in the system. The size of the boiler will depend on the total capacity of all radiators, cylinders and pipes.

3.1. Fire tube boilers

The description of the operation of the fire boilers is very clearly illustrated in Figure 6: hot gases exiting the boiler are aspirated via pipes, which are submerged into a liquid that will heat up. The figure shows that the core of the boiler is connected with the high pressure vessel which has the heating media. Usually, the heating media is water and water is usually recirculated to provide heat to dwellers or is transformed into steam. Several tubes represent a pass. So, the boilers are named using the number of passes, e.g. a five-pass boiler is the one which has five sets. The stack is located in the rear end for the boilers with odd number of passes and at the front with an even number of passes.

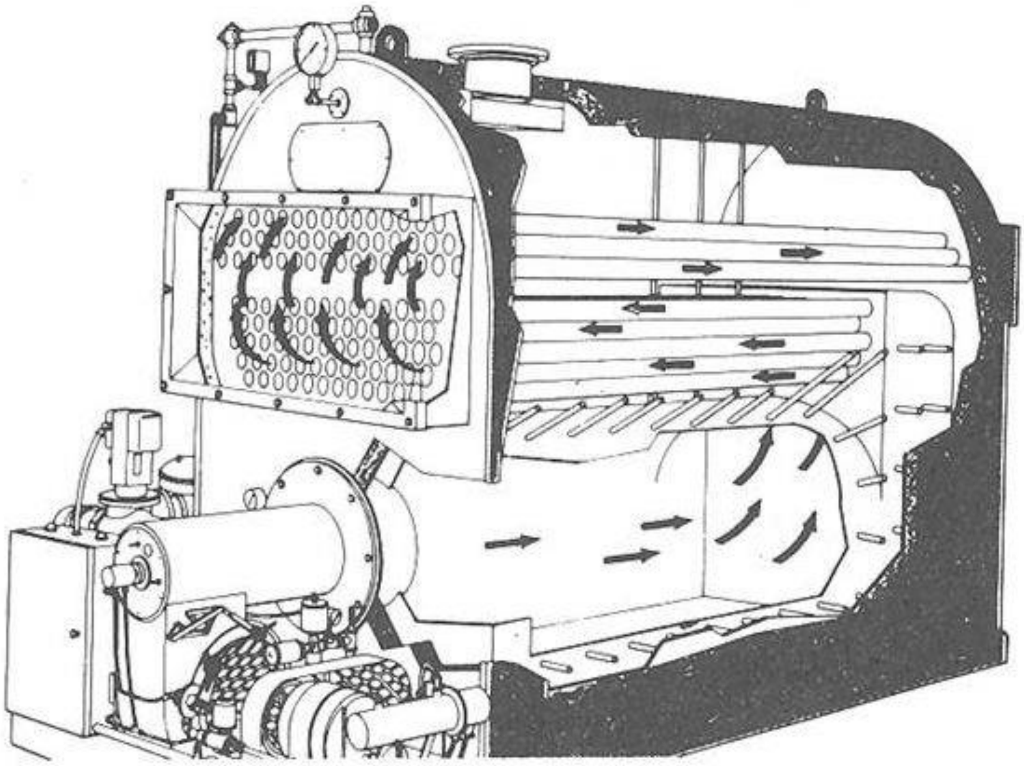


Figure 6: *Gas flow in a fire-tube boiler* (Industrial Wiki, n.d.).

There are multiple advantages of fire-tube boilers. First of all, their production and maintenance is relatively cheap. Their maintenance does not requires specific knowledge and is easy to be implemented. Tubes can be easily replaced. Also, the fire-tube boilers are simple in construction and have reduced requirements for fresh water treatment. Finally, their sizes range 633 MJ/h to 52750 MJ/h.

The disadvantages include their large mass expressed as mass of steam generated per mass of the boiler equipment, a lot of time needed to raise the steam pressure. Because they are relatively large in volume, they are not capable of fast responses to load changes. Also, such boilers cannot economically be used for application requiring pressures above 1.7 MPa. Finally, only limited steam amounts can be produced in there.

3.2. Water-tube boilers

The opposite of a fire-tube boiler is the water-tube one. Figure 7 illustrates the boiler. Water flows through the tubes and flows to the furnace. Water tube boilers are better purposed to provide service to large consumers of steam. The water-tube boilers are primarily used for steam or hot water production in industrial scale and seldom for providing heat.

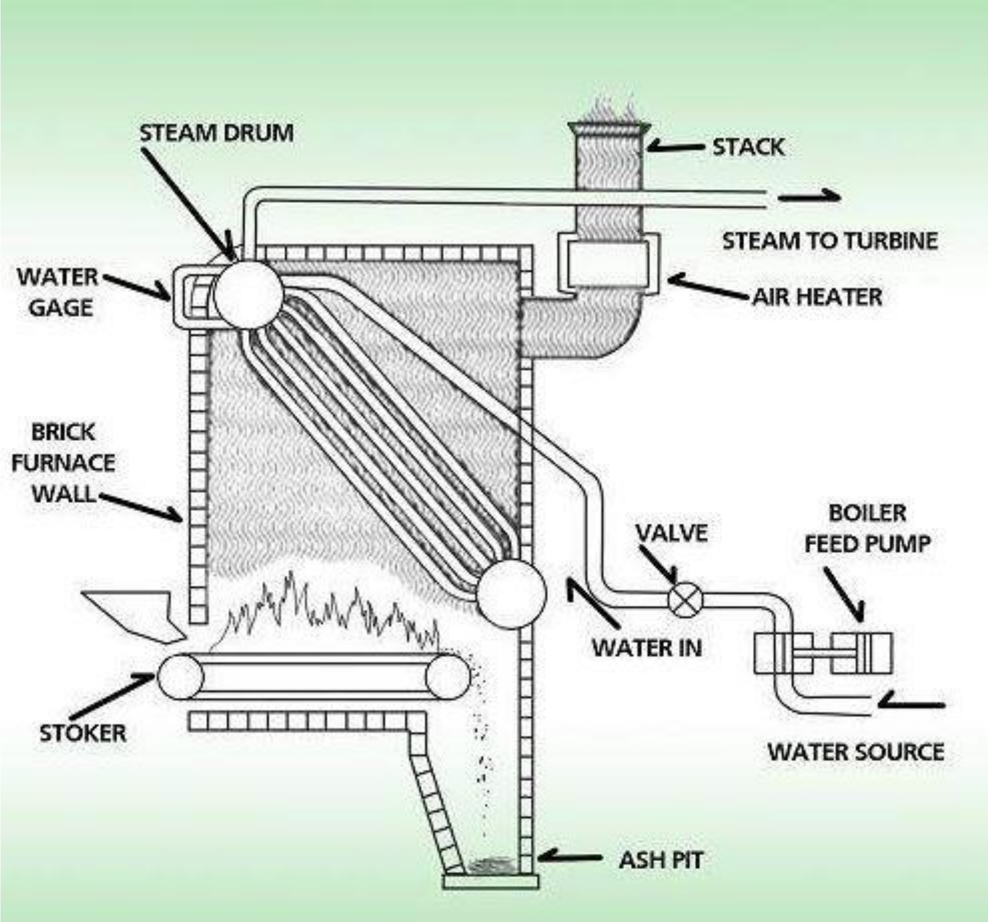


Figure 7: *Water tube boiler* (Industrial Wiki, n.d.).

The benefits of water-tube boilers include their small relative mass in relation to the mass of produced steam. Also, less time needed to raise steam pressure. Such boilers are more easily adjustable to reflect the changes in the load and also can be used to produce more steam. Also, water-tube boilers have a larger variety of sizes as compared with the fire-tube ones. High-pressure of up to 35 MPa can be maintained in such boilers. Finally, they can be operated at high temperatures.

Drawbacks of the water-tube boilers include first of all their high capital cost. Furthermore, cleaning is more difficult since water flows inside the tubes with relatively small diameter. The tubes used are not unified making it difficult to find spare parts. Their physical size may be an issue for some users.

4 Review of gas burners

In gas burners, fuel gas, such as most commonly used natural gas, is oxidized with air, thus allowing for combustion of the fuel gas and formation of a controlled flame, which is used to heat a heating medium, such as water, which is the most common energy carrier in heat plants. Other uses of gas burners include heat transfer through infrared radiation and visible light it produces.

First historical records of exploring gas reserves date back to 250 A.D. when it was used as a fuel in China. In there, natural gas was extracted from shallow wells and then distributed using a system of pipes made of hollow stems of bamboo. Already in the early 17th century natural gas was used for heating and lighting. In the USA, natural gas was first discovered in 1821. Yet, its commercial value natural gas received only after World War II, which facilitated the fast development of a wide range of gas burner for multiple uses in domestic, commercial and industrial applications. A diverse range is also applicable to their capacities which range 30W to 60MW, thus representing a significant difference in the order of magnitude.

Various types of gas burners exist. Atmospheric burners represent devices which are used for gas only and they are usually using high-pressure LNG. In the nozzle mixing burners, gas is not mixed with air until they are discharged from the burners. Surface mix burners are similar to nozzle mixing burners, but mix the gases at the time of ignition and produce a safer, quieter, and more efficient flame. Premix burners use specific design for mechanical mixing and use forced air from a blower or compressor. Sealed premix burners use a return intake (RI) castable tunnel or a multi-port (MP) tip mounted into the furnace wall. Radiant or infrared (IR) burners provide heat from a hot, glowing surface that radiates IR energy. Ribbon burners are elongated devices that are used to curve and shape glass-tubing. Vortex burners can completely incinerate not only fuel gas or oil but also waste gas or waste oil without leaving any unburned carbon.

4.1 Burners classification by operating mode

The classification of burners is presented in Figure 8. The classification identifies general burner operating modes as adopted from Baukal et al. 2004, Reed 1997, and IHEA 2006. The six categories shown in this figure (fuel type, oxidizer type, draft type, mixing type, heating type, and control type) imply fundamental differences in burner operating modes that will change their test protocol. A burner's operation can be described by combining elements from each of these six categories. A brief summary of the meaning of each category follows.

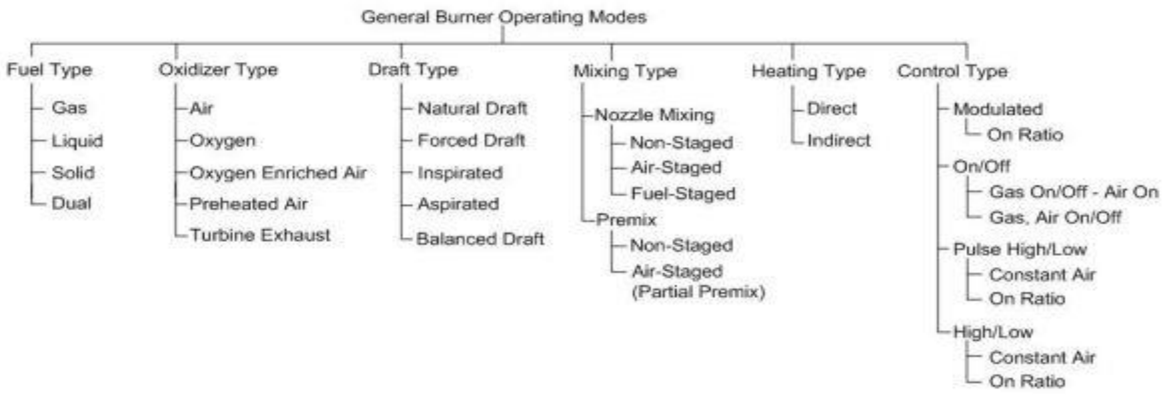


Figure 8: General burner operating modes.

Fuel type. Burners can first of all classified by the type of the fuel used. In the present study, only natural gas-fired burners are considered.

Oxidizer type: Air, oxygen, or their mixture, can be used as oxidizers. Air for combustion is preheated either via an external heating unit or piping that directs the exhaust gases near, or even through, the burner's air inlet to transfer heat from the combustion products to the incoming air. If oxygen is used, it is supplied in compressed tanks. Unlike with air, oxygen is not premixed with air for safety reasons.

Draft type: Draft is defined as the pressure difference that draws combustion air into the furnace and causes combustion products to be exhausted out of the furnace. Each draft type implies a different mechanism of air supply and thus a different control type to maintain an acceptable air/fuel ratio. The amount of air supplied to a natural draft burner is controlled by the pressure difference across the burner and the degree that side doors are open, so air/fuel ratio in a natural draft burner is controlled by adjusting a damper in the furnace exhaust stack to control furnace pressure. The oxidizer supplied to a forced draft burner is blown in and controlled by changing the degree a valve is open. Inspired burners use the motive force of the fuel to entrain their air into a Venturi throat for premixing. Conversely, aspirated burners use the motive force of blown air to entrain fuel. Both inspirated and aspirated burners have spuds or doors on the burner to control the air/fuel ratio in their primary stream; they are adjusted upon installation and should be checked periodically to accommodate the current fuel composition.

Mixing type: If any fuel and gas meet before the burner, the burners are classified as premixed. Otherwise, the burners are named nozzle-mix burners. Flashback is only a possibility for premixed burners and occurs when the flame speed exceeds the burner's exit velocity and the flame enters the burner. The flame could then exist anywhere downstream of the pre-mixing device; this damages the burner and is a safety hazard. The staging subtypes adjust the flame shape and decrease emissions.

Heating type: Indirect heating means the burner is accessorized to protect the load from the combustion products. For example, the burner can fire into a metal or a ceramic tube, or the flame can be restrained by a screen. Flame impingement on the intermediate accessories is a design consideration because impingement can raise temperatures so that material creep is rapid for even small loads.

Control type: Usually the furnace or process temperature is measured by a thermocouple, and the burner's firing rate is adjusted. Update speed for an industrial furnace is on the order of 30 seconds, except in pulsed control, where the burner can turn on and off every 3 seconds. The control system must both adjust the firing rate and maintain an acceptable air/fuel ratio. The most common way to do this is to throttle the air from its high set value to its low set value whenever the temperature is above a set point. The fuel flow is coupled to the airflow with either a pressure regulator or a cam that links the air and the fuel valves to turn in proportion. The cross-links are adjusted upon installation and should be checked periodically to accommodate the local fuel composition.

4.2 Burners classification by primary performance feature

Industrial burners vary strongly in firing capacity, laminar flame speed, a method of mixing, flame shape, flame temperature, and other characteristics. Since the wide range of industrial burners can have multiple end uses (from making gypsum or melting glass to drying paint or pasteurizing food), burners exist that favor performance needs for each of these applications. Tradeoffs in burner design must be made between cost, durability, energy efficiency, temperature distribution, versatility, emissions, and other metrics. Burners have become highly engineered for increasingly competitive performance and often must push the envelope of material properties to accommodate energy economics and regulatory standards. This section classifies burners according to the performance feature that the equipment vendor emphasizes. Burner application was gathered from GTI experience, various recommended applications in burner manufacturers' brochures, and references for the food industry (Fellows 2000), paper industry (Nilsson et al. 1995), chemical process and refinery industries (Baukal 2001), industrial furnaces (Trinks et al. 2004), and burners in general (Baukal et al. 2004).

Eight major types have been identified and they will be described later in the chapter:

1) Radiant burners: burners for radiant tubes, thermal radiation burners, and radiant wall burners;
2) Nozzle mix [low, medium, high] velocity burners;
3) Regenerative burners;
4) Natural draft burners;
5) Boiler burners;
6) Linear grid/in-duct burners;
7) Oxygen-enhanced (oxy-fuel) burners;
8) Flare burners.

4.2.1 Radiant tube burners

Radiant tube and burner systems provide high-temperature heat to loads that should not be mixed with the products of combustion or the flame, either because of a chemical reaction, as with steel, or because of a fine product finish, as with porcelain. The tubes must endure high temperatures and sometimes corrosive chemical environments, so they are made of expensive alloys or ceramics. Radiant tubes are usually limited by the maximum temperature which those tubes can withhold at a certain thermal and mechanical load. The radiant tubes burner ensure a uniform profile for heat release along the length of the tubes and also around the circumference of the tubes. The prolonged firing of a fuel gas with higher heating value might decrease tube life. Burners for radiant tubes are usually nozzle-mix burners with air staged to delay combustion and produce long flames. Inspirited burners exist; when using them, the dfart must be controlled both to maintain the optimum air/fuel ratio and to avoid flashback. Also, since NO_x formation increases with flame temperature, and a higher heating value fuel makes hotter flames, it is likely that NO_x emissions from radiant tube burners will increase when the input fuel changes from its current composition to vaporized LNG.

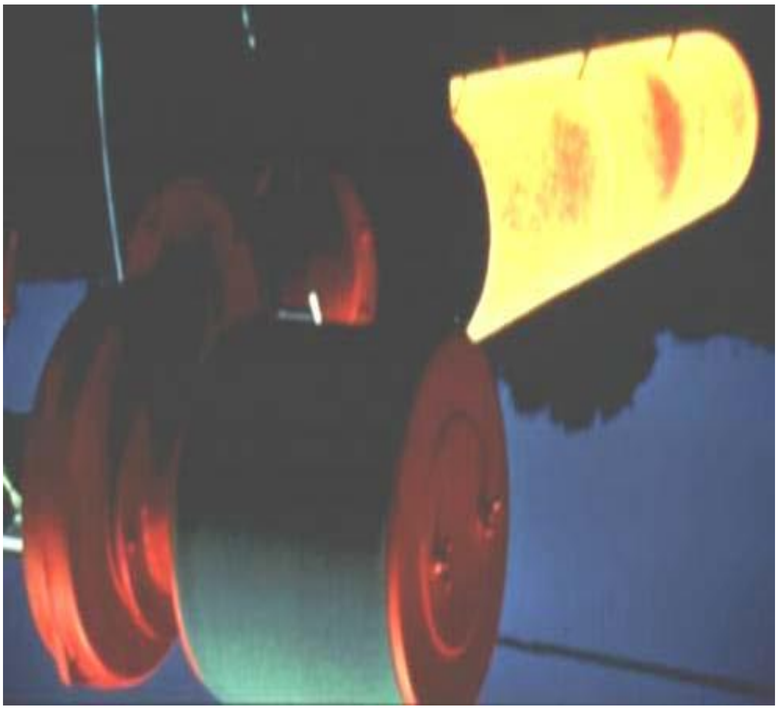


Figure 9: Pyrocore single-ended radiant tube system.

4.2.2 Thermal radiation burner

Thermal radiation burners are designed to provide an even temperature over a surface that is built into the burner, operate at lower temperatures, and are popular for drying applications. They are premixed burners, with the combustible mixture forced through a porous plate which encapsulates the burner. There are two kinds of thermal radiation burners; either combustion takes place within or on the surface of the porous plate, or else the ejected flames impinge a second, solid plate and provide indirect heating, for example, to protect combustible loads, like drying inks. Temperature uniformity, heat-up time, and power output per unit area and per unit energy input are important performance metrics for thermal radiation burners. In thermal radiation burners, air is premixed with fuel and they are incinerated in the radiating surface or above of it. The exact place is determined by the conditions under which the burners are operated and also on the design on the burner. Fuel composition affects the amount of air needed for combustion, and thus the mixture velocity through the burner. If the mixture speed is too low, flashback or flame quenching can happen, depending on the design of the burner. In addition to the operational features, the flashback is an important point in the safety system. If the mixture speed is too high, the flame may blow off or the radiant performance may be hard reduced because the burner surface is not being directly heated by the hot exhaust products. Depending on the specific design of the burner, optimum productivity is reached when the flame is stabilized inside or just above the outer burner exit.

Figure 10: Eclipse thermal radiation burners.

4.2.3 Radiant wall burners

Radiant wall or hearth burners are designed to fire outward so that a furnace wall is heated, thus in turn radiating heat to process tubes that contain reacting chemical flows. Dozens of these burners can be installed in several rows along the furnace wall or hearth, and since they are in service at a chemical plant, any available combustible is used as fuel. The important parameters in the use of such burners are the pressure of the fuel and its composition, which can range a lot depending on the source of the fuel and the process of fuel production. The burners should be required to work with different types of fuel. E.g. those with high heating values during startups of the boilers and those with lower heating values during normal operation times. However, this is a big problem for the boiler designers because the changes in the fuel composition cause changes in the amount of air required for combustion. And therefore, the use of fuels with high heating values are limited by the air induction ability of the boilers. On the other hand, the use of fuels with low heating values would be contained by the maximum available pressure. Radiant wall burners are not expected to be affected by a change in fuel gas composition.

Figure 11: A radiant wall burner block.

4.2.4 High velocity and general nozzle-mix burners

A burner's nozzle geometry can be engineered to shape the flame according to a specific design need. High-velocity burners are the most common; they produce exit velocities in the range of 120–150 m/sec and are used to circulate combustion products through the furnace and promote temperature uniformity. Nozzle-mix burners have no risk of flashback, and can fire with high excess air; circulation can thus be maintained even at a low firing rate. When impingement is a concern, burners that redirect the momentum with their nozzle geometry can be selected instead. Because high-velocity burners can run under significant excess air conditions, these burners can likely fire fuel gases of higher heat content without any flame stability or ignition issues. Higher HHV content gases will likely raise the local flame temperature, however, to promote thermal NO_x formation. The overall flame length may increase, especially in air staged burners. High-velocity burners are simply nozzle-mix burners with a modified burner block to enhance flame speed, so higher local temperatures, a change in flame shape, and increased NO_x formation can be generalized to all nozzle-mix burners.

Figure 12: An Eclipse ThermJet model TJ040 high-velocity nozzle mixed burner.

4.2.5 Regenerative burners

Regenerative burner systems are installed in pairs and fired one after the other. The principle is to recover heat by directing exhaust from the other burner through the refractory of the opposite burner, where it passes over a heat-storing medium that will preheat the other burner's combustion air when it fires. This heat recovery technique nearly halves fuel consumption. The one-box and two-box styles denote different ways to direct the flue gases. Regenerative burner systems are typically nozzle-mix. Because of the high preheat temperatures, thermal NO_x formation is an issue. Fuel staging and direct fuel injection into a sufficiently hot furnace reduce NO_x formation. Burning higher HHV content fuel will make the local flame temperature even higher, meaning NO_x formation should increase. An additional consideration for regenerative burner systems is the control system: if the fuel gas suddenly changes quality, particularly to a higher calorific value, a pressure spike from both the increased temperature and the increase in molar product of combustion could change the valve response, also, since the local flame temperature is expected to rise by using higher calorific value of natural gas, the cycle time is expected to decrease.

Figure 13: A Zedtec regenerative burner.

4.2.6 Natural draft burners

Natural draft burners are attractive because they do not require blowers. In such burners, burning air is entertained into the burner across intake generated by the incoming fuel jets plus the partial vacuum in the furnace created when buoyant combustion products draft up the stack. They are primarily used in petrochemical process heating furnaces. The fuel/air ratio in these burners is controlled by adjusting the opening of air registers on the burner. Premixed and nozzle mixed natural draft burners will likely respond differently to a change in fuel gas composition:

- **Premix natural draft burners**
  A higher Wobbe number fuel gas will increase the heat input to the furnace, and the control system should reduce pressure to compensate. At low enough pressures, a premixed burner risks flashback. Natural draft premixed burners pose a higher risk of a flashback than other premix burners because they operate with low-pressure drops across the burner.

- **Diffusion mix/nozzle mix natural draft burners**
  Flashback is avoided by separating the combustion air from fuels before the ignition zone. Nozzle mixed natural draft burners can contain a wide diapason of fuels without trust for adverse combustion productivity.

Figure 14: A Zeeco natural draft burner.

4.2.7 Boiler burners

Fire-tube boiler burners can fire into tubes that pass through a chamber of water one to four times. The heat from combustion is transferred through the tubes to the water to make steam; the pressure of the steam is measured and controls the firing rate. Water-tube boiler burners are larger and fire into an open chamber surrounded by tubes for water. Boiler emissions are regulated, and boiler burners are classified by their emissions: low NO_x, ultra-low NO_x, and conventional. NO_x-reduction is accomplished through flue-gas recirculation, plus a number of mixing and staging techniques listed in the tree diagram above. The most common operating mode in practice is a conventional burner with flue gas recirculation. Gas with injected nitrogen could increase NO_x, especially if the injected fuel burns hotter. Since boiler NO_x emissions are tightly regulated, this could be of concern. In addition, lengthened flames may impinge fire tubes to decrease tube life, and abrupt composition changes may trigger an unstable response in the pressure controller, because of the higher heat input, the increase in molar product, and the decrease in air/fuel ratio. ANSI standard Z21.13.2004 details experimental setup and procedure for thermal efficiency and ignition tests on small boiler packages that can be cited and possibly modified for industrial-scale units. In-stack NO_x reduction will not be examined, because it is post-combustion and unrelated to the burner.

Figure 15: Hamworthy Peabody Combustion, Inc. 20 MM Btu/hr water tube boiler burner.

4.2.8 Linear grid/ In-duct burners

Linear grid burners. Linear burners used to spread heat uniformly in ambient air and can operate at very low, even near zero, gas pressure. Air and fuel are mixed inside of the burner nozzle, and these burners emit blue flame. Flame luminosity and shape will be affected by a change in fuel gas composition.

Figure 16: A Flynn Burner Corp. ribbon burner.

In-duct burners. In-duct burners are linear burners specifically designed to hold a flame in high-velocity streams that can be humid or oxygen-depleted; some linear burners can be fitted with wings to serve as in-duct burners. Historically, they served to heat air for drying operations, and now they also reheat steam in cogeneration systems for process use in industrial supplement, or to drive steam turbines for electrical peaking combined cycle plants. They are designed for service in humid, oxygen-depleted, and chemical environments, so variation in fuel composition is not expected to adversely affect burner performance.

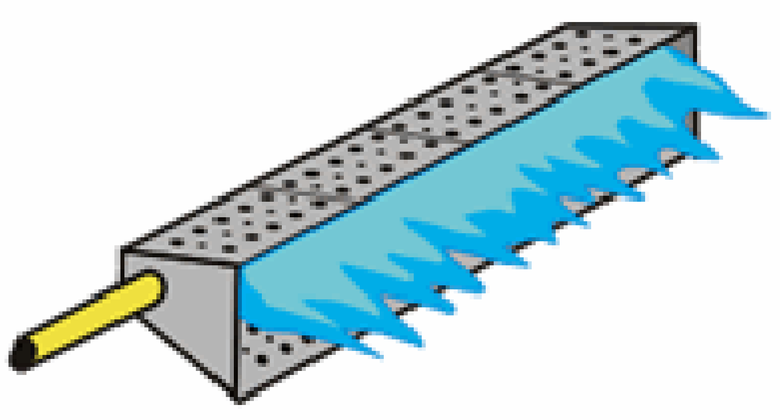


Figure 17: Sketch of a duct burner.

4.2.9 Oxygen-enhanced (and oxy-fuel) burners

Burners with oxygen-enhanced combustion are becoming more widespread in industrial applications. Such systems allows to increase heat efficiencies because the traditional system of air or fuel combustion can be modified for oxygen enhancement or replaced by oxy-fuel or duel oxygen/air burners. Also, processing rates will be increased, flue gas volumes decreases, and emissions formation avoided. Air compressors and preheaters are not needed, reducing capital cost, but care must be taken to ensure safety when handling oxygen, and oxygen must be produced or purchased, meaning the operating cost is higher. The cost is offset partially by decreased energy use, but mostly by the gain in production rate. Oxygen-enhanced and oxy-fuel burners employ the basic nozzle-mix burner design. As such, the research teams expect these types of burners to respond to a change in fuel composition with different flame shape, flame temperature, and emissions. The flame shape is not a critical consideration; these burners are intended to provide intense heat and are used when furnace temperature uniformity is not critical. Furthermore, since these burners produce higher temperature flames by virtue of the higher oxidant concentration, the thermal NO_x emissions are expected to increase more than for typical nozzle-mix design burners.

Figure 18: An Eclipse Primefire 400 Oxy-Gas burner (20 MMBtu/hr).

5 Emissions from boilers

5.1 Emissions formation

Since natural gas is oxidized during its combustion in boilers, molecules of natural gas are being broken down into substances with smaller molecular mass. Those substances include carbon dioxide, water vapor, carbon monoxide, nitrogen mono- and dioxide, sulfur oxides, and other emissions in minor quantities, which are commonly named as volatile organic compounds (VOC). Despite carbon dioxide is given substantial attention due to its impact on climate change, this substance has not toxic impact neither on human beings, not the environment. Furthermore, there are not technologies for carbon dioxide reduction, apart from carbon storage and sequestration, which are still not being widely used. On the contrary, carbon monoxide, which is an indicator if incomplete oxidation process of natural gas and thus is an indicator of possible combustion process improvement, and nitrogen oxides are given larger attention as they are known to have an immediate impact on the natural environment and human beings.

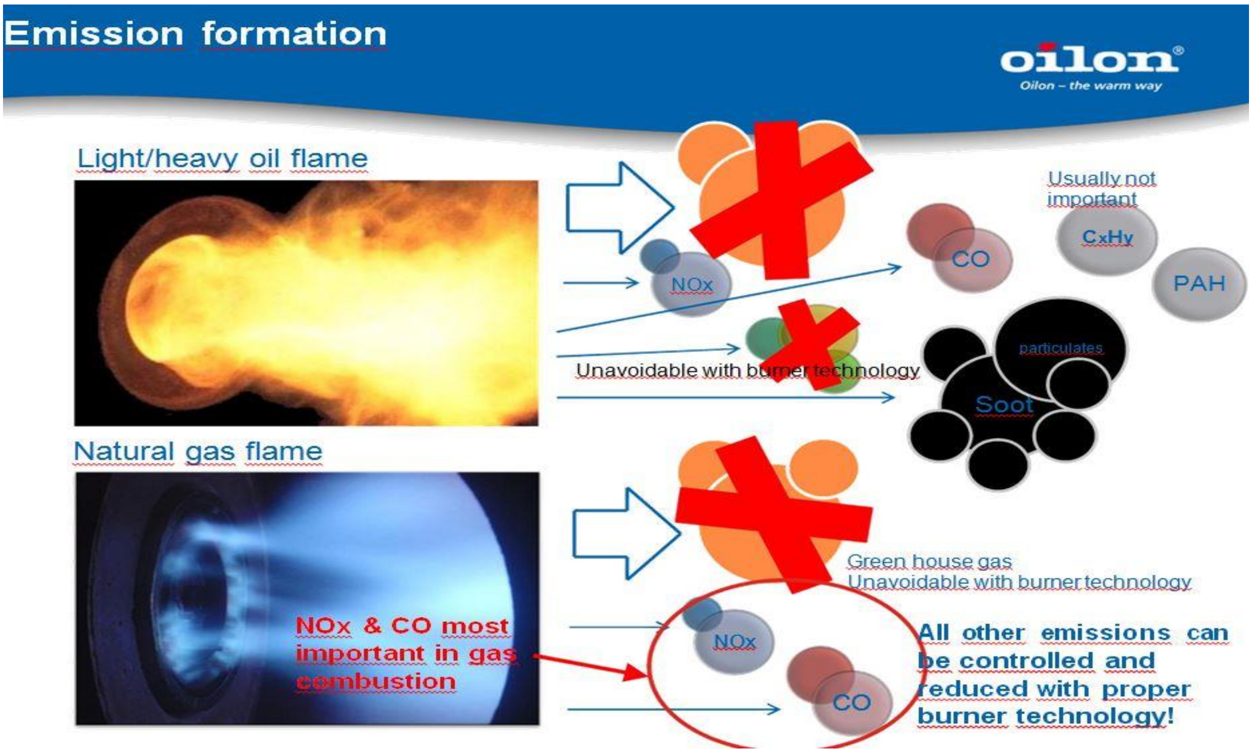


Figure 19: Emissions formation.

5.1.1 Carbon monoxide

Carbon monoxide is a colorless, odorless, and tasteless gas. The gas cab cause toxic impacts on humans and a majority of animals if exposured in concentrations above 35 ppm. Naturally, CO is needed to form ground-level ozone. CO is an intermediate combustion product and is formed and further oxidized into carbon dioxide (CO_2) in normal furnace conditions. CO formation conditions are often in a conflict with the formation conditions of NO_x. CO formation more is likely in low NO_x applications. (Wunning et al. 2009 – Handbook of Burner Technology for Industrial Furnaces, Raiko et al. 2002 – Poltto ja Palaminen)

Carbon monoxide is usually present in flue gases due to several reasons. First of all, it could be because of not sufficient residual oxygen content in flue gases, which prevents effective oxidation of carbon to form carbon dioxide. Also, the low temperature of furnace and flame lead to insufficient oxidation of carbon and formation of carbon monoxide. Furthermore, if flue gases have a too short residence time in the furnace, it leads to the formation of carbon monoxide. Finally, exaggerated air/fuel staging and insufficient mixing lead to carbon monoxide formation.

5.1.2 Nitrogen oxides

Nitrogen oxides (NO_x) is a term commonly used to denote a sum of nitrogen monoxide (NO) and nitrogen dioxide (NO_2). NO_x is the most strictly regulated emissions from burners. Nitrogen oxides primarily derive from i) nitrogen in the combustion air, which contains 78% N_2 by volume, ii) nitrogen bound in fuels, and iii) nitrogen as a part of nitrogen-containing compounds, such as ammonia and hydrogen cyanide. In natural gas combustion, only nitrogen contained in the air should be considered as the other two source of nitrogen can be neglected due to low presence or absence of nitrogen in natural gas and absence of nitrogen-containing components.

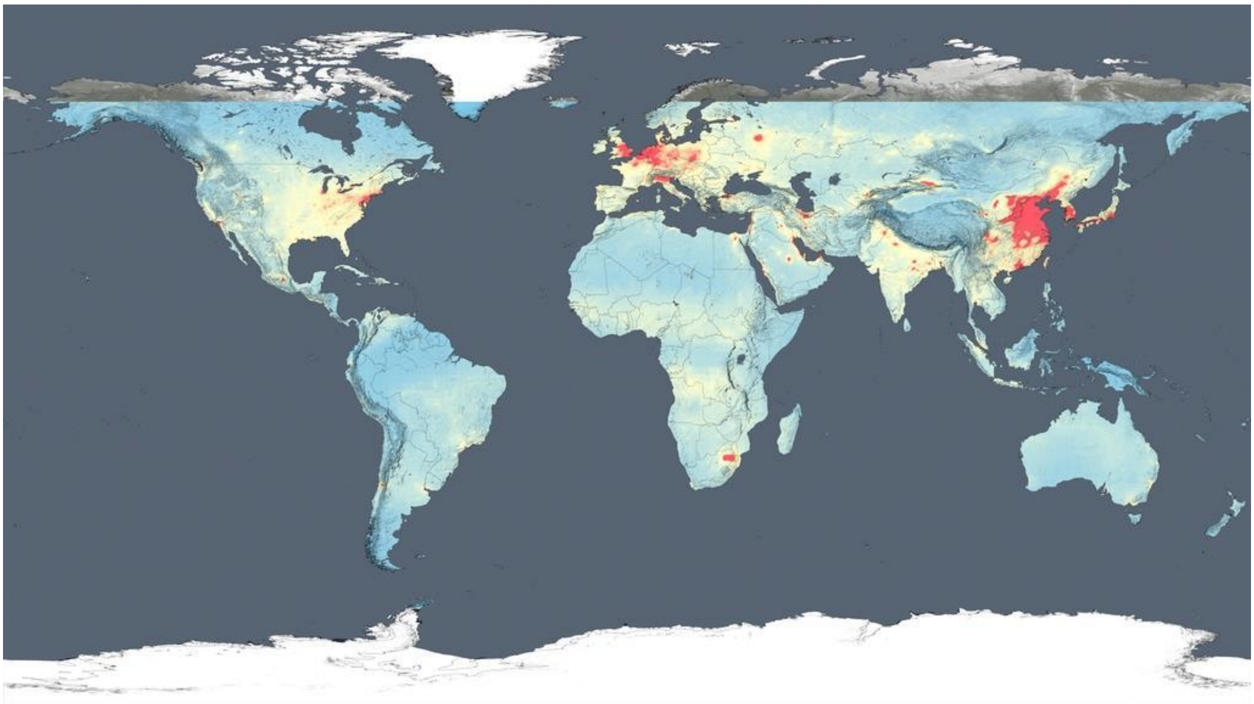


Figure 20: Atmospheric NO_2 concentration – NASA 2014.

Because of the absence of nitrogen in natural gas, the only formation of thermal NO_x should be studied. Because bonding energy of nitrogen molecule is so high that oxygen from combustion air cannot break it in normal combustion conditions, the formation of NO happens via a more complicated reaction path. The reaction path was first introduced in the 1940's and represents the so-called Zeldovich mechanism.

The amount of generated O & OH-radicals is exponentially proportional to flame temperature thus resulting in high-temperature dependency for the whole process. Studies show that Zeldovich NO formation is not significant below 1400 C but in temperatures above 1600 C, it's many times the dominating formation mechanism. For these reasons, the presented mechanism is widely called "thermal NO" (Wunning et al. 2009 – Handbook of Burner Technology for Industrial Furnaces, Raiko et al. 2002 – Poltto ja Palaminen).

Background of prompt NO formation goes back to the 1970's, when Fenimore showed that all NO formation could not be explained with Zeldovich mechanism in hydrocarbon flames where NO_x experiences sub-stoichiometric conditions. Prompt NO formation is only relevant in the flame reaction zone when the combustion is not complete and the needed hydrocarbon radicals (CH) are available. Usually, the formation of prompt NO is very rapid and only slightly dependent from temperature.In conventional burner applications prompt NO contribution to the total emission level is no more than 5 %.However in low NO_x-applications, where the flame is relatively cool and strongly staged, the prompt NO contribution becomes more relevant and should be taken into account in burner combustion performance design. (Wunning et al. 2009 – Handbook of Burner Technology for Industrial Furnaces, Raiko et al. 2002 – Poltto ja Palaminen)

Formation of nitrogen oxides depends on a wide range of parameters. First of all, it depends on the composition of the oxidizer and fuel and their characteristics, such as calorific value, hydrogen/carbon ratio, inert content etc. Pressure and temperature of an oxidizer and a fuel are also known to have an impact. NO_x formation also depends on the technologies applied which affect the distribution of air and fuel, their staging and water injection. Finally, NO_x can be abated using air pollution control systems, such as reburn, selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), and oilon catalytic reduction.

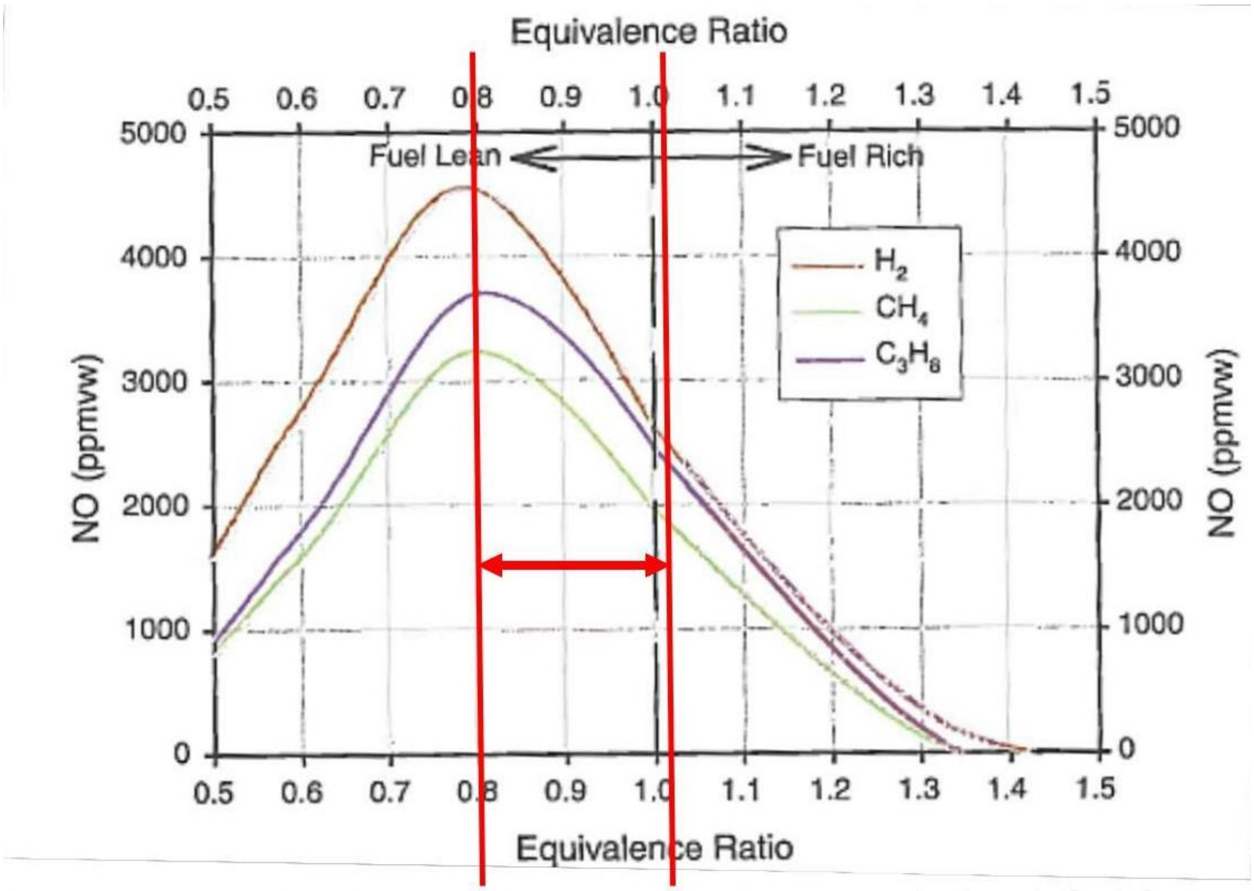
5.2 Emission reduction methods

Complete CO burns out could be promoted by altering the above the process conditions which results in inefficient oxidation of the fuel. However, the problem with process adjustment is related to the conflict with the formation conditions of NO_x. However, some tradeoff is possible to enable simultaneous reduction of both CO and NO_x: choosing larger boilers and adding more residual oxygen. However, these decisions are not something that burner manufacturer can make and there are some downsides related to them as well (investment costs, operational costs). So, one needs to find an optimal balance between CO and NO_x formation.

Optimal balance conditions always depend on many different conditions including fuel and furnace properties. With properly designed burners, adjustments of the flame should be possible through adjustment of the furnace conditions (Wunning et al. 2009 – Handbook of Burner Technology for Industrial Furnaces, Raiko et al. 2002 – Poltto ja Palaminen).

Usually, there tends to be more NO_x when hydrocarbons get heavier and hydrogen/carbon ratio of the fuel molecule decreases. If air would be replaced with pure oxygen as an oxidizer, NO_x emissions will rise drastically. On the other hand, if air acting as an oxidizer is diluted with the recirculated flue gas, the relative portion of inert substances will grow and NO_x emissions will decrease. The moisture content of combustion air will also have an influence on overall NO_x emission: the bigger the relative moisture, the more inert substances there are and thus NO_x will decrease. (Raiko et al. 2002 – Poltto ja Palaminen, Baukal et al. 2001 – The John Zink Combustion Handbook)

NO_x emissions depend on the combustion air/fuel ratio. which can be described using different parameters: residual oxygen level or Lambda in Europe, equivalence ratio or excess air in North America. The maximum NO_x level is usually reached between lambda 1 – 1.25 depending on the burner design. In practice, this means, that NO_x-level can be reduced with more excess air. This is particularly true in premixed and partly premixed type burners.



Adiabatic equilibrium NO as a function of equivalence ratio for air/fuel flames.

Figure 21: Equivalence ratio (Raiko et al. 2002 – Poltto ja Palaminen, Baukal et al. 2001 – The John Zink Combustion Handbook).

5.3 Impact of burner technologies on emissions

There are different ways to reduce NO_x emissions with burner design: i) via air and fuel distribution, ii) via air and fuel staging, iii) via internal flue gas recirculation, and iv) via water/steam injection.

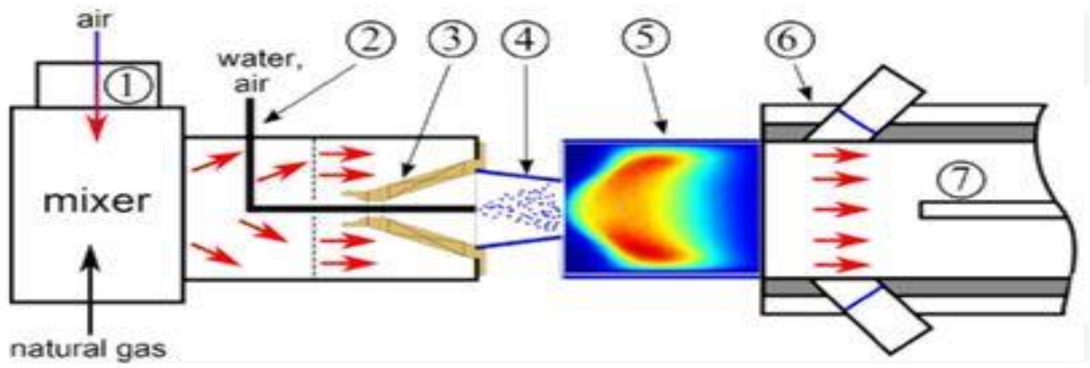


Figure 22: NO_x emissions with burner design.

Via air and fuel distribution. Ensuring that air and fuel are distributed symmetrically/as designed to the burner head is one of the basic functions of the burner head as a component. Usually, this is done with sufficient pressure drop on both gas/air sides. Air cabin design and internal guiding vane structures, among others, will help to achieve even distribution with reduced pressure drop. A common mistake for inexperienced customers is to have improper air ducting before the burner. This is something that cannot be fully compensated with burner design. Uneven flow profile will undermine the effectiveness of air staging in the burner head, thus NO_x and CO emissions will grow bigger than in optimal circumstances.

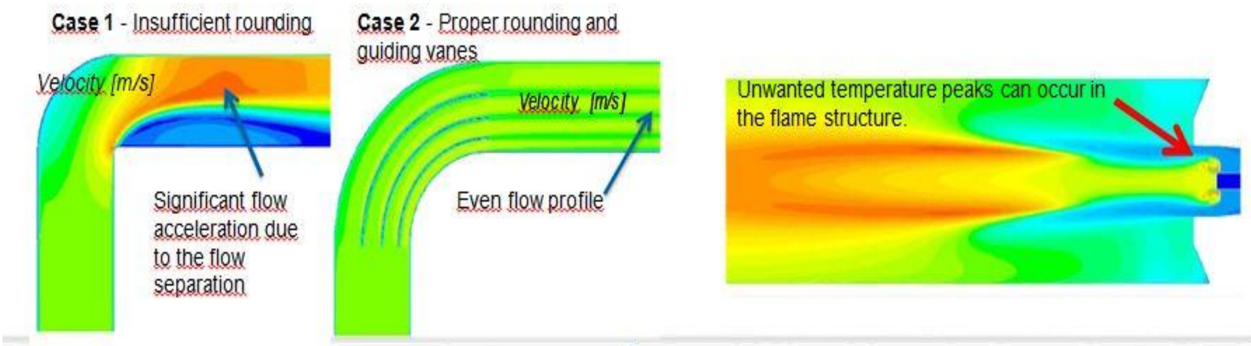


Figure 23: NO_x and CO emissions.

Via air and fuel staging. Air and fuel staging is the traditional and most commonly used primary method for NO_x reduction purposes. Air staging reduces NO_x emissions due to its ability to create local regions for fuel rich and lean mixtures.Inside these regions, there are locally more inert substances available that do not take part in combustion reaction thus lowering the peak temperatures of the flame. Air staging disadvantages: Flame dimensions are increased and furnace size may become too small. Unburned fuel and CO emissions may increase as the flame is less intensive and bigger in size.

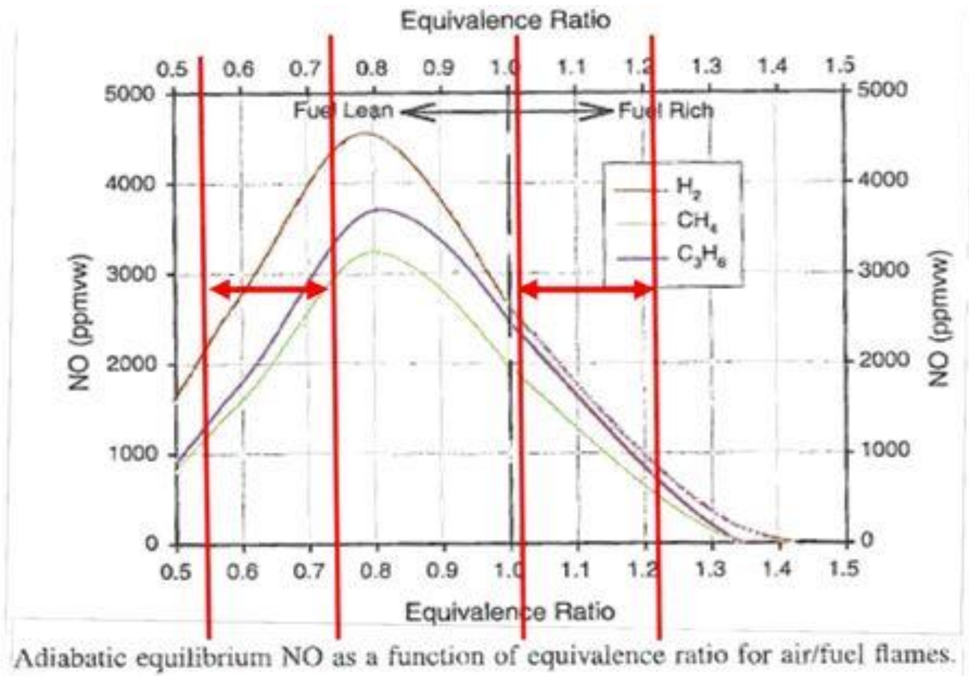


Figure 24: Adiabatic equilibrium NO_x (Raiko et al. 2002 – Poltto ja Palaminen, Baukal et al. 2001 – The John Zink Combustion Handbook).

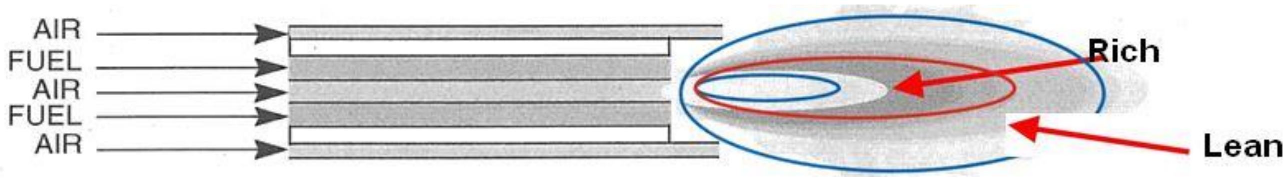


Figure 25: Air and fuel (Raiko et al. 2002 – Poltto ja Palaminen, Baukal et al. 2001 – The John Zink Combustion Handbook).

Via internal flue gas recirculation. Internal flue gas recirculation (FGR) is a process where combustion products inside the furnace are recirculated back into the flame. This is a naturally occurring phenomenon but can be used as an advantage if taken into account properly in the burner design and placement phase. Although the furnace flue gases are relatively hot, they are considerably cooler than the flame itself when recirculated back into the flame root. Internal FGR can be used as a diluent, reducing the flame temperature.

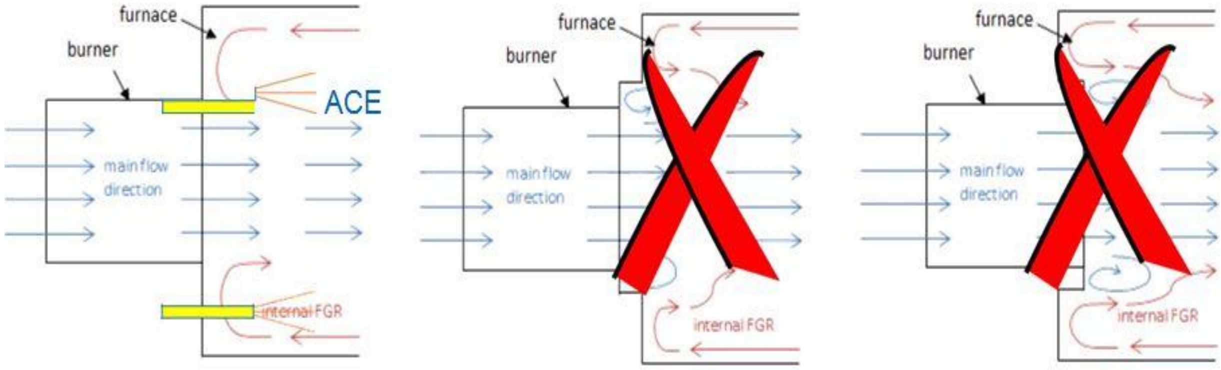


Figure 26: Internal FGR (Baukal et al. 2001 – The John Zink Combustion Handbook).

Via water/steam injection. Water is typically more effective in reducing NO_x emissions compared to steam, but it will have a bigger impact to the boiler efficiency, which will in both cases decrease. This is because of the latent heat absorbed by water and increased amount of flue gases, which both will in turn increase flue gas losses. Water latent heat can be partly recovered in condensing boilers. Water/steam injection also increases the plant operating costs.

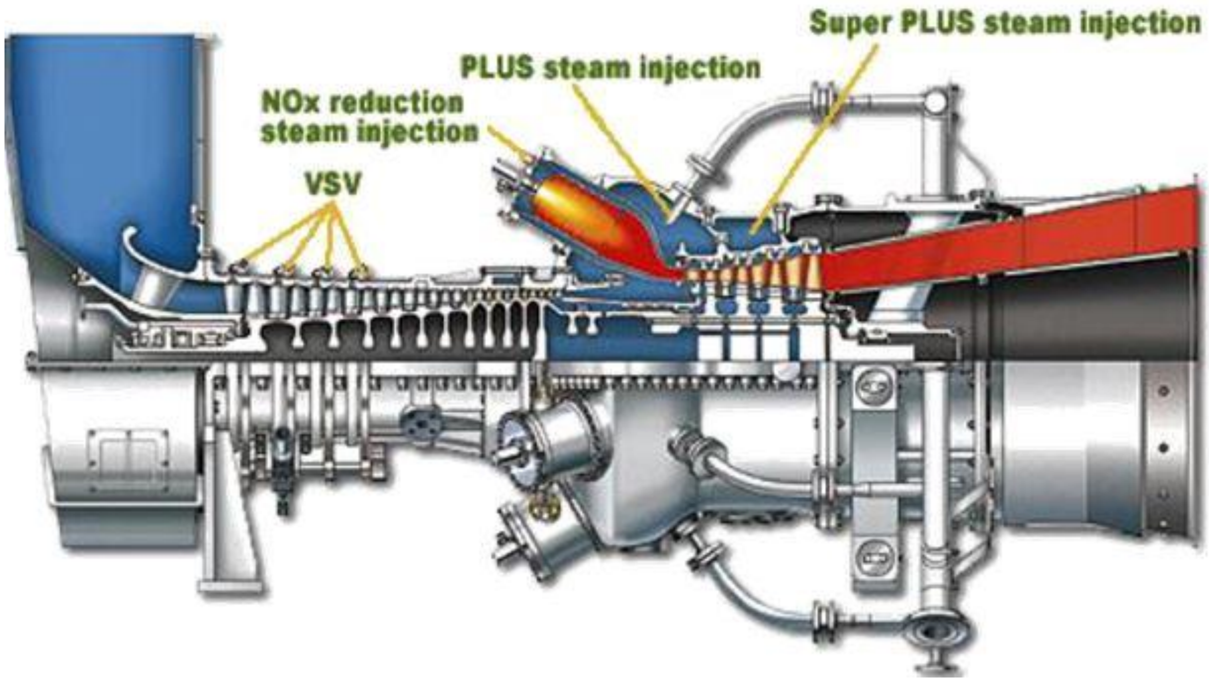


Figure 27: Water/steam injection (Wunning et al. 2009 – Handbook of Burner Technology for Industrial Furnaces.

6 Experience of using gas burners in St. Petersburg

The state unitary enterprise “TEK SPb” (SUE ”TEK SPb”) has a long-lasting history of operating gas burners in St.Petersburg, Russia. Out of all boilers operated by SUE ”TEK SPb”, around 500 heat plants have installed capacity of up to 12 MW.

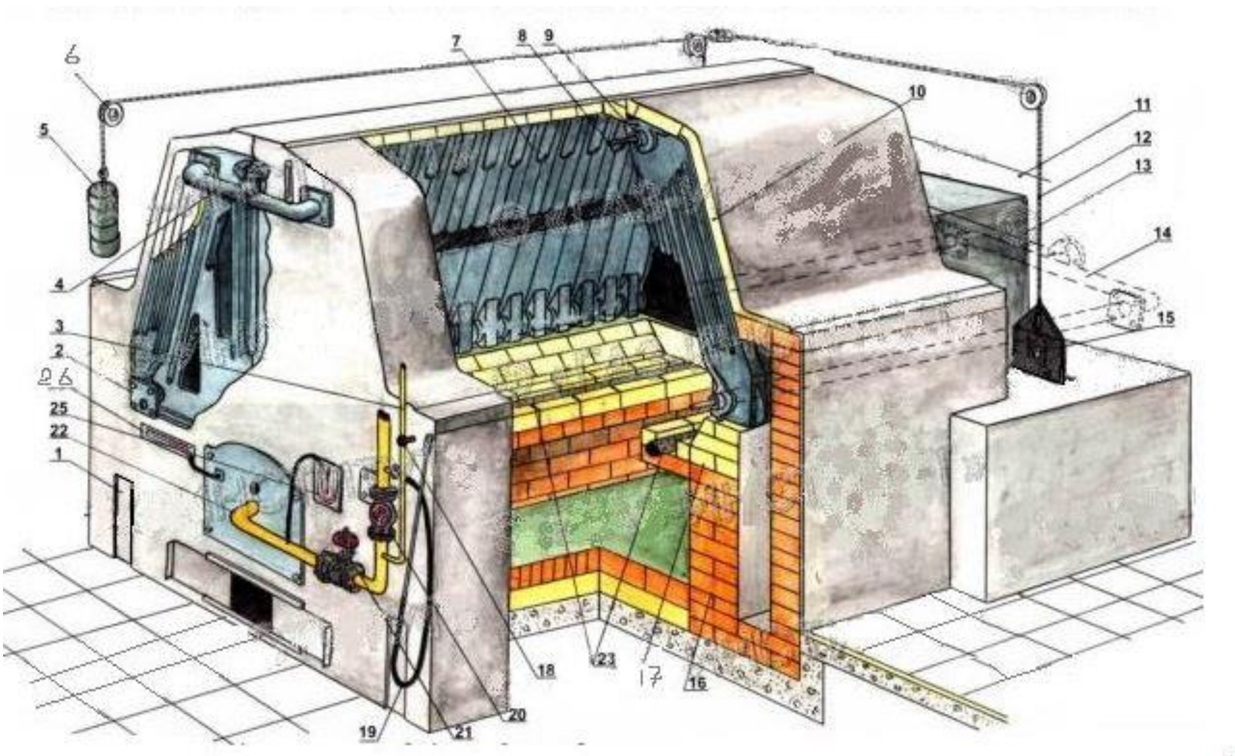


Figure 28: *Cast iron boiler «Universal 6».*

The boilers at SUE ”TEK SPb” are made of cast iron and have low heat generation efficiency of 75-80% and therefore they have high fuel consumption. Furthermore, auxiliary equipment is somewhat outdated, while automatic control and management devices are faulty. Also, the systems of continuous measurement of heat produced and water consumed are missing oftentimes. However, closure of such heat plants and connection of dwellers to district heating system is impractical due to dense construction in St. Petersburg. Therefore, renewal and restoration of currently operated heat plants is seen as an acute task of SUE ”TEK SPb”

The current tendency to and legislative requirements on energy efficiency, as well as economic drives for the reduced unit cost of heat generated, require innovative solutions based on new technological solutions, new materials, and equipment, increased quality control in heat plants. However, increasing pressure on the reduction of capital costs, on the other hand, resulted in the selection of cheaper and less reliable equipment. Furthermore, no consideration is given to possible incompatibility of the new equipment with already existing heat and piping systems, as well as with the quality of water used and future operating costs. Such inappropriate considerations result in a reduced lifetime of heat plants and their premature outage.

As of 2018, SUE ”TEK SPb” runs 68 automated heat plants with installed capacity in the range of 0,2-15 MW, which work on different kinds of fuels. Those heat plants are built using the domestic and overseas equipment. A part of the boilers represents stand-alone heat plants, whereas some of them are built in or to the same buildings with apartments, while 11 boilers are located in containers. Furthermore, SUE ”TEK SPb” has one heat plant located in a ceiling of a building with a capacity of 93 kW using Italian boilers.

Long-lasting experience of more than 20 years, as well as the analysis of technical literature and technical information provided by manufacturers, allows estimating the efficiency of further selection of technological solutions and the key apparatus (boilers, pump, and heat exchangers).

6.1 Solutions for heat plants and heat supply systems

Heat and hot water supply systems are implemented as single- or double-pipe systems. Dead-end hot water supply systems, where water is not recirculated and is supplied in one way only, are not implemented anymore since such systems result in unreasonably high waste losses cause by its higher consumption by dwellers in order to get water of desired high temperature. Furthermore, insufficient water recirculation in heat exchangers during the periods of low water consumption results in their pollution by physical impurities. Anticorrosive protection in double-pipe systems is implemented by introducing complexons (mainly “Hydro-X”). Deaerating of water is not implemented, except for heat plants, where automated deaerators are installed, and which work on the principle of superheated water.

Experience of using new equipment showed that the use of new boilers when using old piping system does not maintain theoretical efficiency, as well as a reliable heat supply for consumers. Heat plants under the operation of SUE “TEK SPb” are equipped with fire-tube, water-tube and cast iron heat boilers produced in 8 countries and implemented in 15 modifications. A wide variety of manufacturers, equipment used and their modifications results in:

- necessary training of personnel for each type of equipment;
- the complexity of selection of reserve parts;
- difficulties with repayments and technical service;

- impossible creation of centralized control system;
- lack of emergency troubleshooting.

Long-lasting operational benefits originate from the quantitative control of the amount of heat generated and supplied because it becomes possible to:

- avoid the need to make double-pipe systems;
- use modern pipes made of composite materials in heating networks and internal house networks.

However, it worth mentioning that lack of legislation on federal and regional levels currently limits a wider application of pipes made of composite materials.

For heat supply systems with an installed capacity of less than 1MW, the following concept of modular heat plants could allow for:

- the high efficiency of heat plants regardless of their loads;
- increased reliability of heat supply;
- unification of equipment, technological solutions and control systems;
- performance of preventive measures and repairmen all year round without reduced quality and reliability of heat supply;
- reduction of time and cost needed for project planning;
- easy setup, especially during restoration and refurbishment of old boilers.

The current state of equipment of heat supply in some districts of St. Petersburg does not allow flawless operation of heat plants. Furthermore, no one can guarantee the stable and reliable supply of natural gas, especially during the low-temperature season. For this reason, heat supply in isolated systems should be studied more comprehensively, which will require:

- a possible installation of cogeneration units or a possibility to connect mobile electricity generating units;
- installation of burners for incineration not only of natural gas but also for incineration of diesel oil;
- provision of special equipment for diesel oil transportation from mobile delivery units to burners for emergency response units.

Heat plants built in the 90s have tight assemblies, which make their repairment complicated. Therefore, their modernization should be planned under safe conditions.

6.2 Boilers and burners

For thermal energy generation in heat plants, two- and three-way steel fire-tube boilers made in Germany, USA, Denmark, Finland, and Russia (“Teplo-gas progress” Ltd. and “ZioSab”, Podolsk city), cast iron boilers (“Buderus”, “Ferroli”, “De Dietrich”, “Fulton”, “Liberty”) and automated water heating boilers made in Russia are installed. Apart from it, in one heat plant, French boilers UTM-50 are being used. In general, boilers are equipped with burners made by “Oilon”, “ELCO”, and “Weishaupt”.

Long experience of using cast iron boilers made by “Buderus” proved their superiority compared with other domestic and overseas boilers in terms of reliability and cost-effectiveness. Sections of these boilers are made of special, corrosion and high temperature resistant grey cast iron (grade GL 180M) developed by “Buderus”. Design features of boilers allow to use them with high efficiencies and minimal emissions of flue gases. As also generally known, cast iron boilers are sensitive to the temperature difference of incoming and outcoming water. If this difference raises to the critical zone, the boiler could crack. For example, the maximum temperature difference in boiler types “De Dietric” made in Russia is 25-30 °C. To prevent such drawback, boilers made by “Buderus” use the principle of Thermostream. The core idea of Thermostream technology is to mix cold water coming from the consumers with warm water, which is being sent to the boiler. Therefore, temperature increase occurs in the higher zone of the boiler before it reaches the heat exchanging surface of the boiler. Therefore, the even sudden supply of cold water to the boiler will not result in reaching critical temperature difference and its destruction.

As per the advantages of cast iron boilers, they are not sensitive to the quality of water being recirculated, use of light thermal insulation, the good ability for being repaired because of their assembly and disassembly without welding.

The main advantage of steel boilers over cast iron ones is their higher efficiency. There is no significant difference in designs of steel fire-tube boilers made by domestic and overseas companies. Modern fire-tube boilers are the most efficient when operated within the range of installed capacity of 0,2-15MW. Boilers of this type at SUE “TEK SPb” operate using premix gas burners with the maximum excess air ratio α=1,03-1,05. It worth mentioning that overseas burners oftentimes use a higher excess air coefficient of 1,2-1,25 to maintain more stable combustion process. However, it results in the efficiency loss by 1,5-2,0%.

Considering that fire-tube boilers have lower pipe surface when compared with water-tube boilers, due to the use of sheet steel, their cost is significantly lower than the cost of water boilers. At the same time, their reliability increases. Steel fire-tube boilers are much less sensitive to the temperature difference, than cast iron boilers, and can withhold the difference of 50-60 °C.

Fire-tube boilers are advantageous over water-tube boilers because they have negligible hydraulic resistance, and therefore lower energy requirements for heat carrier medium transportation. The total hydraulic resistance of fire-tube boilers is 0,02-0,03 MPa. Another their advantage is their good suitability for repairment and possibility to use light and cheap insulating materials, which work under lower ambient air temperature.

Disadvantages of fire-tube boilers include relatively low efficiency of heat exchange both from flue gases and from the water. However, by using various turbulators located in the flow of hot gases, this coefficient of heat exchange increases from 50 to 100-120 W/(m*h*K). Low heat exchange from water is explained by free water flows near surfaces of the tube bundle in the boiler. Considering that surface boiling occurs on the surface of the pipes and reverse chamber, strict compliance with the requirements for the supply water is needed to ensure high reliability, especially when working with hard fuels.

Reliability of fire-tube boilers depends also on the design of the boilers. For example, for three-way boilers, reliable operations are guaranteed at a minimal load of at least 40%, for two-way boilers - at 25%. This is because of the fact that exhaust fumes are rapidly cooled at higher load in three-way boilers operating on solid fuels and as a consequence active dew generation results in fast boiler workout. Another disadvantage of the fire-tube boilers is their high dimensions.

Water-tube boilers require a lower specific amount of metal per unit of structure because of the use of tubes with low diameters, which allows to intensity heat exchange processes in boilers. They have lower water volume and, as a consequence, allows for the fast temperature increase. Furthermore, the safety of boilers operation is ensured since even accidental rupture of boiling tubes will not break the entire boiler. The average lifetime of water-tube boilers is 18-25 years. To ensure the high functional reliability of water-tube boilers, strict control of makeup water is required. Under good conditions of water pretreatment, the scale-free regime could be maintained.

Unfortunately, not many overseas boilers can perform efficiently good work for long-term under Russian conditions. Technical specifications required water to be soft and treated. The pressure in the natural gas supply system should be not less than 20 mbar. Luckily, the problem of water quality is not as acute in St. Petersburg as in many other cities; water in the Neva river is soft. However, in some cities located in the region of St. Petersburg, this problem is of high importance. If the heating system is assembled correctly and is being operated without leaks of circulating water, the installation of a small water purification system might solve this problem. Even is a small amount of impurities will precipitate, it will reduce the lifetime of the boiler, but not much. Usually, a five-year warranty is given by manufacturers to their boilers, while expected lifetime is estimated to be 25-30 years. A much worse situation is when the system requires continuous water makeup or there is illegal water extraction. Then, the lifetime of the boilers is significantly reduced.

In SUE "TEK SPb", only one heat plant with the fire-tube boiler, which has been used for 7 years, was repaired after detecting leakage. During repairment, significant difficulties with repairmen of defected pipes were encountered. For example, repair of boiler "Witermo-2,5" (Finnish company "HOYRYTYS") was performed without consideration of manufacturers instructions, which was not supplied by the company-supplied. Lack of the manufacturer's instructions on repair of the boiler resulted in the generation of cracks in the tube sheets and the need for their replacement. Manufacturing and replacement were done by the specialists of the company.

In St. Petersburg, natural gas supply (stable pressure and absence of suspended particles) is the most acute problem. For stable and emergency-free work of burners, the pressure in the pipeline should be constant and not less than 20 mbar.

Burners with forced air supply can be gas, diesel, heavy fuel oil, or combined burners. Therefore, boilers are uninformed. However, one should purchase a boiler and a burner separately, which makes it more expensive. Moreover, burners with forced air supply are noisier and more difficult in their setups.

Atmospheric burners, which are widely used in Europe, work only on natural gas, can be operated at lower pressure, when compared with combined burners, cheaper and simpler. At the same time, the efficiency of atmospheric burners is higher than 90%. During cold ambient air temperature season, heat plants located in a historical part of St. Petersburg might have lower than required gas pressure. When pressure drops, burners continue to burn. At the same time, the flame becomes low and therefore efficiency drops. But what is even worse is that nozzles of the burners burn out. And if boilers will operate under such conditions for a long time, a more frequent replacement of the burners will be required.

Burner manufactured by “Oilon” and “Weishaupt” with forced air supply, installed in the boilers with the minimal capacity of 0,5 MWt, require the installation of noise-abating enclosures if the heat plants are located in the same building as living apartments. Burners made by “Weishaupt” operate without complaints, whereas following malfunctions were notices when operating burners made by “Oilon”:

- burning-out of starting electrodes;
- unsatisfactory work of “gas-air” regulators;
- unstable operation in the “big flame” mode;
- occasional operational incidents with the power regulator KS 90;
- destruction of bearings of a blower fan.

6.3 On the efficiency of boilers

According to the data of domestic and overseas manufacturers of cast iron and fire-tube boilers, the efficiency of new boilers ranges 92-95%, while it can rise to 98-99% if economizer is installed and when calculating using lower heating values as accepted in Russia. However, it should be also considered that foreign specialists assume that the heat losses to the environment are constant under varying ambient air temperature. Therefore, when using Russian methodology, the calculated efficiency is usually overestimated by 1-2%. Besides, water-tube boilers the maximum efficiency is reached at low loads of 20-30% and it further decreases with the load increase. It occurs because the temperature of exhaust fumes increases more intensively as compared with the degree of excess air coefficient decrease. Since boilers are used at 50-100% of their load in real life, their operational efficiency decreases by 2-4% from the efficiency stated by the manufacturers.

The analysis of steel water boilers operated in Russia showed that domestic fire- and water-tube boilers with a capacity of up to 2MW and equipped with automated burners made overseas are not worse than overseas boilers in terms of their reliability, maintainability, and energy efficiency.

6.4 Heat exchangers

As heat exchangers used in heating and hot water supply systems in the majority of heat plants, movable plate heaters made by 10 companies in 6 countries are installed. At three heat plants, plate heat-sealed heat exchangers of a type SWEP Reheat made in Sweden are installed. At two heat plants, heat exchangers of a type Rudo Cel ½ made by “Viessmann” (Germany) are installed for hot water supply.

Both plate and shell-and-tube type heat exchangers are used. Overseas companies usually supply plate heat exchangers. Domestic companies only made auxiliary equipment, while plates themselves and sealing rubber are obtained abroad. The reason for not making plates domestically is the lack of technology for the production of special “soft” corrosion-resistant and chlorine-resistant steel in Russia.

Overseas manufacturers of plate heat exchangers assumed by default that tap water is necessarily pretreated before being used in the heat plants. Whereas, tap water has a high hardness (determined by the contents of calcium and magnesium) in many regions in Russia and also in some district of St.Petersburg. In such cases, water pretreatment systems should be considered. It is known that carbonate is deposited most effectively in the temperature range 60-70 °C. Therefore, stabilization of the temperature of water incoming into heat exchangers, which could be controlled with the frequency controlled pump, which should be installed at the cross-over pipe between the feeding and reverse piping systems. The hot water supply system should be automated. Frequency converter, and therefore pump control is maintained by an electronic automated system, which controls the temperature of water incoming to the heat exchanger. Application of such a scheme allows prolonging the intervals between maintenances by several times.

Plate heat exchangers have the effect of self-cleaning. However, when the circulation degree between primary and secondary contours of heat exchangers decreases to below 65% from its nominal capacity, the effect of self-cleaning vanishes.

Many heat plants are installed on the old piping systems in houses, which however are often corroded and have significant amount of suspended solids and salts. These impurities are oftentimes entrained and are brought to the plate heat exchangers. Moreover, in many cases, makeup water is supplied directly from tap, meaning that water was mechanically and chemically treated, including chlorine. However, chlorine corrodes non-stainless steel.

Therefore, in this case, possible presence of impurities in water, which increases thermal resistance of heat exchange, should be considered for the following reasons:

- to enable long-lasting reliable exploitation of the exchangers accounting for the scale and other impurities formation on heat exchanging surfaces;
- introduction of margin, which guarantees required working parameters as compared with the theoretical models obtained when developing equations for heat exchange and pressure losses, which have limited precision;
- maintenance of given parameters at specific differences of temperature or consumption of water from required values.

At the same time, manufacturers of plate heat exchangers do not oftentimes account for such factors. Analysis of using plate heat exchangers made by Alfa-Laval showed that the reduction of thermal efficiency was reduced by:

- 5% after the first year of their operation;
- ca. 15% after the second year;
- more than 25% after the third year.

Reduction of the heat exchange coefficients during normal use of the exchanger after three years was more than 30%.

Some manufacturers in order to reduce the costs use plates made of steel of lower quality - AISI 304 and sealing plates of NBR. In this case, the expected lifetime of heat exchangers reduces significantly and sealing plates will need to be changed faster. Therefore, plates in heat exchangers should be made of anticorrosive and chlorine-resistant steel AISI 316, whereas sealing plates should be made of high temperature-resistant rubber EPDM. In such cases, the lifetime of heat exchangers will be at least 30 years and sealing rubber will need to be replaced only ones in 7-9 years. It worth mentioning that sealing plates make up the largest share of costs of heat exchangers. Furthermore, the shape of the sealing plates and their installation methods should be considered when choosing in heat exchangers. Also, plates of the same size made by same or different manufacturers could have a different angle of rolls to a horizontal axis of 30o (so-called “hard” plates) and of 60o (so-called “soft” plates). Hard plates are known to have higher heat exchange efficiencies and high pressure losses and vice versa for the soft plates. Pressure losses required increased electricity consumption, whereas low heat exchange efficiency requires relatively higher dimensions and amount of metals per unit of structure.

Despite the requirements of sanitary rules (SR) 41-101-95, point 4.37, some of the heat plants are not equipped with magnetic slime separators, which result in their pollution. Experience shows that in some cases, heat exchangers were cleaned during the first year of their exploitation with their complete disassembly.

Nowadays, shell-and-tube small-size heat exchangers appeared on a Russian market. E.g. “think-walled heat exchanging apparatus intensified” (TTAI) made by “Teploobmen”, the city of Sevastopol. This equipment, according to the data of manufacturers, has 10 times better mass/size parameters that modern plate heat exchangers. Furthermore, they have the ability to be completely fitted for a required system. Such equipment also has the self-cleaning ability and can be easily and completely disassembled with the complete ejection of the pipe bundle. Heat exchangers TTAI can be located along the walls as heated towel rails in bathrooms, under the roof and be located at a single element in a bundle of tubes without requiring another basement for its installation than those required for the pipes. Another benefit of using TTAI is their low thermal inertia, which always remains within one minute time. However, looking at their design it can be assumed that they are sensitive to hydro blows. However, SUE “TEK SPb” does not yet have experience of its exploitation.

6.5 Pumps

Most of the heat plants are equipped with foreign pumps made by “Wilo” and “Grundfos” of “dry” type and with “wet rotor”. In “wet” pumps, the rotor of a motor is submerged together with the working wheel in a pumped medium. Liquid lubricates the bearings and cooled down the motor at the same time. Water-tightness of the electrical circuit is maintained by a separator, made of stainless nonferrous steel. Rotor shaft can be made of ceramics, bearings - of ceramics or graphite. The body of the pumps for heating systems is oftentimes made of cast iron. Pumps of this type are almost silent and can work years without technical maintenance, and when needed, their maintenance does not require laborious operations.

The drawback of “wet” pump is their low efficiency of 10-50%. For the dry-type pump, the efficiency is 40-80%, which is the reason to favor them in large heating and hot water supply systems. As it was already mentioned, lubrication of the wet-type pumps is maintained by recirculating water, which means that recirculation should be continuous. Furthermore, this is only possible at a horizontal placement of the shaft. If the pump is placed vertically or in a suspended condition, it could fault rather quickly.

According to the information of “Grundfos” system, the company started manufacturing GRUNDFOS MAGNA pump. The design of such pumps includes permanent magnets, which allowed to increase the efficiency of the pumps by 30%. Furthermore, new pumps include internal filters, which is important since many pumps are sensitive to dirty water and especially to metallic particles.

6.6 Automation and management systems

Automation and management systems (AMS) of heat plants are performed individually using industrial specifically or freely programmed controllers (Honeywell, Vitotronik, Frisquet, etc.). Heat supply is maintained using operator’s temperature regime. At some heat plants, smooth automated control of heat plants load is not implemented. Maintainance of required temperature regime is implemented by periodical activation and deactivation of boilers or by a two-stage change of their load (50-100%).

The technical level of automation systems allows to control the heat plants and to provide full information about their performance. AMS systems are implemented at their best in 6 heat plants. For the SCADA systems, program packages of cold water supply provided by Honeywell and In Touch were installed. At heat plants built during the end of the last century, automation systems are implemented by sending one alarm signal to an electronic pager. Heat plants are equipped with domestic and overseas (Germany and France) equipment for controlling gas, water, and heat consumptions.

6.7 Proposals for selection of equipment during further renovations

1. To limit the equipment used to 2-3 domestic or overseas companies
2. At heat plants with a capacity of <1MW, the modular concept should be implemented
3. At heat plants with a capacity of >1MW, the number and capacity of the installed boilers should be determined by:
   - peak load during winter and summer seasons
   - the type of the load (heat supply, ventilation, hot water supply) and the regime of their consumption
   - the possibility to implement the most efficient load of the boilers.

4. Selection of the technological design and equipment of the heat plants should be done by making techno-economic assessments and analysis of alternatives by considering the materials of the piping system, as well as of the heating system:
   - When refurbishing the heat plants and still using old heat supply pipes, only double-pipe systems should be applied for heat and hot water supply
   - When building new or completely replacing the old systems, single-pipe systems with double -pipe systems can be used
   - If existing heat plants are being refurbished to supply enough heat for the new customers, the customers should be connected using a double-pipe systems
5. The experience of using various equipment showed that the most reliable equipment was manufactured by “Buderus” (cast iron boilers), “Viessman” (heat-pipe boilers) and “Weishaupt” (burners).
6. When choosing fire- and water-tube boilers, domestic heat plants equipped with foreign burners should be preferred.
7. To increase heat efficiency, condensing heat exchangers should be installed in hot gases after the boilers.
8. Pump made by “Grundfor” and “Willo” of the most optimal capacity should be preferred.
9. Application of automation systems based on frequency converters for control of energy generation is reasonable if corresponding techno-economic justifications are made. It should be considered that the use of frequency control of pumps will lead not only to reduced energy consumption but also to the reduction of operating expenses associated with their maintenance.
10. If the pump using submerged rotors equipped with built-in filters, their washing with reverse water should be foreseen.
11. Main requirements to plate-type heat exchangers used in heat supply systems:
    - they should be dismountable,
    - preferably, single-pass exchangers,
    - if a two-stage heating system is used, each stage should be equipped with a separate heat exchanger,
    - plates in heat exchangers should be made of rust- and chlorine-resistant AISI 316 steel, while sealing plates of thermally resistant rubber EPDM,
    - design of sealing plates should be considered (size, configuration, mounting system). The most preferred sealing plates are those made by “Alfa Laval Potok” in Korolev city, Moscow region.

12. To protect equipment from rust and solid impurities, magnetic slurry removal should be considered. The most efficient slurry clarifiers are those with large volume. They should be installed to treat water before it enters the heat plant.
13. Shell-type heat exchangers should be small in size and with enhanced heat exchange efficiency, as well as to have the self-cleaning ability.
14. Complexions should be used to protect equipment from rust. For heat and hot water supply systems, one of the following systems are proposed:
    - Installation of water deaeration system;
    - Use of piping systems made of rust-resistant materials
    - Application of special inhibitors of rust, which are accepted by a governmental body "Sanepidemnadzor", which is the body controlling hygiene- and sanitation-relation issues in Russia
    - installation of electromagnetic equipment to reduce the generation of solid particles on the surface of heat exchangers.
15. Container-type heat plants providing heat and hot water and having a capacity of 3 MW and higher should have a small area of 2-2,5 m^2 for making possible repair work.
16. When designing and building heat plants without personnel, a toiler and a sink should be installed anyways.
17. The contract on supply and assembly of equipment should contain conditions on providing technical support documentation in the Russian language.
18. Develop special plans for increasing vitality of heat plants during emergency situations (e.g. interruptions in gas supply) in isolated zones of operations. E,g, to foresee possible connection of mobile units for electricity generation to provide lightning.
19. Organizational issues:
    - to make a single service center for operation and maintenance of equipment
    - to create a single support service
    - to develop a training program for personnel and continuously enable their training.

7 Life cycle assessment

Draft: the LCA part will include calculation of emissions using the methodology on "Determination of emissions of pollutants to atmosphere during incineration of fuels in boilers with installed capacity of less than 30 tons of steam per hour or less than 30 Gcal per hour" (NII Armosphera, 1999). This methodology is used in Russia by companies to report their emissions to the government. The emission values were used to model the environmental impact of fuel combustion and its environmental impact.

7.1 Calculation of emissions

7.1.1 Information on the boiler, fuel used, and heat produced

In this thesis, the environmental impact of operating the old heat plant, which was renewed in one of the regions of St.Petersburg, Russia, was compared to that of new one. The modernization of the boilers included the increase in their capacity and closure of two neighboring heat plants. During modernization, cast iron boilers with slot burners ("Energia-3M", "Universal-6", "Universal-3") were demolished. Slot burners are implemented as tubes with perforated gas-releasing holes which are embedded in a slot channel for air supply. Instead of those boilers, four automated water-heating boilers of a type "Turboterm – 3150" made in Russia were used. The new boilers are intended for heat and hot water supply for private and public buildings.

The "Turmoterm" boiler represents a steel all-welded fire-tube boiler with a reverse furnace. A convective part includes a second path in the fire-tube and packets of flue gas tubes of bigger diameter. The "Turboterm" boilers are equipped with the automated gas three-step burners "GP-280T" made by "Oilon", Finland. The key parameters of the burners are presented in Table 2.

Table 2. Key parameters of the new burners.

	Unit	Value
Burner type	-	GP-280T
Exploitation number	-	1-№1229031 2-№1229030 3-№2246001 4-№2246002
Manufacturing year	-	2013(for 1,2), 2012(for 3,4)
Capacity	kW	500-3500
Power of the engine	kW	7,5
Current	A	14,7
Rotation	rpm	2855
Program relay	-	LFL1.322

Table 3 shows the characteristics, fuel consumption, and energy yields of three old heat plants which were replaced with one new heat plant “Turboterm”. The results show that the new heat plant has an increased efficiency of heat generation compared to the old ones: around 92% in the new versus around 80% in the old heat plants. Furthermore, annual heat generation also increased significantly. As a consequence, the specific fuel consumption was reduced from 130 kg/Gcal in the old heat plants to 103 kg/Gcal in the new one. These data were used in the LCA part of the study considering the consumption of fuel. Also, emissions were calculated accounting for the fuel consumption given in Table 3.

Table 3. Characteristics, fuel consumption, and energy yield of three old heat plants which were replaced with one new heat plant.

№ heat plant	Boiler type	Capacity, MW	Average efficiency, %	Own needs, %	Gas consumption, m^3/a	Specific fuel consumption, kg/Gcal
Old № 1	Energia-3 M	0,52	80,59	3,00	336384	127,3
	Energia-3 M	0,52	80,95	3,00	336384	126,7
	Energia-3 M	0,52	80,62	3,00	336384	127,2
Old № 2	Universal-6	0,45	75,12	3,00	290435	136,6
	Universal-6	0,45	78,70	3,00	290435	130,2
	Universal-6	0,45	77,98	3,00	290435	131,4
	Universal-6	0,45	78,51	3,00	290435	130,5
	Universal-6	0,45	78,47	3,00	290435	130,6
Old № 3	Universal-3	0,42	77,34	3,00	271694	132,9
	Universal-3	0,42	79,76	3,00	271694	128,7
	Universal-3	0,42	80,00	3,00	271694	128,3
	Universal-3	0,42	77,74	3,00	271694	132,1
	Universal-3	0,42	78,56	3,00	271694	130,7
	Universal-3	0,42	79,54	3,00	271694	129,0
Average						130,2
New № 1	Turboterm	3,15	92,40	1,50	1931054	103,0
	Turboterm	3,15	92,20	1,50	1931054	103,2
	Turboterm	3,15	92,30	1,50	1931054	103,1
	Turboterm	3,15	92,40	1,50	1931054	103,0
Average						103,1

Annual emissions of the old and new heat plants were calculated using the methodology “Determination of emissions of pollutants to atmosphere during incineration of fuels in boilers with installed capacity of less than 30 tons of steam per hour or less than 30 Gcal per hour” (NII Armosphera, 1999). The methodology is used to calculate only nitrogen monoxide, nitrogen dioxide, carbon monoxide, and benzo(a)pyren emissions. An example calculation of emissions according to this methodology is presented in Appendix 1. Those emissions mainly contribute to acidification and eutrophication in natural environment.

Emissions of greenhouse gases are not regulated in Russia, so their calculation is not within the reporting guidelines. Only methane is calculated for the purging situations, which take place for only several hours a year, so their impact on the overall emissions is negligible and thus was omitted. Emissions of carbon dioxide were calculated using the IPCC guidelines are given in the Appendix A. Table 4 collects the emissions of the most representative gases from heat plants.

Table 4. Annual emissions of the most representative gases from old and new heat plants.

	Old heat plants №1-3	New heat plant №1
NO_2, t/a	3,54	9,79
NO_2, kg/Gcal	0,156	0,189
NO, t/a	0,58	1,59
NO, kg/Gcal	0,0252	0,0308
CO, t/a	11,7	19,6
CO, kg/Gcal	0,517	0,379
Benzo(a)pyren, t/a	0,000000301	0,00000447
Benzo(a)pyren, kg/Gcal	0,0000000133	0,00000000865
CO_2, t/a	5350000	968000
CO_2, kg/Gcal	236	187

As can be seen, the emissions from the new heat plant was higher than those of the old ones. At first, the emissions are higher because of the higher natural gas consumption and heat generation. However, the specific emissions of nitrogen oxide and monoxide as well as benzo(a)pyren which were calculated using the Russian methodology were higher on the new heat plants. There were two reasons for the higher emissions. First, specific emissions of nitrogen oxides (K_{NO_x}) were higher in the new heat plans. The specific emissions were calculated using Equation 2 which only considers the higher fuel consumption in the new plan but fails to consider also the higher heat generation. Second, the coefficient accounting for the impact of excess air on formation of nitrogen oxides ($\boldsymbol{\beta}_a$) was set to 1,225 in the new heat plant, while it was taken as 1 in the old one. Due to these reasons, the specific emissions of nitrogen oxides were higher in the new heat plant. The emissions of carbon monoxide and carbon dioxide were calculated using other equations and methodologies, and thus were lower in the new heat plant.

7.2 LCA methodology

The principles of LCA are explicitly stated in international standards ISO 14040 (SFS-EN ISO 14040, 2006) and ISO 14044 (SFS-EN ISO 14044, 2006). According to the standards, each LCA study shall include: 1) goal and scope definition, 2) life cycle inventory, 3) life cycle impact assessment, and 4) interpretation.

7.2.1 Goal and scope definition

The goal of this study was to assess the global warming potential, or also referred to as carbon footprint or climate change, of heat generation in some of the boilers operating in St.Peterburg or its region using primary data from the boilers. The functional unit was generation of 1 Gcal of heat.

7.2.2 System boundaries

The study included the provision of natural gas, its combustion and formation of emissions.

7.2.3 Life cycle inventory

The formation of emissions and consumption of natural gas was calculated as shown before. The data on the environmental impact of natural gas provision was taken from the Professional database embedded in GaBi ts software (version 8.7.0.18). The data set "Natural gas mix; technology mix; consumption mix, at consumer, Finland" was used to model the provision of natural gas. Finland was chosen as the natural gas mix was missing for Russia and because Finnish natural gas mix was completely based on the natural gas imported from Russia. The amount of natural gas consumed, as well as emissions from its combustion are taken from Section 7.1.

7.2.4 Life cycle impact assessment

The global warming potential was calculated using the characterization factors developed by the Intergovernmental Panel on Climate Change (IPCC) and published in the fourths assessment report in 2007 (IPCC, 2007). Some of the factors are presented in Table 5.

Table 5. Selected characterization factors used in the LCIA phase of the study (IPCC, 2007).

Greenhouse gas	Chemical formula	Characterization factor
Carbon dioxide	CO_2	1
Methane	CH_4	25
Dinitrogen monoxide	N_2O	298
Chlorofluorocarbon-11	CCl_3F	4750
Chlorofluorocarbon -12	CCl_2F_2	10,900
Chlorofluorocarbon -13	$CClF_3$	14,400
Halon-1301	$CBrF_3$	7140
Sulphur hexafluoride	SF_6	22,800

7.3 Results

The results of the LCA part of the study are presented in Figure 30-Figure 34 for several impact categories. Figure 30 shows the impact of the heat generation in the old and new heat plants on climate change. The results indicated that the climate change impacts are reduced from 307 kg CO2-eq/Gcal to 243 kg CO2-eq/Gcal, which represents a 21% reduction. The reduction originates from the increased heat generation efficiency, which means lower specific fuel consumption. The efficiency was increased from 80 to 92% on average.

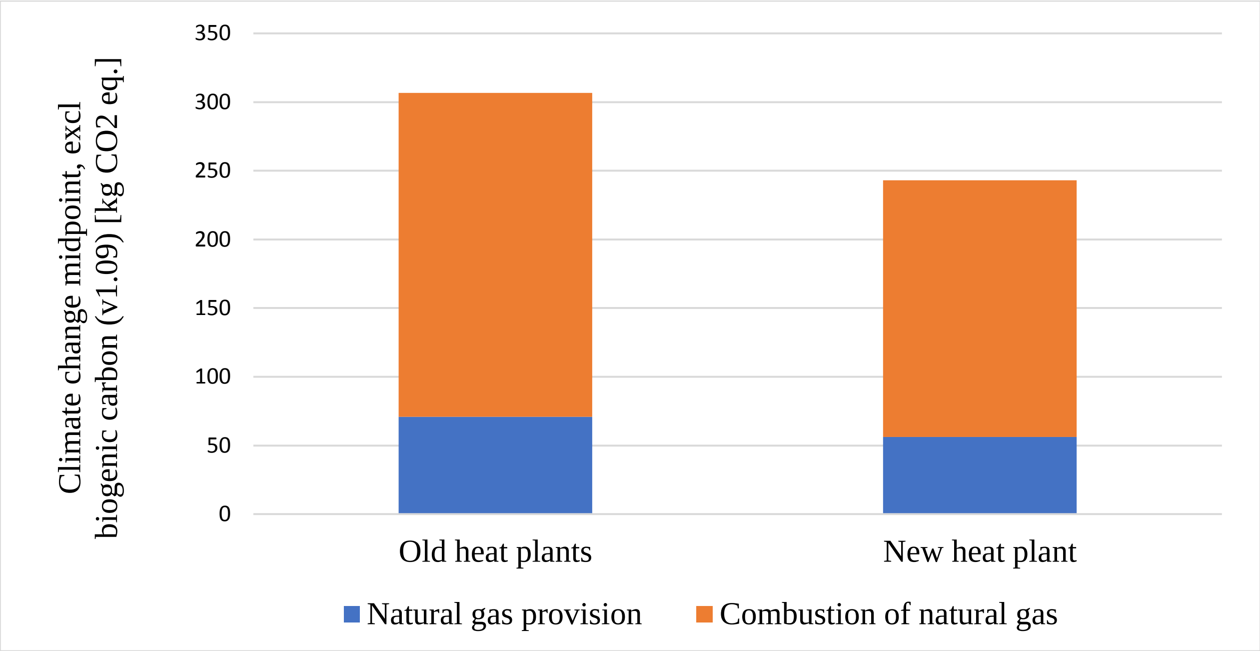


Figure 29. Climate change impact of old and new heat plants per 1 Gcal of heat generated.

Figure 30 to Figure 33 show acidification, eutrophication and photochemical ozone formation potentials. The emissions which contribute to those impact categories are nitrogen dioxide and nitrogen monoxide. Because the emissions of nitrogen oxides were higher in the new heat plants as it was discussed in Section 7.1.1. At the same time, the impact across those impact categories was reduced in the new heat plant due to lower amount of natural gas needed, yet the reduction was lower compared to induced impact due to higher release of nitrogen oxides.

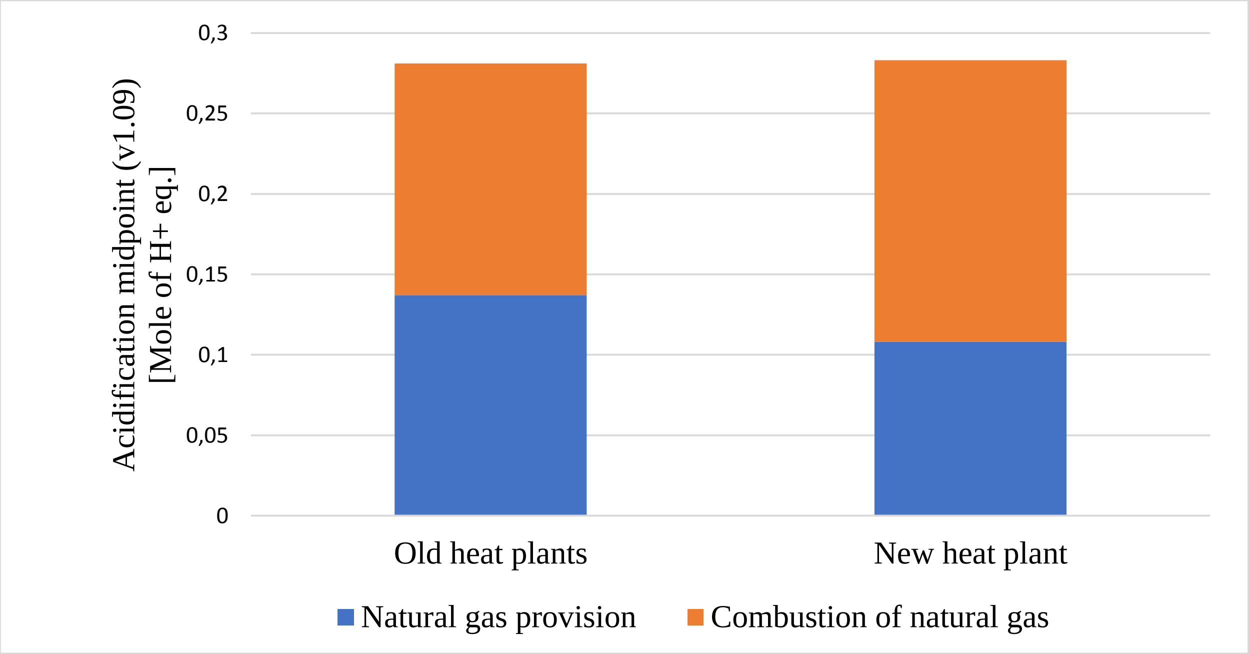


Figure 30. Acidification potential of old and new heat plants per 1 Gcal of heat generated.

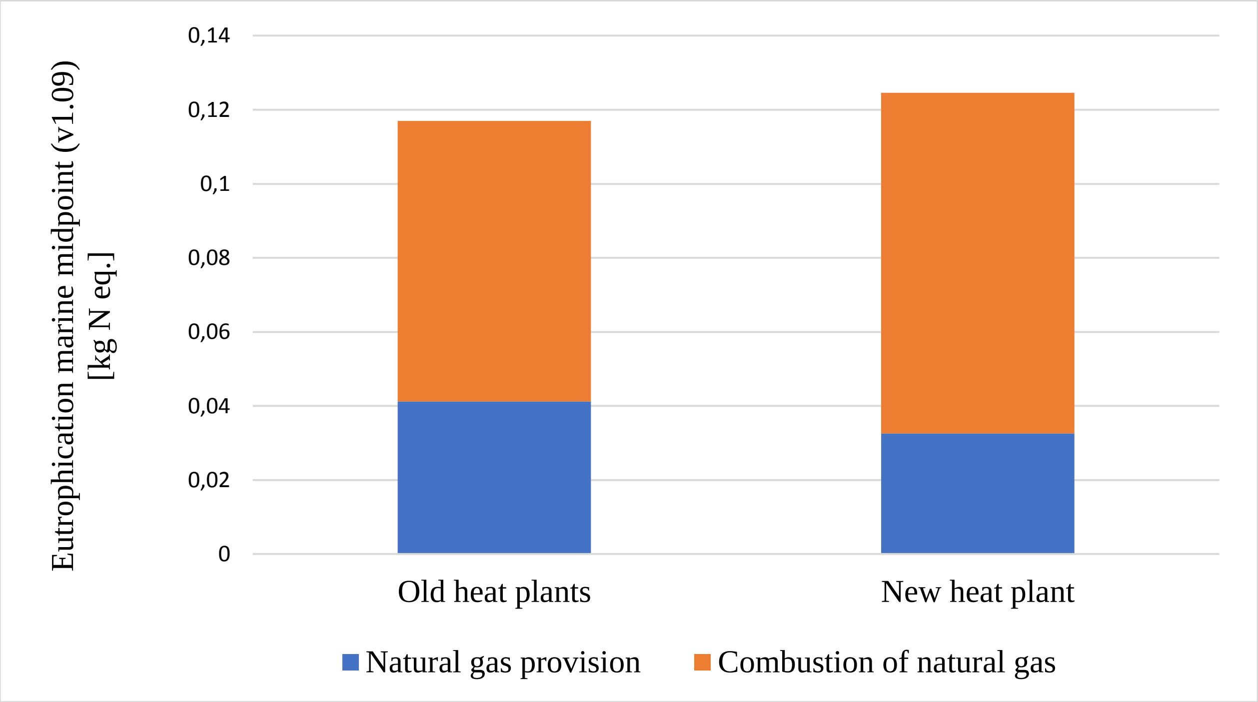


Figure 31. Marine eutrophication potential of old and new heat plants per 1 Gcal of heat generated.

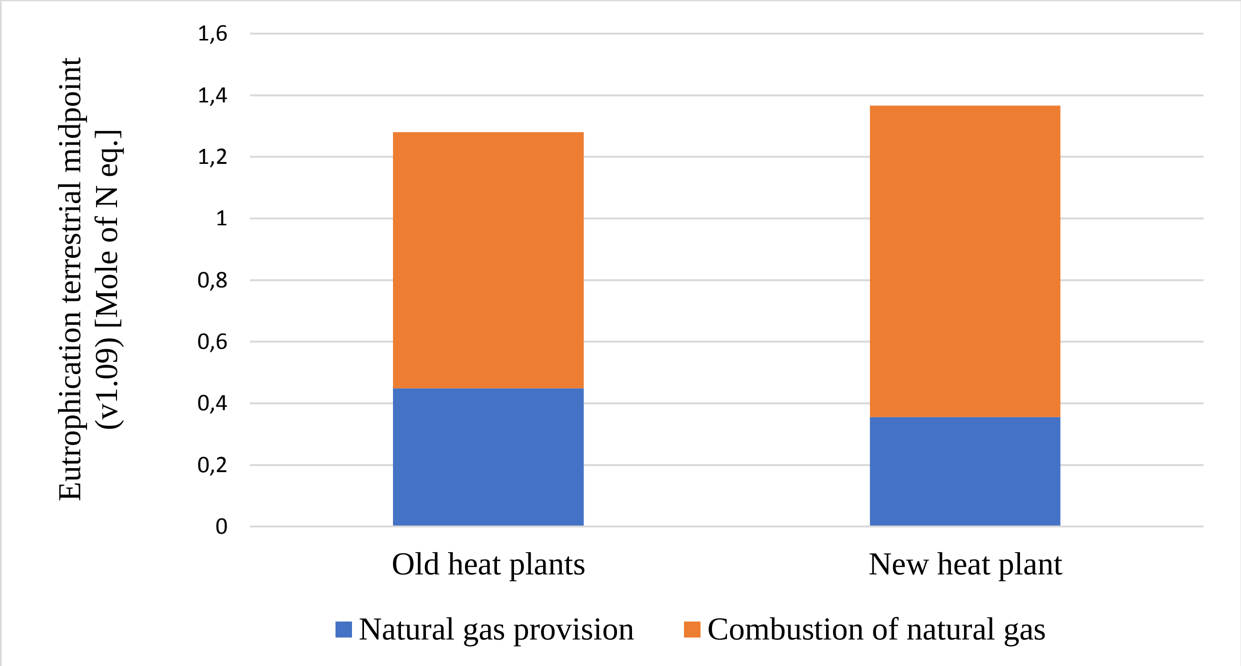


Figure 32. Terrestrial eutrophication potential of old and new heat plants per 1 Gcal of heat generated.

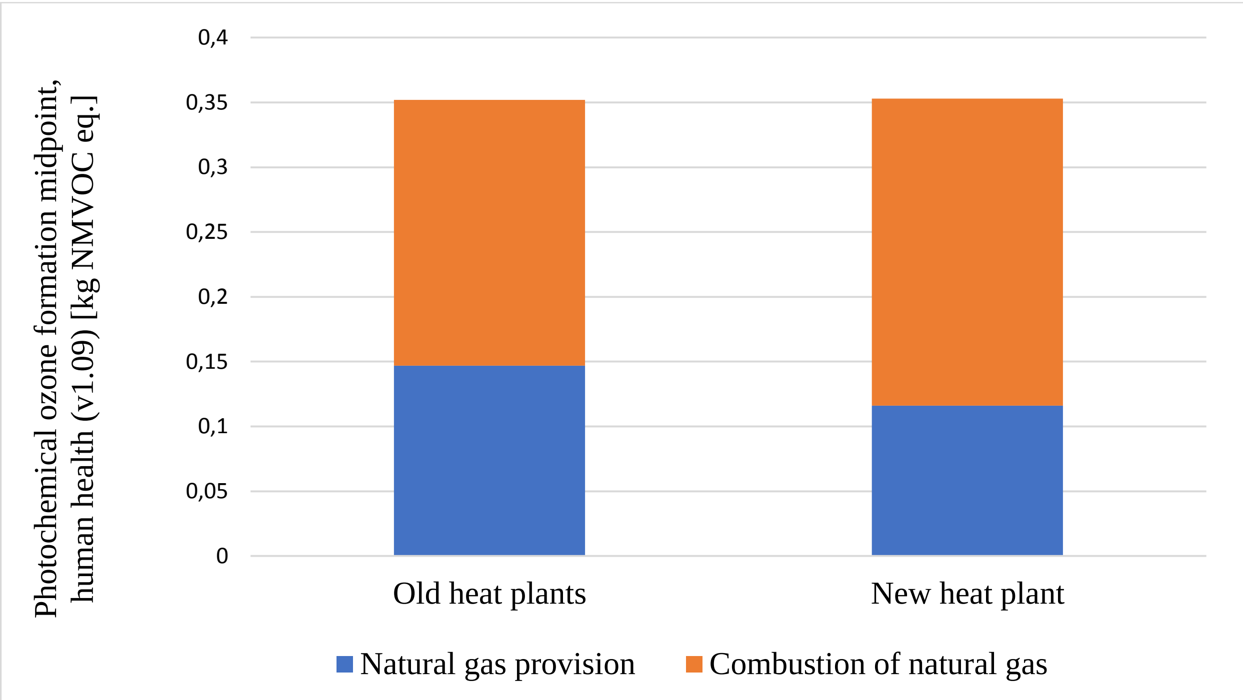


Figure 33. Photochemical ozone formation potential of old and new heat plants per 1 Gcal of heat generated.

Figure 34 shows the impact of the old and new heat plants on the consumption of fossil resources from the environment. As can be seen, the lower consumption of natural gas led to the reduction of the impact by 21%, which is as much as the reduction of the impact on climate change.

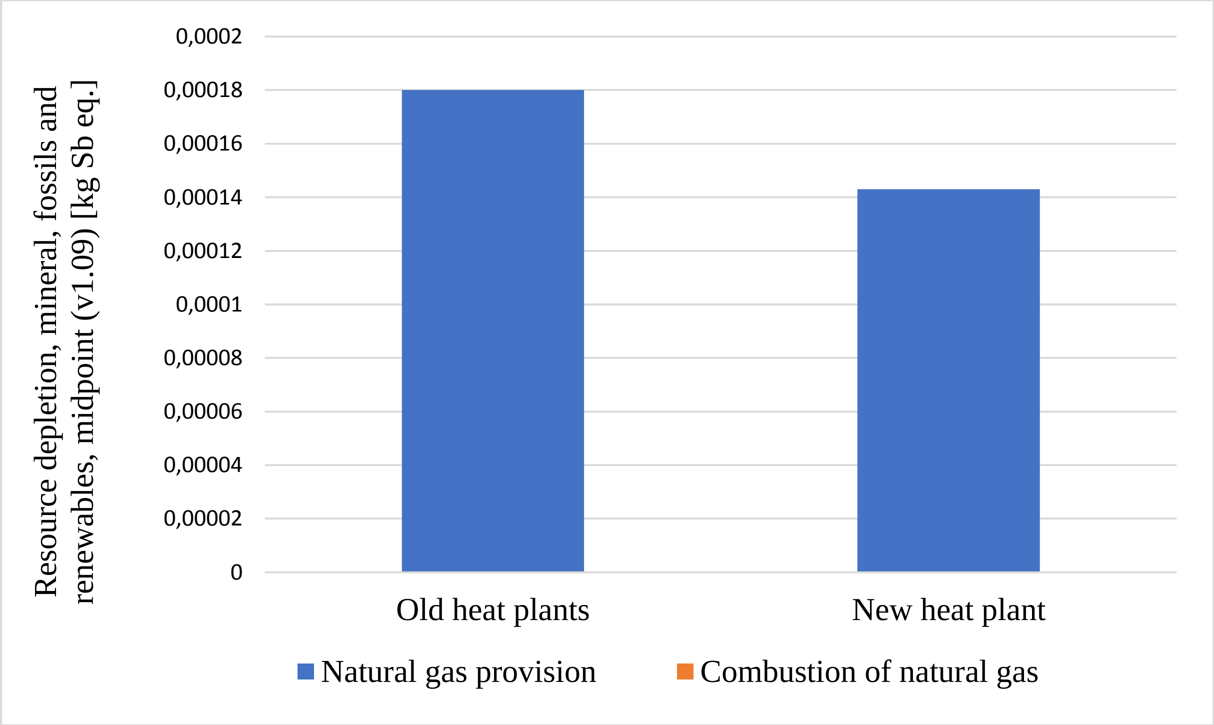


Figure 34. Mineral, fossil and renewable resources depletion potential of old and new heat plants per 1 Gcal of heat generated.

7.4 Discussion

The relative contribution of modernization of heat plants was assessed in this thesis. Because there are no statistics on district heating in Russia, the data from Finland were taken as a proxy. According to Energiateollisuus (2017), 36 600 GWh of district heat was produced in Finland. Considering its population of 5,5 mil inhabitants, per capita district heating is therefore 6650 kWh. Provision of such amount of heating vie the old heating plants emitting 0,264 kg CO2-eq./kWh would result in emitting 1760 kg CO2-eq. per person annually. The same calculation for the new plant emitting 0,209 kg CO2-eq/kWh leads to emission of 1390 kg CO2-eq. per person per year. At the same time, according to Benini et al. (2014), the climate change impact of an average European is 9440 kg CO2-eq annually. Considering these data, the personal carbon footprint could be reduced by 364 kg CO2-eq, which is 4% of the annual carbon footprint of a person.

8 Conclusions

The literature study of gas burners was implemented in this thesis. Furthermore, the analysis of the gas burners, boiler, and heat plants at large, implemented at SUE “TEK SPb” was discussed. Finally, the environmental impact related to the modernization of the heat plants in one of the districts of St. Petersburg, Russia, was calculated.

As a result of the modernization of the old heat plants, the reduction of environmental impact was noticed, first through reduced consumption of natural gas, and as a consequence through reduced emissions. By implementation of municipal programs on closure of local heat plants and step-wise transition towards centralized district heating, significant reduction of emissions was also observed. This reduction was achieved as a result of the use of modern technologies for gas incineration, as well as due to replacement of old boilers and by the use of energy-efficient equipment with high efficiencies and the use of automated systems. Analysis of the boilers showed that fire-tube boilers with automated burners are energy efficient and have high heat generating capacity.

Apart from environmental impact reduction, other improvements were achieved. When implementing modernization of heat plants, safe operating environment was planned as to avoid problems similar to those in old heating plants. The problems were due to dense equipment placement, which hindered their operation and repair. Also, old equipment was physically and morally worn out.

Calculation of environmental impact of the old heat plants, which were demolished and replaced with the new one showed possible reduction of the environmental impact. The calculations showed that the climate change impacts were significantly reduced by 21%, as well as the natural gas consumption. The reduction of the environmental impact across other studied impact categories, i.e. acidification, eutrophication and photochemical ozone formation potential, was increased. The largest reason to the increase was the calculation principle of the emissions, which was dictated by the methodology applied in Russia to report the emissions at hat plants. The methodology proposes to use a coefficient which only accounts for the increased fuel consumption in the new heat plan due to its increased capacity and omits the fact that more heat is being generated. It was concluded that the use of this methodology for comparative assessment of heating plants should be carefully considered since the calculation principles do not support comparative studies and are only applicable to attributional impact calculation. The results of the environmental impact assessment showed that the personal carbon footprint could be reduced by 4% due to modernization of heat plants, provided that the data used in the calculations could be applicable to the Russian conditions. The policy of “TEK SPb” should be focused on the use of more advanced boilers and burners to reduce the specific emissions of nitrogen oxides, and carbon mono- and dioxide by increased heat generation efficiency and the use of automation.

References

ASHRAE, ANSI/ASHRAE 55:2004 Thermal Environmental Conditions for Human Occupancy, ASHRAE Standard, 2004

Ahmad Z., Principles of Corrosion Engineering and Corrosion Control, 2006

Annual report on execution of the federal budget, Finance M, 2017

Baukal, C. E., *The John Zink Combustion Handbook,* New York, NY: CRC Press LLC, 2001.

Baukal, C. E., et al., *Industrial Burners Handbook,* Ed. Baukal, C. E., New York: CRC Press LLC, 2004

Baukal C. E.,, Gebhart B., Experimental Thermal and Fluid Science, Surface Condition Effects on Flame Impingement Heat Transfer,1997

Benini, L., Mancini, L., Sala, S., Manfredi, S., Schau, E. M., & Pant, R. (2014). Normalisation method and data for Environmental Footprints. Luxemburg.

Brand Finance, “Global 500 2017“, 2017

Energiateollisuus. (2017). Kaukolämpötilasto.

Fellows, P. J., *Food Processing Technology,* Boca Raton, Florida: Woodhead Publishing Limited, CRC Press LLC, 2000.

Finance, M. of. (2017). Annual report on execution of the federal budget.

Hellevang H., Carbon capture and storage (CCS), Petroleum Geoscience: From Sedimentary Environments to Rock Physics, Second Edition, 2015

IEA. (2015). Statistics. Russian Federation. Natural gas imports vs. exports. Retrieved August 14, 2018, from https://www.iea.org/statistics/?country=RUSSIA&year=2015&category=Key indicators&indicator=NatGasImportsExports&mode=chart&categoryBrowse=true

IEA. (2018a). Natural gas information. OVerview. https://doi.org/10.15713/ins.mmj.3

IEA. (2018b). Statistics. World. Total Primary Energy Supply (TPES) by source. Retrieved August 14, 2018, from https://www.iea.org/statistics/?country=WORLD&year=2015&category=Key indicators&indicator=TPESbySource&mode=chart&categoryBrowse=false

Industrial Heating Equipment Association. *Fundamentals of Industrial Process Heating.*IHEA, 2006.

Industrial Wiki. (2018). Boiler Types and Classifications - Wiki - odesie by Tech Transfer. Retrieved November 15, 2018, from https://www.myodesie.com/wiki/index/returnEntry/id/3061

International Energy Agency ,Natural gas information. Overview ,IEA,2018

IPCC. (2006). IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5, Waste. Retrieved from http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html

IPCC. (2007). 2.10.2 Direct Global Warming Potentials - AR4 WGI Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing. Retrieved August 31, 2018, from https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html

Joachim G. Wünning , A.Milani “Handbook of Burner Technology for Industrial Furnaces“

Lund H., Renewable Energy Systems, Academic Press, 2010

Nilsson, L. J., E. D. Larson, K. R. Gilbreath, and A. Gupta, “Energy Efficiency and the Pulp and Paper Industry.” Berkeley, California: American Council for an Energy Efficient Economy, 1995.

NII Armosphera. (1999). Методика определения выбросов загрязняющих веществ в атмосферу при сжигании топлива в котлах производительностью менее 30 тонн пара в час или менее 20 гкал в час.

Oil & Gas Journal, Worldwide look at reserves and production, OGJ, 2012

Saner D., Vadenbo C., Steubing B., Hellweg S., Regionalized LCA-based optimization of building energy supply: Method and case study for a swiss municipality, Environmental Science and Technology,2014

SFS-EN ISO 14040. (2006). Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006).

SFS-EN ISO 14044. (2006). Environmental management – Life cycle assessment – Requirements and guidelines (ISO 14044:2006).

Trinks, W., M. H. Mawhinney, et. al., *Industrial Furnaces,* Sixth Edition. Hoboken, New Jersey: John Wiley and Sons, 2004.

Wagner, J. C., “NO_X Emission Reduction by Oscillating Combustion,” Final Report, GTI Project No. 61111, for U.S. Department of Energy Contract No. DE-FC36-96EE41260. Des Plaines: Gas Technology Institute, 2004.

World Energy Outlook 2015. Executive Summary, IEA ,International Energy Agency,2015

Wunning et al. 2009 – Handbook of Burner Technology for Industrial Furnaces, Vulkan-Verlag, 2009

Appendix 1. Example calculation of emissions

Emissions of NO_x, SO_2, and CO

The methodology "Determination of emissions of pollutants to atmosphere during incineration of fuels in boilers with installed capacity of less than 30 tons of steam per hour or less than 30 Gcal per hour" (NII Armosphera, 1999). The actual heat generation (Q_T) was calculated as:

$$Q_T = \frac{\frac{B_P}{Time}}{3{,}6} \cdot Q_r[\ MW]. \qquad (1)$$

Emissions of nitrogen oxides. Specific emissions of nitrogen oxides (K_{NO_2}) were calculated as follows:

$$K_{NO_X} = \ 0{,}0113 \cdot \sqrt{Q}_T + 0{,}03, [\frac{g}{MJ}]. \qquad (2)$$

Coefficient accounting for the air temperature ($\boldsymbol{\beta_t}$) was calculated as follows:

$$\beta_t=1+0.002\cdot(t-30)=1; \qquad (3)$$

where t – temperature of hot air (30 °C).

Coefficient accounting for the impact of excess air on formation of nitrogen oxides ($\boldsymbol{\beta}_a$) was set to 1 because the boiler operates according to the required conditions. In general: $\boldsymbol{\beta}_a = 1{,}225$.

Coefficient accounting for the impact of flue gases recirculation through burners ($\boldsymbol{\beta_r}$) was calculated as follows:

$$\beta_r=0.16*\sqrt{r}=0 \qquad (4)$$

where r – degree of flue gases recirculation (0%).

Coefficient accounting for the multi-stage supply of air to the burners ($\boldsymbol{\beta_d}$) was calculated as follows:

$$\beta_d=0.022* \delta=0 \quad (5)$$

where δ – portion of air fed to the intermediate zone (0%).

Emissions of nitrogen oxides M_{NO_x} were calculated as follows:

$$M_{NO_x} = B_P \cdot Q_r \cdot K_{NO_X} \cdot \beta_k \cdot \beta_t \cdot \beta_a \cdot (1-\beta_r) \cdot (1-\beta_d) \cdot k, [\frac{t}{a}]; \quad (6)$$

$$M_{NO} = 0{,}13 \cdot M_{NO_x}, [\frac{t}{a}]; \quad (7)$$

$$M_{NO_2} = 0{,}8 \cdot M_{NO_x}, [\frac{t}{a}]. \quad (8)$$

Emissions of sulphur dioxide. Content of sulphur in natural gas (Sr) was zero, therefore calculations for the emission of sulphur dioxide were not implemented.

Emissions of carbon monoxide. Losses of heat due to chemically incomplete combustion of fuel (q3) were set to 0,2%. Coefficient accounting for incomplete combustion due to presence of incomplete combustion of carbon monoxide in flue gases (R) was set to 0,5. Specific emissions of carbon dioxide (C_{CO}) were calculated as follows:

$$C_{CO} = q_3 \cdot R \cdot Q_r , [\frac{g}{m^3}]. \quad (9)$$

Heat losses due to mechanically incomplete combustion of fuel (q4) were set to 0%. The mass of carbon monoxide emitted (M_{CO}) was calculated as follows:

$$M_{CO} = 0{,}001 \cdot B_P \cdot C_{CO} \cdot \left(1 - \frac{q_4}{100}\right), [\frac{t}{a}]. \quad (10)$$

Emissions of CO_2

Emissions of carbon dioxide were calculated using the default values of the IPCC report (IPCC, 2006). The mass of carbon dioxide emitted was calculated as follows:

$$M_{CO_2} = \frac{44}{12} \cdot Q \cdot NCV \cdot EF \cdot (1-Sf) \cdot F; \quad (11)$$

where Q – mass of fuel combusted, m^3/a;

NCV – net calorific value, MJ/m^3;

EF – emission factor, kg C/TJ (taken from (IPCC, 2006) for natural gas);

Sf – carbon storage factor, taken from (IPCC, 2006) for natural gas;

F – oxidation efficiency, taken from (IPCC, 2006) for natural gas.

Converting the value to specific emissions, we get 1,25 kg CO_2/m3 natural gas, or 37 400 kg CO_2/TJ. Table 2.2 of Chapter 2 of (IPCC, 2006) states the specific emissions of carbon dioxide emitted during stationary combustion of fuels at 56 000 kg CO_2/TJ as a default value including the range between 54 300 – 58 300 kg CO_2/TJ. Those values are higher than the ones calculated using the formula above. Therefore, a sensitivity analysis should be performed on those values.