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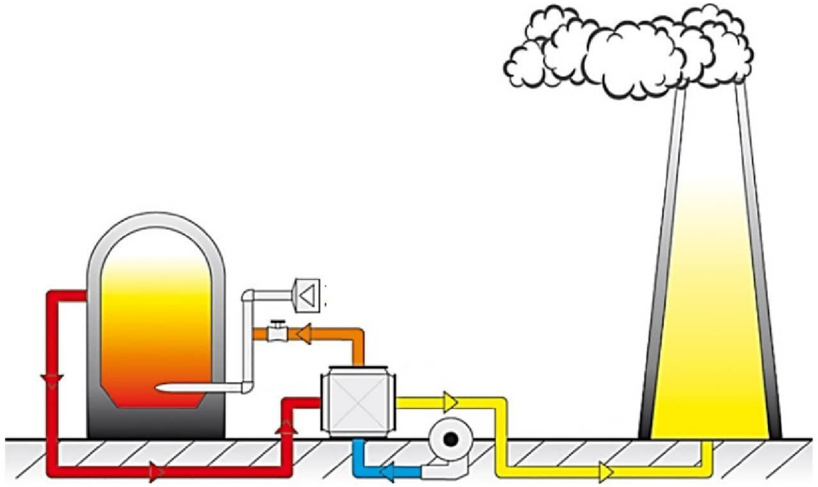
A. K. KINZHIBEKOVA

SECONDARY ENERGY RESOURCES AND THEIR UTILIZATION



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A. K. Kinzhibekova

SECONDARY ENERGY RESOURCES AND THEIR UTILIZATION

Study guide

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Reviewers:

Y. V. Prikhodko – Candidate of technical sciences, professor, Toraigyrov University;

A. K. Mergalimova – PhD, associate professor, Head of the Department of Heat Power Engineering, KATRU named after S. Seifullin;

M. G. Zhumagulov – PhD, professor, Eurasian National University named L. N. Gumilev.

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The study guide contains basic concepts related to secondary energy resources and methods of their use in industry. The aim of the study guide is to teach the effective integration of the energy potential of secondary energy resources into the technological scheme of various industrial enterprises. The study guide is intended for students of the Master's Degree Programme in Heat Power Engineering.

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Introduction

The discipline «Use of Secondary Energy Resources» is a part of the cycle of disciplines (optional) read to master students of the educational program «Heat Power Engineering».

The textbook is aimed at formation of knowledge and skills in the field of utilization of secondary energy resources and training of effective involvement of their energy potential in the technological scheme of industrial enterprises.

The discipline «Utilization of secondary energy resources» is a discipline of choice of the professional block of the variative part, which forms skills in the field of energy saving at industrial enterprises and other facilities.

Theoretical and practical bases of the discipline are the knowledge obtained during the study of such disciplines as «Scientific and technical problems of heat power engineering and heat technology». The acquired knowledge will be used in the fulfillment of master's thesis. The available interdisciplinary links of the discipline give a master student a systematic view of the complex of disciplines studied, which provides the appropriate theoretical level, required competencies and practical orientation in the training system.

1 Types and directions of utilization of secondary energy resources. Determining the volume of output and utilization of secondary energy resources

1.1 The concept of secondary energy resources

When converting one form of energy to another, only a portion of the energy can be utilized. The size of this usable fraction depends on the type of energy and the conversion technology employed [1].

Energy waste refers to the amount of energy that is not directly used as productive energy in the manufacturing of finished goods. There are several types of energy waste:

1) Internal energy waste that is cycled back into the technological process (high potential).

2) External energy losses that become secondary energy resources (medium potential).

3) Unavoidable losses within the technological process or installation (low potential) [1].

Secondary energy resources (SER) play a crucial role in the energy balances of enterprises, especially energy-intensive industries. SER are the energy potential contained in wastes, byproducts, and intermediate products generated by heat-technological installations. This SER can be partially or fully utilized to provide energy to other installations or the original process [2].

SER should not be regarded as supplementary energy sources without cost. Instead, they arise from the intrinsic inefficiencies present in technological production methods. Consequently, the main objective should be to minimize the generation of SER by optimizing fuel consumption within the production process itself. This represents a critical endeavor in enhancing the efficiency of thermal engineering production, as it is an essential component of these processes, aimed at maximizing energy and resource utilization [2].

The energy waste that is redirected back to the input of a technological unit is referred to as internal energy waste, while the energy waste repurposed in other units is termed external energy waste. The technological unit that generates this energy waste is identified as a source of energy and energy resources.

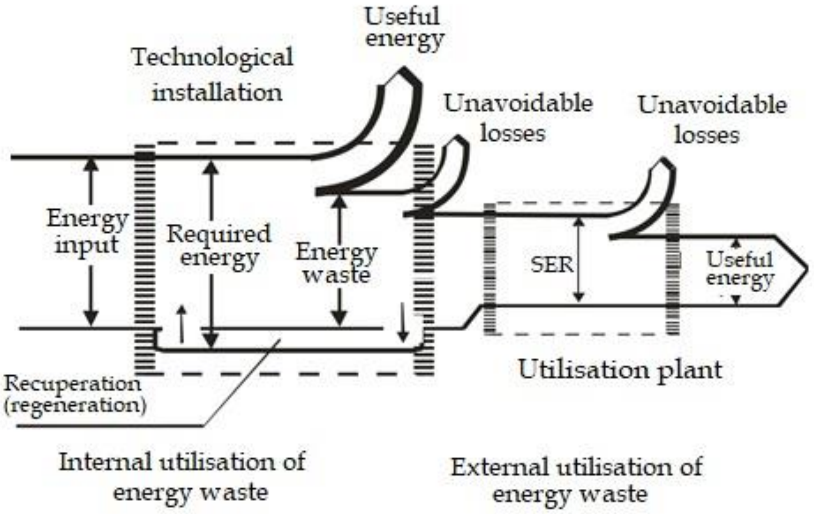


Figure 1.1 –Energy balance of the technological process

1.2 Classification of SER

All SER can be categorized into three primary groups:

1) Combustible (fuel) SER refer to products of technological processes that contain combustible components, enabling their use as fuel. This category includes combustible gases generated from melting furnaces, combustion chambers, and other sources, as well as combustible waste from chemical and petrochemical processes, ferrous and non-ferrous metallurgy, and the gas industry. Additionally, the forestry and wood processing industries contribute to the production of combustible renewable energy sources.

2) Thermal SER are products resulting from technological processes where the temperature at the output of a furnace or unit is significantly higher than the surrounding temperature, indicating the presence of excess physical heat. Examples of thermal SER include hot water, steam, the heat from steam-air mixtures, and the heat of steam condensate, along with the physical heat of flue gases and waste heat from thermal technological devices.

3) SER under pressure consists of the energy from gases, liquids, and vapors ($P > Pat$) originating from installations operating at overpressure. The energy must be reduced before being released into the atmosphere to ensure safety and compliance [1]. SER under pressure refers to the energy from gases, liquids, and vapors ($P > Pat$) that originate from installations operating under overpressure, which must be minimized before their release into the atmosphere.

Combustible SER are categorized into three types:

- Solid: This includes waste from the wood processing industry (such as wood waste, hydrolysis production waste, and pulp and paper mill waste), agricultural and municipal waste (including straw, yard waste, and general municipal refuse), as well as solid industrial waste.

- Liquid: This encompasses combustible liquid waste and liquid industrial byproducts.

- Gaseous: This group consists of residues from chemical and thermochemical processes involving raw materials (such as plastics, rubber, and byproducts from electrode production), as well as gases from blast furnaces and coke ovens.

Thermal SER includes the following (see Figure 1.3):

- Combustion byproducts from boilers and industrial furnaces (including gases and slags), and waste steam (with a potential temperature of over 500 ºC);
- Heat from working fluids and coolants in cooling systems (with an average potential temperature ranging from 100 to 500 ºC);
- Heat from ventilation air and running water (considered low potential, at temperatures below 100 ºC).

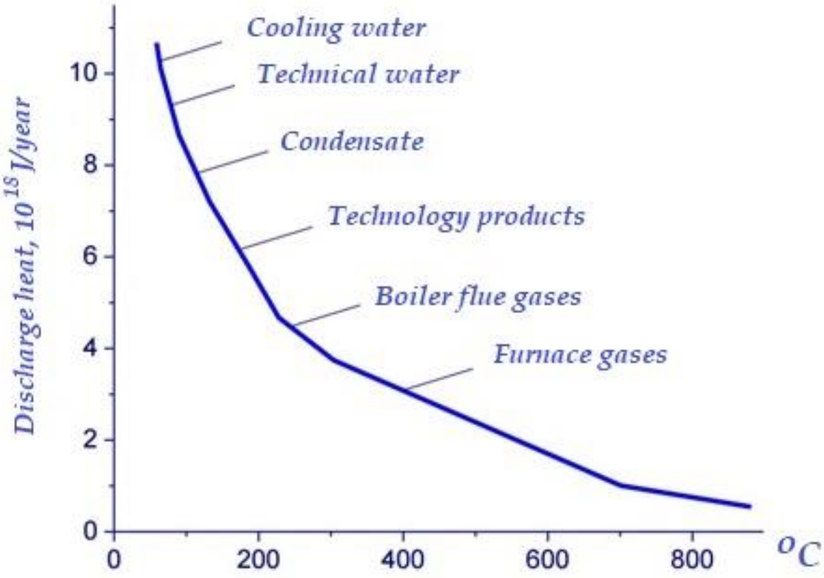


Figure 1.2 – Distribution of thermal energy waste

Glossary

The following concepts and terms are used in relation to secondary energy resources.

Total energy losses - the energy potential of all material flows at the output of the heat technology installation (appliance) and all energy losses in the installation.

Total production of secondary energy resources is the mass of secondary energy resources produced in a given unit over a given period of time.

The potential yield of secondary energy resources is the possible (maximum) amount of energy that can be economically used in recycling facilities.

The ratio of energy use (production) from secondary energy resources is the ratio of the actual use of energy from secondary energy resources to the planned production.

The reserve of use of secondary energy resources is the amount of energy that can be added to production.

Possible fuel savings at the expense of secondary energy resources - the amount of energy obtained when all quantities of secondary energy resources are fully used.

The coefficient of use of secondary energy resources is the ratio of the actual fuel savings due to the use of secondary energy resources. It is determined both for a single source of secondary energy resources and for a group of units, as well as in total for all types of secondary energy resources.

A recovery facility is a facility for the production of high potential energy resources from renewable energy sources.

1.3 Utilization of SER

All types of secondary energy resources can be utilized by consumers as fuel or for producing heat, cold, electrical energy, and mechanical work through specialized recycling facilities, depending on their characteristics.

It is important to highlight that utilizing a portion of energy waste within the technological process (internal use) offers greater energy and economic efficiency compared to relying on renewable energy resources (external use). Therefore, it is essential to develop strategies for utilizing water and energy resources after implementing measures to enhance the efficiency of technological equipment, which serves as a source of these resources.

In technical terminology, the use of secondary energy resources is called recycling. If the energy of the technological process products is returned to the same technological process, it is called recovery [3].

Secondary energy resources can be recycled in two ways:

- Directly (without altering the type of energy carrier).

- By obtaining a higher potential or a different type of refrigerant at recycling plants.

The schematic representation of secondary energy resource recovery illustrates the distinct energy resource streams along with their quantitative indicators.

Depending on the type and characteristics of the working fluids, there are four primary applications for secondary energy resources:

- Fuel: This involves the direct use of combustible components as fuel.
- Heat: This refers to the utilization of heat generated from secondary energy resources or the heat or cold produced from secondary energy resources in processing plants or absorption chillers.
- Energy: This pertains to using mechanical or electrical energy derived from secondary energy resources in recycling facilities (stations).
- Mixed: This involves the simultaneous use of thermal, electrical, or mechanical energy from secondary energy resources.

Secondary energy resources designated for use as fuel should be utilized entirely (100 %) for that purpose.

The feasibility of using secondary energy resources during the transformation of energy carriers is determined by the likelihood of electricity generation at the recycling facility [3].

Thermal SER of metallurgy

Large thermal secondary energy resources are utilized by various industries, including ferrous and non-ferrous metallurgy, chemical, oil refining, petrochemical, building materials, gas, heavy machinery, and several others. These sectors make substantial use of high, medium, and low potential heat.

High-quality heat is primarily employed to alter the physical-chemical properties of raw materials and semi-finished products through processes such as melting, heating, and combustion. Examples include the melting of metals in metallurgy, the burning of non-metallic minerals in the building materials industry, and the intensification of chemical reactions.

Currently, high-quality heat accounts for 26 % of total useful energy consumption, with an equivalent 26 % of fuel and energy resources being dedicated to its production. Nearly 90 % of high-quality heat is consumed in industrial applications. Specifically, about 33 % of the total high-grade heat consumption is attributed to smelting, 40 % to heating, and just over 20 % to roasting ores and minerals. The majority of high-grade heat (over 90 %) is generated by combusting various fuel types directly within technological units [4].

Thermal secondary energy resources encompass a variety of systems, including ferrite, pyrolysis, ore thermal furnaces, divinyl and soda furnaces, limestone furnaces, cauldrons, and both radiative and convective heaters powered by oxygen and methane. They also include the physical heat from product streams (such as ammonia, methane, and urea) from synthesis columns, natural gas converters, CO and waste gases from nitric acid production, devices used for producing sulfuric acid, and heat generated from waste gases from nitric acid manufacturing. Additionally, thermal secondary energy resources consist of cooling water, condensate, distillate liquids, secondary boiling steam, ferrite, and slag from ore thermal furnaces. In the oil refining and petrochemical sectors, fuel secondary energy resources arise from combustible gases generated during soot production, waste gases from monomer synthesis for synthetic rubber and other chemicals, methane-hydrogen fractions from ethylene production, and various types of combustible waste from hydrocarbon processing. Thermal secondary energy resources also include the physical heat of flue gases, cooling water, residual steam, secondary boiling steam, and fusel oil from synthetic rubber production.

Key sources of secondary energy resources are derived from oil refining processes, synthetic rubber and synthetic alcohol production, and carbon black manufacturing. Oil refineries primarily harness waste heat from process furnaces, catalyst regeneration in catalytic cracking units, and the combustion of hydrogen sulfide during sulfur and sulfuric acid production. In the gas industry, secondary thermal energy resources include the physical heat from compressor station exhaust gases, gas processing furnaces, and cooling heat from gas processing product streams.

Modern gas turbine units utilized to power natural gas-fired compressors typically operate with an efficiency of 26-28 %. The flue gas temperatures from gas turbine units generally range from 600 to 700 K, reaching up to 800 K for non-regenerative units. Heat losses via flue gases can be as high as 70 %. The widespread adoption of secondary energy resources is hindered by the limited number of energy-intensive consumers. Currently, the heat from gas turbine exhaust gases is mainly used to heat the compressor stations themselves, surrounding settlements, and small greenhouse farms, with the total usage not exceeding 15 % of the available resources.

By cooling flue gases below their dew point and condensing the water vapor produced during gas combustion, the utilization factor of natural gas can be improved to 95 in relation to the gas’s total calorific value. The available heat from flue gases may be used directly in contact with the heated medium, eliminating the need for intermediate coolers and reducing metal consumption on the heating surface (referred to as a contact economizer).

These economizers can cool combustion byproducts to below the dew point (around 330 K), leading to water condensation in flue gases.

The recovered heat from flue gases can also be applied in drying processes and other low-temperature applications, such as heating oil in pipelines near compressor stations. Heavy, power, and transport engineering firms generate heat and energy resources from physical heat produced by martensitic furnaces, thermal furnaces, exhaust gases, and heat from the evaporative cooling of martensitic furnaces, as well as from exhaust steam generated by presses and hammers.

In the building materials industry, secondary thermal energy resources include the physical heat from waste gases produced by tunnel, mine, rotary, bath, and other furnaces, along with heat generated from furnace cooling, condensate, and waste steam. Thermal secondary energy resources are also present in other industries.

One of the primary goals in enhancing technological processes across all sectors is to thoroughly identify the available heat and energy resources and to utilize them efficiently and sustainably for production needs and to meet internal consumption requirements.

1.4 Determination of the volume of output and utilization of secondary energy resources

The production of secondary energy resources is characterized by energy potential:

- for combustible secondary energy resources - low calorific value;
- for thermal secondary energy resources - enthalpy difference;
- for surplus secondary energy resources - isentropic expansion work [1].

The own production of secondary energy resources is calculated either per unit of plant operation time (hours) or per unit of output.

The specific (hourly) production of secondary energy resources is the product of the specific (hourly) quantity of the energy carrier and its energy potential [1]

$$q^{th} = G \cdot \Delta h = G(c_1 t_1 - c_2 t_2),$$

$$q^{c} = G \cdot Q_l^{w},$$

$$q^{s} = G \cdot L,$$

$$L = h_1 - h_2 = \frac{(p_1 - p_2)}{\rho} = \frac{R}{k-1}(T_1 - T_2).$$

The total SER output for the time period under consideration is determined on the basis of specific output:

$$Q_{SER} = q \cdot T \quad or \quad Q_{SER} = q \cdot P\ ,$$

where P – quantity of production or consumption of raw materials, fuel for the period under consideration, pcs;

T – time of operation of the unit-source of SER, s.

The coefficient of production or utilization due to SER is the ratio of actual SER to possible production

$$\sigma = \frac{Q_{act}}{Q_{pos}}.$$

The ultimate goal of using secondary energy sources is to save primary fuel and reduce the cost of its purchase. The fuel consumption when using thermal secondary energy sources is determined by the following formulae

$$\Delta B = \frac{0.342}{\eta_{sub}} \cdot Q_{pos} \cdot \sigma = \frac{0.342}{\eta_{sub}} \cdot Q_{act} (ton\ of\ equivalent\ fuel),$$

where 0.0342 is the coefficient of equivalent conversion of 1 GJ into t.e.t;

Q_{act} – actual utilization of thermal SERs (GJ/year);

η_{sub} – efficiency of the substituted power plant, with the indicators of which the efficiency of the utilization unit of the heat and power unit - the source of heat and power resources is compared. As a rule, an industrial boiler house or CHPP is considered as a substituted unit.

The required data for calculating the production of secondary energy resources generated from heat energy equipment is gathered from the technical specifications of the equipment or from the results of balance and adjustment tests conducted on the equipment that serves as sources for these resources.

The output of secondary energy resources from the equipment is influenced by various technological factors, which can lead to significant discrepancies in the production schedule for these resources. Typically, calculations rely on the potential production of secondary energy resources within the recovery unit under a steady-state process condition.

Possible SER production in the utilization plant is determined by the formula [1]

$$Q_{SER} = G_{out}^{SER} \cdot c \cdot (t_1 - t_2) \cdot \beta \cdot \eta_{ut} \cdot T_{act},$$

where Q_{SER}– amount of heat received in the utilization plant (kJ);

G_{out}^{SER}– SER output (kg/h);

c – heat capacity of the heat carrier at the outlet of the heat-processing unit - the source of SER (kJ/kg·ºC);

t_1, t_2 – temperature at the inlet and outlet of the utilization plant, ºC;

β – coefficient, taking into account the mismatch between the mode and number of hours of operation of the utilization plant and process equipment - source of secondary energy resources (β = 0.8–0.95);

η_{ut} – utilization plant efficiency (η_{ut}= 0.75–0.96);

T_{act}– actual time of SER utilization, h.

When developing measures to improve the efficiency of the use of fuel and energy resources, or when selecting options for the use of secondary energy resources, it is necessary to determine the running costs. The annual running costs are determined by the formula [4]

$$C= K \cdot E_n + C_{oper},$$

where C – annualized present value costs (c.u.);

E – normative coefficient of comparative efficiency of capital investments (E_n= 0.15);

K – capital expenditures (c.u.);

C_{oper}– annual operating costs (c.u.).

The economic efficiency of utilizing secondary energy resources or implementing equipment modernization measures is determined by comparing the minimum annual costs associated with each option. The option with the lowest annual costs is regarded as the most economically efficient. In calculating the economic efficiency of secondary energy resource utilization, the savings in current fuel expenses are also considered.

Two energy (or heat) supply scenarios are analyzed:

1. Supplying energy to the consumer while integrating secondary energy resources;
2. Providing the same amount of energy to the consumer without utilizing secondary energy resources.

These options must be compared under the same conditions, including the quantity and type of energy supplied to the consumer, uniform technical improvements to heating circuits and equipment, and equivalent reliability of electricity supply.

If the generation of secondary energy resources allows for the production of energy beyond the requirements of a specific enterprise, the economic efficiency calculation should reflect the necessity of fully utilizing these secondary resources by supplying energy to a nearby industrial facility. The costs associated with the construction and operation of the recycling facility are factored into the expenses for the secondary energy option. The economic impact of using secondary energy resources is therefore calculated as the difference between the current annual costs of the compared options:

$$\Delta E = C_{oper}^{w.ut} - C_{oper}^{ut} + E_n(K_{w.ut} - K_{ut}).$$

The use of renewable energy sources is economically justified if the cost saving E has a positive sign. The indices «w.ut» and «ut» show energy supply options without and with the use of secondary energy sources.

2 Combustion of combustible secondary energy resources

2.1 Sources of combustible secondary energy resources

Combustible secondary energy resources consist of gaseous, solid, or liquid wastes produced during the creation of primary products. These wastes possess sufficient chemical energy and can be utilized as fuel. The primary sources of combustible secondary energy resources include sectors such as metallurgy, oil refining, chemicals, forestry and wood processing, agriculture, and utilities.

Examples of combustible secondary energy sources are:

- combustible gases emitted from furnaces and metallurgical production facilities (including furnace gas, marten gas, ferroalloy gas, coke oven gas, converter gas, and others);
- combustible gases from chemical manufacturing;
- wood waste;
- byproducts from hydrolysis processes;
- waste generated in the pulp and paper industry;
- waste from ammonia and caprolactam production;
- agricultural residues (such as straw and plant stalks);
- municipal waste [5].

The combustion processes of fossil fuels and renewable energy sources (RES) differ significantly due to the higher quality composition of fossil fuels. The combustion technology for various types of combustible secondary energy resources varies greatly, influenced by differences in density, moisture content, and fuel fractions.

To enhance the efficiency of burning combustible secondary energy resources, proper preparation is essential. The initial fuel must be processed to create a more effective fuel that is suitable for combustion with optimal energy performance. Solid combustible secondary energy resources require recycling to ensure uniformity and reliable flow control during combustion.

2.2 Combustion of combustible SERs in the metallurgical industry

Metallurgy is among the most fuel-intensive industries, as numerous technological processes occur at high temperatures, resulting in a substantial decrease in fuel efficiency. Consequently, a significant portion of the energy generated at the plant is expelled as energy carriers, which can subsequently be repurposed as secondary energy resources (SER). This is especially true for highly flammable renewable energy sources (RES).

Combustible secondary energy resources from metallurgy and machinery manufacturing enterprises include: [1]:

- blast furnace gas - a by-product of blast furnace production, obtained as a result of incomplete combustion of coke (Q = 4.6 MJ/m^3);

- coke gas - product of coke burning in coke ovens (Q = 15-18 MJ/m^3);

- ferroalloy gas - smelting of ferroalloys in electric furnaces (Q = 11.3 MJ/m^3);

- converter gas - mixture of waste gases obtained during conversion of pig iron into steel in the oxygen-converter process (Q = 8.2-8.4 MJ/m^3);

- combustible solid and liquid production wastes (Q = 4,2 MJ/kg).

Industrial gas emission during smelting of 1 ton of steel is presented in figure 2.1.

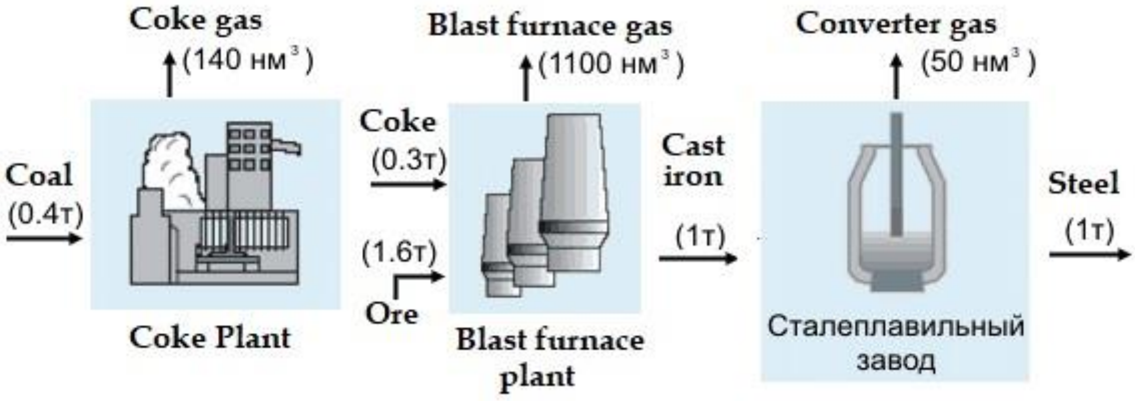


Figure 2.1 – Industrial gas emissions during smelting of 1 ton of steel [1]

To ensure the continuous combustion of combustible renewable energy sources (RES), several fundamental conditions must be met:

- there must be an adequate mixture of fuel and oxidant (air) in a controlled ratio.

- the furnace flame needs to transfer some of its heat to the incoming fuel to maintain a continuous combustion process.

It is essential to recognize that combustible secondary energy resources (SER) burn in a gaseous state within the flame, with approximately 80 % of the energy being released as gas.

When mixing fuel with air, achieving good contact between the oxygen in the air and the combustible components of the fuel is crucial. The more effective this contact, the faster and more complete the combustion process will be. Mixing is most efficient when the fuel is in its gaseous form, allowing for optimal ratios between the two gases, leading to rapid combustion and better control, as adjustments can be made by injecting more or less fuel.

The main advantages of utilizing combustible secondary energy resources include:

- reduction in the purchase of external fuel delivered to the plant, which lowers the costs of metallurgical products.

- the capability to create combustible mixtures that yield the most suitable calorific value for specific technological processes, such as coke ovens and natural blast furnaces.

Fuel saving from the use of combustible SER is determined by the formula [6]

$$B_{Sav.SER}^{com} = \frac{Q_{SER}^{com}}{Q_{eq.f}} \cdot \frac{\eta_1}{\eta_2}, \tag{2.1}$$

where Q_{SER}^{com} – heat of combustible SERs used during the calculation period (decade, month, quarter, year);

$Q_{eq.f}$– calorific value of fuel equivalent, $Q_{eq.f}$=29,3 MJ/kg;

η_1– fuel utilization coefficient in the fuel-using unit when operating on SER fuel;

η_2– fuel utilization coefficient of the fuel-using unit when operating on substituted fuel.

Heat of combustible SER used during the calculation period is determined by the product:

$$Q_{SER}^{com} = V_{SER}^{com} \cdot Q_{SER}^{low}, \tag{2.2}$$

where V_{SER}^{com}– amount of combustible gas used during the calculation period:

$$V_{SER}^{com} = M_p \cdot v_{SER}^{com},, \tag{2.3}$$

where M_p– basic product yield;

v_{SER}^{com}– specific yield of combustible secondary energy resource per unit of the main product.

Taking into account the expression (2.2) and $\frac{1}{29,3} = 0,0341$the formula (2.1) takes the form:

$$B_{Sav.SER}^{com} = 0.0341 \cdot V_{SER}^{com} \cdot Q_{SER}^{low} \cdot \frac{\eta_1}{\eta_2}. \tag{2.4}$$

2.2.1 Blast Furnace Gas

Materials are continuously introduced into the furnace, while the final products, including slag and blast furnace gas, are discharged from it. Throughout the blast furnace smelting process, chemical reactions occur among carbon, iron oxide, blast air, coke, and other components present in the ore. The blast furnace gas is a by-product of these interactions (figure 2.2).

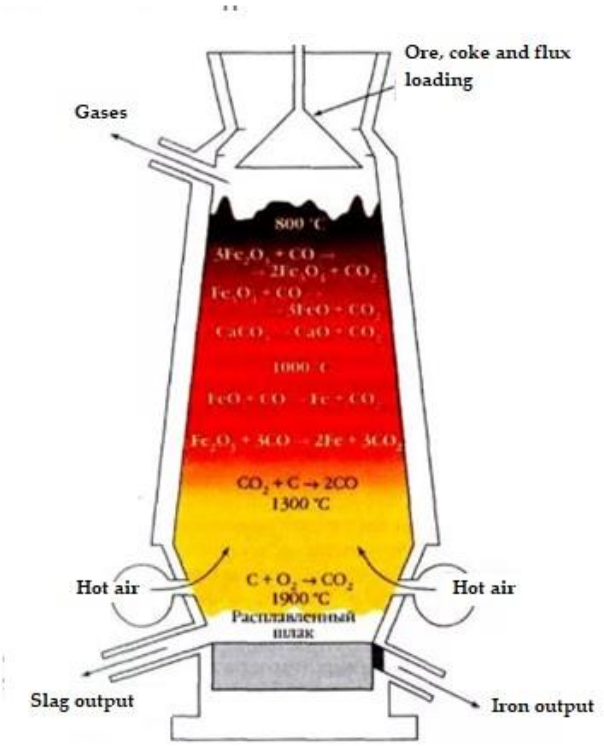


Figure 2.2 – Blast furnace

Chemical properties and composition:

- carbon monoxide (CO) - 24.5-32 %;
- carbon dioxide (CO_2) - 12.5-19 %;
- methane (CH_4) - less than 0.2 %;
- nitrogen (N_2) - 46-52.5 %;
- oxygen (O_2) – none;
- hydrogen (H_2) - 5-8 %;
- flammability temperature - 630-680 °C;
- heat of combustion: 4.6 MJ.

When it exits the blast furnace, the gas contains 50 kg of dust for every tonne of pig iron produced. To prepare it for further use, the gas must undergo several cleaning stages. Initially, it passes through dust collectors for a dry cleaning process. Following this, it is directed to scrubbers, where it undergoes a second stage of cleaning using water.

Only after this process does the gas enter the main blast furnace gas collector before being distributed to consumers.

In blast furnace production, the volume of blast furnace gas generated is influenced by various parameters:

- the basic technological scheme of the ironmaking process,
- the type and quantity of energy sources used in the furnaces
- the composition of the charge materials and the molten pig iron,
- the capacity and design characteristics of the blast furnaces.

Utilization

The main consumers of blast furnace gas are:

- blast furnace air heaters ~35 %;
- CHPP boilers ~30 %;
- coke-chemical production ~25 %;
- heating furnaces of rolling shops ~10 %.

It is evident that the majority of the fuel is utilized by blast furnaces for heating air heaters and the coke batteries of the Combined Heat and Power Plant (CHPP), which constitute the first category of consumers. The second category includes the process furnaces of rolling mills, while the third comprises the boilers of blower stations that supply air to the blast furnaces.

Given the low calorific value of blast furnace gas, metallurgy often employs gas mixtures, such as coke oven gas-natural gas and blast furnace gas-coke oven gas-natural gas. Efficient combustion of blast furnace gas presents significant challenges due to the following factors:

1) The low heat of combustion of blast furnace gas (4000-4500 kJ/m^3) and the substantial presence of inert gases (56 % N_2 and 14 % CO_2) lead to a considerable reduction in the temperature within the steam generator's furnace. Additionally, the luminosity of the combustion products from the blast furnace gas is low, which adversely affects the performance of the radiant heating surfaces.

2) As a result of the same steam capacity, the mass flow rate of flue gases through the steam generator increases, leading to higher steam superheating temperatures, elevated flue gas temperatures, and potential overload of flue gas scrubbers. Consequently, the steam capacity of conventional steam generators is reduced to 70-75 % of their nominal value when converted to blast furnace gas.

The issue of enhancing the efficiency of boilers operating on blast furnace gas has become increasingly prominent. One effective solution is the preheating of blast furnace gas, which has been shown to improve the productivity of boilers dedicated solely to burning this gas. For instance, raising the temperature of the blast furnace gas by 100 °C can increase the unit's productivity by 3.5-4 %. This type of combustion can achieve temperatures of 1400-1500 °C under standard conditions, with further increases possible by preheating the air before combustion.

When operating the boiler on blast furnace gas or on a mixture of blast furnace gas and natural gas, it is crucial to monitor gas pressure in the boiler gas lines upstream of the control valves. Ensuring uniform distribution of gas and air across the burners, as well as preventing thermal deformations in the furnace and boiler gas ducts, is essential. In the case of dual combustion of blast furnace gas and natural gas, monitoring the furnace's operation is necessary. If a blue flame appears near the super heater, indicating suboptimal performance of the blast furnace gas burners, adjustments to the blast furnace gas and air supply to each burner must be made. At the same boiler load, the superheated steam temperature increases as the volume of top gas increases, necessitating a reduction to maintain normal temperature levels.

2.2.2 Coke oven gas

Coke oven gas is one of the most efficient gaseous fuels.

Coke gas is a product of the thermal decomposition of coal molecules and is obtained simultaneously with coke during coal distillation in chamber furnaces. This process is carried out at a temperature of 900-1200 ºC (figure 2.3).

Chemical properties and composition:

- H_2: 55-60 %;
- CH_4: 20-30 %;
- CO: 5-7 %;
- CO_2: 2-3 %;
- N_2: 4 %;
- unsaturated hydrocarbons: 2-3 %;
- O_2: 0,4-0,8 %;
- heat of combustion: 15-19 MJ/m^3.

The volume of gas produced is directly proportional to the set temperature and the cycle time. Depending on the initial characteristics of the coal, approximately 74-78 % solid coke and 15-18 % gas are generated during a high-temperature treatment lasting 13-14 hours.

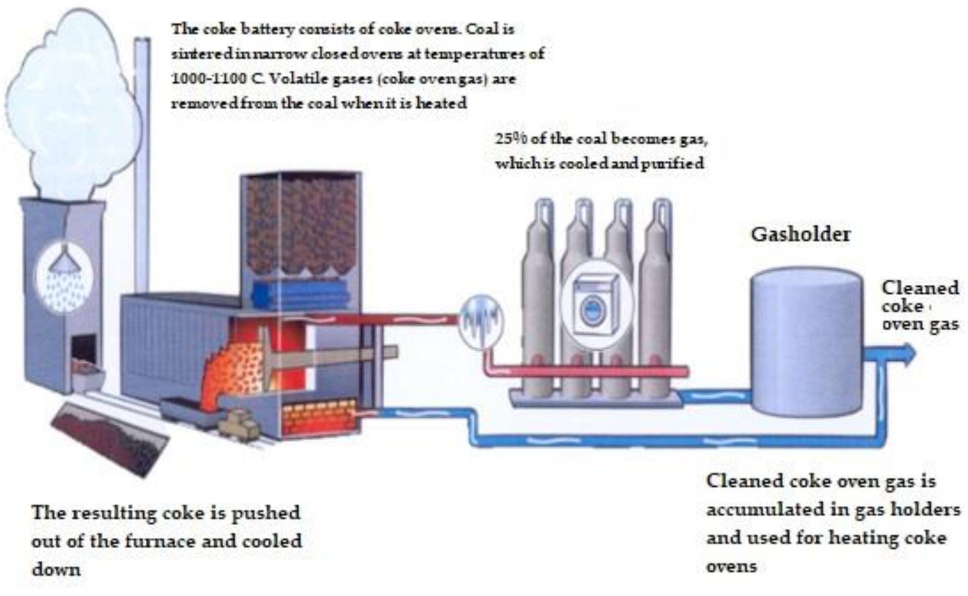


Figure 2.3 – Conversion of coal into coke

Utilization

Each tonne of material yields an average of 400-460 m³ of gas, which can be used as fuel only after the extraction of valuable chemical products. When combusted, the gas can reach temperatures of 2000 °C.

Coke gas possesses a high calorific value of 15-19 MJ/m³, making it one of the most efficient gaseous fuels available. The volume fraction of combustible components in the gas is around 93 %, resulting in impressive efficiency metrics.

Currently, coke oven gas is widely and safely employed as a fuel source:

- at metallurgical plants,
- in municipal economic activity,
- as a raw material for production.

This fuel is utilized in the ceramics and glass industries, as well as for heating steam boilers and in metallurgical plants. In numerous cities, coke oven gas is also employed for district heating purposes.

It is important to highlight that the presence of hydrogen sulfide in combination with coke gas is completely undesirable, regardless of whether coke gas is used as fuel or as a raw material for chemical products. Consequently, an effective cleaning process is essential. [9].

Advantages of using coke gas as a fuel

- combustion of fuel without waste;
- does not require the use of traction equipment;

- easy management and regulation of processes;
- easy starting and stopping of processes.

Example of coke oven gas utilization (Spain)[10]

The Profusa SA plant in Bilbao, Spain, generates high-hydrogen coke gas as a by-product of its coke production process. Since August 1995, this coke gas has been utilized in a GE Jenbacher 12 gas engine to generate 7,164 kW of electricity. The gas released during this process is then used to produce steam for various technological needs.

The plant's specialized engines are designed to operate on 100 % coke gas, 100 % natural gas, or a blend of coke and natural gas at a ratio of 60 % to 40 %. The gas production and combustion process is illustrated in figure 2.4.

2.2.3 Ferroalloy gas

Ferro-alloy gas is a mixture of waste gases from the ferro-alloy furnaces in which the ore is reduced.

Chemical properties and composition:

- H_2: 2-10 %;
- CH_4: 0,5-5 %;
- CO: 70-90 %;
- CO_2: 2-20 %;
- N_2: 2-4 %;
- SO_2: 0,2—0,52 %;
- heat of combustion: 8,2-8,4 MJ/m^3.

Gas output is uniform: from 400 to 800 m^3 per ton of alloy, depending on the type of alloy. Ferroalloy gas belongs to the group of gases with high combustion temperature of 2230 - 2240 °C.

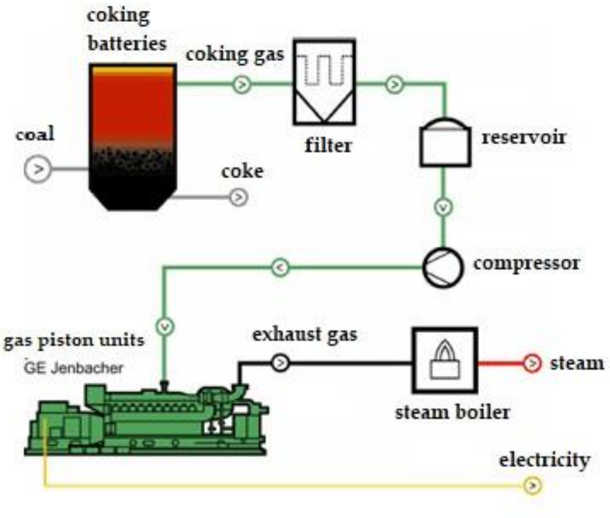


Figure 2.4 – Scheme of coke oven gas utilization at Profusa, Spain

Utilization

Ferroalloy gas, which contains fine dust particles, can only be utilized as fuel after undergoing a two-stage wet cleaning process due to its high dust content. The gas is directed to a wet gas treatment unit that includes an inclined stack, sludge separator, Venturi scrubber, and drift eliminator.

In boiler plants, ferroalloy gas is used as a substitute for natural gas.

2.2.4 Converter gas

Converter gas is a mixture of waste gases, which are produced during the conversion of pig iron to steel in the basic oxygen process.

Chemical properties and composition:

- CO: 74 %;
- CO_2: 13 %;
- N_2: 13 %;
- heat of combustion: 8,4-9,2 MJ/m^3.

The temperature of the gases exiting the converter neck increases from 1250-1300 °C at the beginning of the oxygen cleaning process to 1600-1700 °C in the middle and at the end of the process. The gas output is roughly 55 m^3 per tonne of steel.

The exhaust gas removal and purification system typically includes a converter gas cooler, a waste heat boiler, and a downstream gas purification system. The cooler utilizes the heat from the exhaust gases to heat and evaporate water. This process of generating steam and hot water enhances the technical and economic performance of the operation. Furthermore, cooling facilitates the cleaning of gases after dedusting. The most commonly used gas cleaning devices are Venturi tubes (for wet gas cleaning), while electric filters and fabric filters (for dry gas cleaning) are used less frequently. Different facilities may implement various gas cleaning systems, usually comprising two or more scrubbers arranged in series, ensuring that the dust content in the treated gas is below 0.1 g/m^3.

Two fundamentally different gas cleaning and degassing schemes are employed: one with combustion of carbon monoxide in the converter gas cooler and one without. In the first scheme, air is drawn through the gap between the converter neck and the OPG, using its oxygen to convert CO to CO_2 through combustion.

Example 1:

At the Aceralia plant in Spain, GE Jenbacher gas engines were proposed for use with converter gas produced by the steel mill. During testing, modifications were made to the combustion chamber (including piston shape and compression ratio) and turbocharger parameters to enhance efficiency for this specific gas. Additional safety measures were implemented to prevent poisoning from toxic carbon monoxide (CO), which is the main combustible component. After operating the test engine for 3,000 hours, the steel mill opted to purchase an additional 11 JMS-620 modules, resulting in a total power output of 20.4 MW. Figure 2.5 illustrates the power plant.

Figure 2.5 – Power plant on converter gas from Aceralia plant

Example 2 [11]

This method involves sampling the gas generated during the blowing process in the metal converter, followed by cooling and cleaning it in a scrubber equipped with Venturi tubes. The gas is then collected and averaged in a gas tank before undergoing further cleaning to achieve a dust concentration of 10 mg/m³

The cooled and purified converter gas is directed to the gas mixing station, while coke gas is simultaneously released from the dry coke quenching chamber. After the coke gas undergoes cooling and dedusting, a chemical separation process is employed to recover the coking products. The recovered coke gas is then sent to a variable pressure adsorption unit, where hydrogen is extracted under varying pressure conditions. This hydrogen is subsequently introduced to the gas mixing station, where it is combined with the converter gas at a volume ratio of 0.50 to 0.65.

2.3 Combustion of combustible SER from chemical production

Gaseous residues from the chemical industry, arising from the processing of carbonaceous raw materials and containing a specific amount of chemical energy, can be utilized as fuel and energy resources. These combustible synthetic energy resources (SERs) are generated during the production of ammonia, methanol, acetylene, caprolactam, caustic soda, yellow phosphorus, and calcium carbide [1].

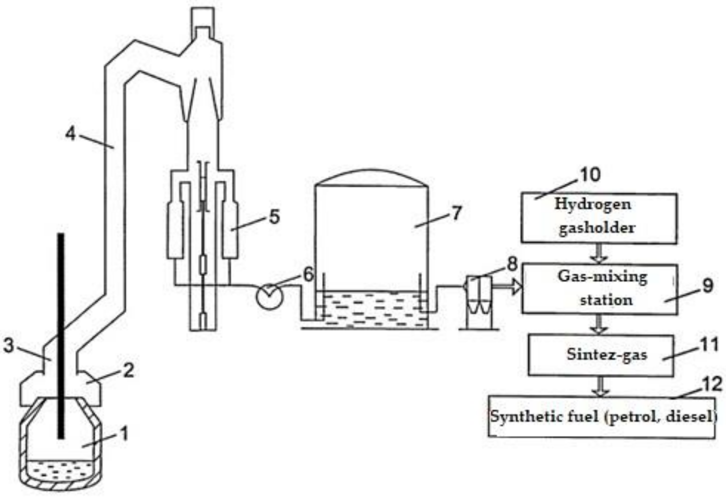


Figure 2.6 – Method of converter gas utilization

- The production of ammonia, tank and scrubbing gases produces the CO fraction as well as liquid hydrocarbons that can be used as fuel.
- Methanol production produces tank and scrubber gases.
- Acetylene production - soot sludge and high homologues of acetylene.
- Gas and hydrogen purification in caprolactam production.
- A significant amount of hydrogen is released during the production of caustic soda.
- Combustible furnace gases are generated in the production of yellow phosphorus and calcium carbide.

The primary challenge in utilizing combustible water-energy resources lies in the necessity to collect, transport, and sometimes construct specialized burners for their combustion. This also involves enhancing existing burners and developing new combustion techniques.

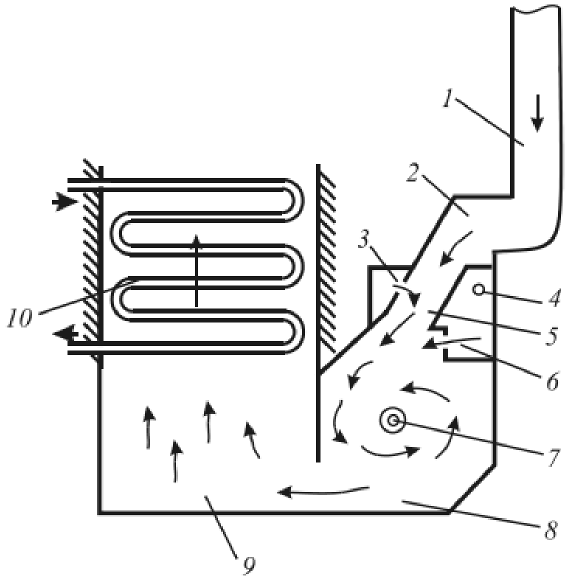
In some cases, the gases contain nitrogen, carbon dioxide, water vapor, and other components. The presence of over 50 % impurities (ballast) in conventional burners renders the industrial combustion of gaseous waste from chemical production either ineffective or impossible, especially due to significant fluctuations in gas composition and consumption. These factors contribute to a low intensity of the combustion process when using standard heaters.

Therefore, when incinerating flue gases that contain a high level of impurities, it is essential to employ specialized burners in the following scenarios:

- maxim umutilization of gas heat;
- recuperative heating of the gases;
- addition of high calorie fuel to the flame to stabilize combustion;

- complete pre-mixing of gas with air in an intensive mixer before starting combustion;
- maximum flame reduction.

Figure 2.7 illustrates a plant designed for the combustion of high ballast gas. The combustion process utilizes a cyclone heater, where air and exhaust gases are pre-mixed before entering the system. Exhaust gases flow into combustion chamber 8 via pipe 1, while air is introduced through pipe 2, with the airflow being facilitated by a fan.



1 – pipe; 2 – channel; 3, 6 – air holes; 4 – annular collector; 5 – mixer; 7 – burners; 8 – combustion chamber; 9 – afterburning chamber; 10 – heat exchanger

Figure 2.7 – Installation for combustion of highly ballasted gases generated during soot burning on catalysts

Air from the annular collector 4 enters the mixer through openings 5 and directly into chamber 8 through openings 6. The combustion process occurs in chambers 8 and 9. The physical heat produced from combustion is captured in a tubular heat exchanger 10, which contains water or another coolant. The combustion chamber reaches high temperatures of 940 °C due to the combustion of auxiliary fuel (either high-calorific gas or fuel oil) in the seven burners located in the system.

The mass fraction of the added natural gas (x) is typically determined by the stable combustion temperature, which ranges between 1150 °C and 1300 °C:

$$x = \frac{\mathrm{h}_{SER} - \mathrm{Q}_{SER}^{w}}{Q_{ng}^{w} - h_{ng}},$$

where $\mathrm{h}_{\mathrm{SER}}$ and $\mathrm{h}_{\mathrm{n.g}}$– enthalpy of combustion products of combustible SER and natural gas;

$\mathrm{Q}^{\mathrm{w}}_{\mathrm{SER}}$ and $\mathrm{Q}^{\mathrm{w}}_{\mathrm{n.g}}$– working heat of combustion of combustible SER and natural gas.

2.4 Incineration of combustible wood waste

Recycling hardwood waste, lignin, and similar materials is currently garnering considerable attention. Approximately 50 % of the wood harvested by the forestry and woodworking industries goes to waste. One of the key objectives is to eliminate this waste through combustion to generate heat.

There are several types of wood waste:

- sawdust (uncut young shoots, needles, leaves);
- heartwood, bark and rotten wood.

With the exception of sulfur, wood has a composition similar to that of solid fuels. Wood waste from certain industries often exhibits a high moisture content, with waste from woodworking companies typically ranging from 45 % to 55 % moisture content. Additionally, the moisture content in wood peel can reach as high as 80 %. Meanwhile, waste generated from woodworking and furniture production generally has a moisture content of about 10 % to 20 %. Despite its high humidity, wood demonstrates a significant yield of volatile substances, which helps maintain a stable combustion process [12].

Shredded wood waste also differs in particle size:

- wood dust with particles smaller than 0.5 mm;
- sawdust - less than 5-6 mm, chips from grinding machines - less than 30 mm;
- large chips with a particle size greater than 30 mm.

The granulometric composition is assessed through sieving. The methods used for incinerating wood waste vary based on the size and moisture content of the particles. Wood dust that does not contain abrasive particles is typically incinerated using the flame-vortex method. In contrast, if abrasive particles are present, the incineration is carried out in cyclone furnaces. Larger wood waste can be effectively burned in liquid form or in furnaces with dense linings. Additionally, preliminary processing of local wood waste may involve the production of briquettes, which can be utilized in dense bed furnaces.

Preparation for incineration

There are the following methods of preparing fuel for combustion [13]:

1) no pre-processing;

2) light processing - drying, crushing, pressing, extraction;

3) deep (thermochemical or biochemical) processing – pyrolysis, anaerobic digestion, fermentation.

The wood waste combustion process involves pre-sorting and drying. Drying any type of fuel is essential to enhance its heat of combustion. However, it is important to recognize that drying is an energy-intensive process, and its implementation must be economically justified. Wood fuels and domestic waste are primarily shredded and compacted, while oil seeds are typically extracted through pressing. Biofuels with a moisture content below 50 % are subjected to pyrolysis, whereas those with a moisture content exceeding 50 % undergo anaerobic fermentation. Table 2.1 outlines sources of combustible secondary energy resources along with their processing methods and estimated efficiencies.

Combustion occurs in a fluidized bed furnace with partial recirculation of flue gases, ensuring complete combustion of the fuel present in the gases. This combustion process is utilized to extract heat, which is then transferred to an energy carrier – either steam or hot water – that can be delivered directly to consumers.

Table 2.1 - Sources of combustible SER and methods of their processing before combustion

Biomass sources	Processing methods	Efficiency, %
Forestry, wood processing waste (pulp)	Without recycling	70
	Pyrolysis	85
Agricultural crop waste (straw, haulm, etc.)	Without recycling	70
	Pyrolysis	80
	Anaerobic digestion	80
	Fermentation	50
Animal waste (manure, dung, droppings)	Anaerobic digestion	50
Domestic and industrial waste (garbage)	Without processing	50
	Pyrolysis	60
	Anaerobic digestion	50

Pellet combustion (figure 2.8)

The heat generated from burning pellets can be converted into electricity through the use of steam or gas turbines. Pellets are currently manufactured in countries like Germany, Finland, and Sweden from waste produced by the forestry and wood industries, including sawdust, shavings, and milling residues.

Wood pellets feature low moisture content (W = 8 %), high density (with values ranging from 1100 to 1300 kg/m³), and a high calorific value (Q = 19 MJ/kg) when compared to raw materials used independently as fuel. They typically measure between 20 and 50 mm in length and have diameters of 4 to 10 mm. Unlike conventional wood, wood pellets compete on equal footing with other types of solid, liquid, and gaseous fuels. They are also efficient for long-distance transport and require minimal storage space [14].

The technology for pellet production involves several steps, including coarse crushing, drying, fine grinding, pressing, cooling, sorting, and packaging. Natural resins are used without any additives, with lignin serving as the binder.

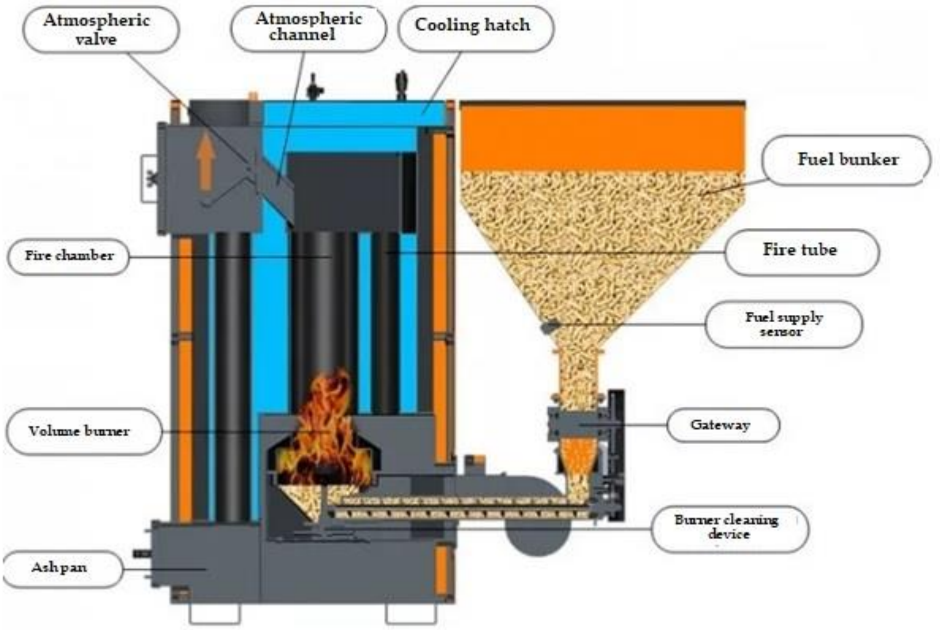


Figure 2.8 – Pellet combustion

The production of pellets requires 3 % of the potential energy. This type of fuel can be burned in either mechanized or manual boilers. Consequently, combustible secondary energy resources present an opportunity to replace primary fuels, thereby enhancing energy production using our own energy resources.

Burner

To ensure effective combustion, wood must be ground into very fine particles (dust). These particles are transported by the movement of air. Whirl combustion facilitates excellent mixing and combustion, akin to that of gas or fuel oil. However, producing wood dust is a costly process, which limits the use of wood dust boilers. In practice, the types of wood fuel utilized can range from wood chips to whole logs. Consequently, the technology for burning wood and other solid fuels is more complex than that used for burning gas or fuel oil.

Principle of operation (figure 2.9) [15]:

1. Fuel is supplied to the hopper.
2. A special element rotates in the hopper so that the fuel does not hang.
3. Fuel is fed from the hopper to the auger inlet.
4. The screw feeds the fuel into the fire.
5. The fuel ignites in the combustion chamber. The temperature of the gases produced is 1000 - 1200 °C.
6. The blower provides the air needed to burn the fuel.
7. The air is supplied through a window with a screen that dilutes the flue gases to the required temperature (150 - 900 °C).
8. A desiccant at a given temperature is fed to the drying unit.

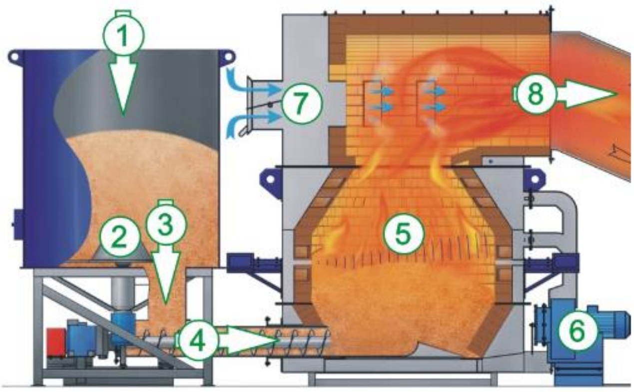


Figure 2.9 – Principle of operation of wood waste combustion boiler

Burning sawdust

Boilers burning sawdust usually consist of the following elements

- raw material feeding device;
- nets in the mesh section of the equipment;
- waste collection container
- hot air distributor in the fireplace;
- wood-burning stove. It has a number of openings arranged in a specific sequence that allows the air supply to be regulated, thus ensuring uniform combustion over time;
- a heat exchanger where the gases that heat the refrigerant are released and then released into the chimney (figure 2.10).

2.5 Incineration of agricultural wastes

Based on an analysis of their physical and chemical properties, agricultural waste can be classified into two categories:

1) residues from the processing of seeds and grains in oil and flour mills, such as sunflower hulls, millet hulls, oat hulls, etc.;

2) residues from the processing of stalks, for example, in rope manufacturing, including stalks, straw, bales, etc.

The chemical composition of these fuel types is generally consistent, comprising approximately 50 % carbon, 0.1-2 % sulfur, 6 % hydrogen, and around 40 % oxygen. This fuel is highly reactive and contains a significant amount of volatile matter, approximately 80 %.

The elemental composition of the ash is marked by a rise in alkaline elements (primarily K_2O) and notable variations in the mineral composition. The ash softening temperature (determined after ashing in a muffle furnace) is around 1300 °C. Low-melting compounds of sodium and potassium may transition into the gas phase, condensing on particles as the gas temperature decreases, ultimately resulting in the formation of sticky deposits on convective heating surfaces.

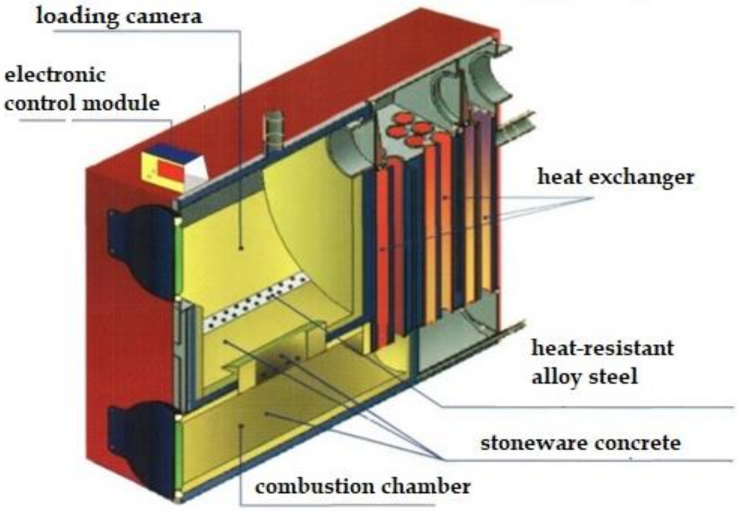


Figure 2.10 – Design of sawdust boilers

There are at least three challenges associated with the combustion of agricultural residues:

- Typically, the chemical composition and physical properties of agricultural waste differ significantly from those of conventional energy fuels. This difference creates substantial difficulties when attempting to burn waste using traditional methods, leading to issues such as slag formation, corrosion of heating surfaces, low combustion efficiency, and contamination of convection surfaces.

- The industry has yet to produce specialized boilers designed for burning various types of waste, with the exception of some wood waste. As a result, combustion devices, fuel preparation, and supply systems necessitate specialized equipment.
- The issue of gas emissions is crucial since industrial and agricultural wastes have complex compositions that can lead to elevated concentrations of harmful components, which are not commonly found in traditional incineration processes.

Considering these factors, it can be concluded that the most appropriate incineration technologies for dry waste include cyclonic pre-combustion systems and low-temperature vortex circuits. For wet waste and larger boilers, fluidized bed technology shows promise. In all scenarios, it is essential to install mechanisms for cleaning the convective heating surfaces. Low ash and sulfur content contribute to favorable environmental performance for both low and high-temperature incinerators, eliminating the need for desulfurization and facilitating easier filter operation.

3 Deep processing of combustible secondary energy resources to produce efficient fuels

3.1 Pyrolysis (Dry Distillation)

Pyrolysis is the process of thermally decomposing organic feedstocks in the absence of or with limited oxygen, resulting in the production of derived fuels in solid, liquid, and gaseous forms. The primary raw materials for pyrolysis can include wood, coal, slate, agricultural waste, and municipal waste. The end products of pyrolysis consist of gases, liquid condensate in the form of tar and oil, and solid residues in the form of charcoal and ash [1].

The products of pyrolysis exhibit the following characteristics:

- Solid Residue: Comprising a maximum of 25-35 % by mass, the solid residue consists primarily of charcoal, which contains 75-85 % carbon and has a calorific value of approximately 30 MJ/kg.
- Liquids: The condensed vapors account for a maximum mass fraction of about 30%. This includes viscous phenolic resins and effluents, which can be further divided into pyrolytic acids, mainly acetic acid, methanol (around 2 % maximum), and acetone. The resin is a complex mixture of various substances, including carbon, hydrogen, and oxygen, and is capable of burning to release significant amounts of heat. Upon heating, the resin evaporates, generating volatile products known as resin vapors. The liquid products can either be separated for use in the chemical industry or combined into a crude fuel with a calorific value of approximately 22 MJ/kg.
- Gases: The greatest mass fraction obtained from gas generators during pyrolysis is approximately 80 %. The gas mixture produced, which often includes nitrogen, is referred to as wood gas, syngas, or generator gas. This gas mixture comprises primarily nitrogen (N2) at 45-60 %, hydrogen (H_2) at 10-17 %, and carbon monoxide (CO) at 14-30 %, along with trace amounts of methane (CH4) at 1-4 % and carbon dioxide (CO_2) at 6-12 %. Additionally, the mixture contains resin vapors, wood vinegar (acetic acid or CH_3COOH), water vapor, and more. Among these gases, carbon dioxide (CO_2) results from the complete combustion of carbon; however, it cannot be further combusted and thus is considered a detrimental component of pyrolysis gas. Nitrogen (N_2) is an inert and non-flammable gas. Wood and peat are the sources that yield the highest volumes of gas. The heating value of these gases in air ranges from 5 to 10 MJ/kg (or 4 to 8 MJ/m^3). These gases can be utilized directly in diesel engines or carbureted spark-ignition engines, although the primary challenge lies in effectively removing ash and condensed pyrolysis products.

The following formula shows the material balance of pyrolysis of fuel without access to oxygen [17]:

$$B = G_{steam} + G_{gg} + G_{sr},$$

where B is the fuel consumption subjected to pyrolysis, kg/s;

G_{steam} - steam output during pyrolysis, kg/s;

G_{gg} - output of generator gas, kg/s;

G_{sr} - solid residue yield, kg/s.

The material balance of fuel pyrolysis in specific values per unit weight of fuel will be as follows

$$b = g_{team} + g_{gg} + g_{sr}.$$

The following formula shows the heat balance of pyrolysis of fuel without access to oxygen:

$$Q_l^w + Q_{pyr} = g_{gg} \cdot Q_l^{gg} + Q_{ph.h}^{gg} + g_{sr} \cdot Q_l^{sr} + Q_{ph.h}^{sr},$$

whereQ_l^w– lower working heat of combustion of fuel, kJ/kg;

Q_{pyr}– heat to be supplied to the fuel for pyrolysis, kJ/kg;

Q_l^{gg}, Q_l^{sr}– heat of combustion of generator gas and solid residue, kJ/kg;

$Q_{ph.h}^{gg}$, $Q_{ph.h}^{sr}$– physical heat of generator gas and solid residue obtained in the pyrolysis process, kW.

The following formula provide a methodology for determining the physical heat of the generator gas and solid residue

$$Q_{ph.h}^{gg} = c_{gg} \cdot g_{gg}\left(t_{gg} - t_o\right) + c_{st} \cdot g_{st}(t_{st} - t_o) + r \cdot g_{st};$$
$$Q_{ph.h}^{sr} = c_{sr} \cdot g_{sr} \cdot \left(t_{gg} - t_o\right).$$

where c_{gg}, s_{st}, s_{sr}– average heat capacity of generator gas, steam and solid residue, kJ/(kg·°C);

r– heat of vapourisation of water, kJ/kg;

t_o– initial fuel temperature, °C.

Gasification is a process similar to pyrolysis, but it is specifically designed to optimize the production of gaseous fuel products. The equipment utilized for the partial combustion of biomass to maximize the output of combustible gases is known as gas generators.

To effectively carry out the gasification of wood, it is essential to maintain an equilibrium temperature of approximately 900 °C. During the pyrolysis phase, the goal is to produce charcoal at temperatures between 600 and 700 °C.

At a temperature above 900 °C, coal is gasified together with water vapour and carbon dioxide [17]:

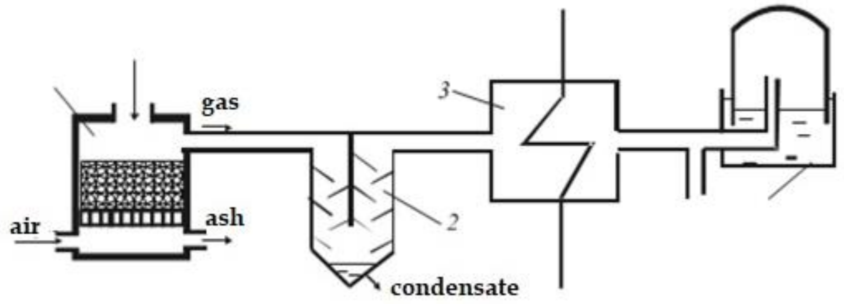
$$C + H_2O = CO + H_2 - 11\ \text{MJ/kg};$$
$$C + CO_2 = 2CO - 14.6\ \text{MJ/kg}.$$

Advantages of fuel gasification include:

1. Temperature Control: When burning fuels with high moisture content, achieving high temperatures can be challenging. In contrast, gas produced from the same fuel allows for higher temperatures, as moisture (or ballast) can be removed from the gas, and the gas can be heated easily prior to combustion.
2. Reduced Air Requirements: Gas combustion requires less excess air ($\alpha = 1.02\text{-}1.05$) compared to solid fuel combustion ($\alpha = 1.2\text{-}1.3$). This reduction in excess air leads to increased combustion temperatures and, consequently, improved efficiency in extracting the energy contained in the fuel.
3. Easier Automation: The automation of fuel combustion processes is more straightforward with gasification.
4. Ash Management: During pyrolysis, ash does not melt at temperatures below 1000 ºC, preventing the activation of the gas generator.

These benefits contributed to the widespread adoption of generator gas for thermal energy production during the 1920 s and 1960 s, prior to the large-scale development of oil and gas resources. However, a significant challenge in generating power through gasification has been the low calorific value of generator gas compared to liquid fuels and natural gas. This issue necessitates the use of specialized equipment, such as gas engines and turbines, which must be specifically designed or modified to operate on low calorific fuels. The diagram of the pyrolysis plant is illustrated in figure 3.1 [18].

Fuel is introduced into the gas generator (1), where gas is produced. This gas then moves to the condensate drain (2), where moisture is separated from it. Following this, the gas passes through a heat exchanger (3), where any residual heat is utilized for the plant's internal requirements, such as pre-drying the fuel. The cooled gas is either directed to the end user or stored in a pressurized gas storage tank, known as a gas holder (4). Vertical units that are loaded from the top are preferred for this process.

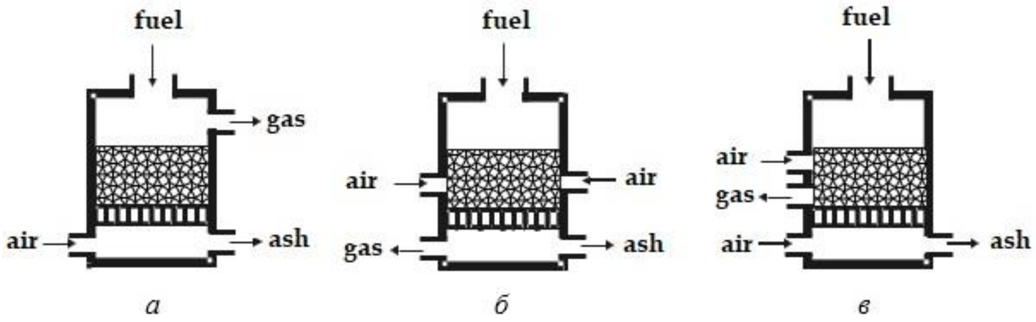


1 – gas generator; 2 – condensate drain; 3 – heat exchanger; 4 – gas holder

Figure 3.1 – Pyrolysis installation

3.2 Layer gasification of fuel

Gasification processes can be implemented using different schemes. Simple ones involve layers. Layer gasification can be a direct process (figure 4.2, a) with opposite supply of air and fuel, or a reverse process (figure 4.2, b) with fuel and air supplied from above [19].



a– direct; b – reverse; c – mixed

Figure 3.2 – Layered diagrams of gasification processes

In the direct process, air is introduced at the bottom of the gas generator, optimizing conditions for achieving the highest combustion temperatures and ensuring the complete combustion of fuel carbon. This approach allows for a significant reduction in unburned fuel carbon to just 1-2 % of the initial amount. Flue gases flow through the fuel bed from the bottom to the top, cooling down while becoming enriched with volatile tar fractions and water. However, the presence of water vapor in the generator gas reduces its calorific value. As the gas that contains tar cools, it can lead to blockages in the gas pipelines.

The mixed or horizontal process can be viewed as an intermediary between direct and reverse gasification (as depicted in figure 3.2, c). This method is particularly well-suited for gasifying high-ash fuels. The aforementioned stratified systems are among the simplest in terms of technical implementation and are commonly employed in autonomous heating systems, industrial facilities, and small power plants.

For gas generators, suitable fuels include wood chips, lump peat (with lump sizes ranging from 1 cm^3 to 200 cm^3), or mixtures of lump peat with sawdust or shavings. While sawdust and shavings can be used as fuel, this may lead to a reduction in power output by 20-40 %, owing to fuel suspension in the hopper and uneven gas production. Lignin, a byproduct from hydrolysis processing, is also an excellent fuel for gasifiers. Moreover, gas generators can operate with any type and quality of wood (including bark, pine needles, and decayed wood) with moisture content of up to 50 %.

Several conditions must be satisfied for the success of the pyrolysis process. The incoming material needs to be pre-sorted, dried, and crushed to minimize non-combustible impurities. One vital parameter influencing the temperature and the yield of products is the air-fuel ratio, which typically consists of about 30 % of the air required for complete fuel combustion.

It operates at temperatures below 600°C and is easy to operate. In this case, fuel gasification can be divided into four stages:

1) 100-120 °C - the material entering the gas generator falls and is freed from moisture;

2) 275 °C - the exhaust gases consist mainly of N_2, CO and CO_2; acetic acid and methanol CH_3OH are obtained;

3) 280-350 °C - exothermic reactions begin, releasing a complex mixture of volatile chemicals (ketones, aldehydes, phenols, ethers);

4) above 350 °C - all types of volatile compounds are released, CO formation occurs and H_2 formation increases, part of the carbon is stored in the form of coal mixed with ash residues [20].

Combustible products undergo thermal decomposition (pyrolysis) [21]:

$$CN_4 = C + 2N_2;\ C_2N_4 = 2C + 2N_2;$$

Conversion:

$$C_2H_4 + 3N_2O = CO + CO_2 + 5N_2.$$

Thermal pyrolysis and conversion take place with heat absorption. Secondary reactions also occur with heat absorption:

$$3C + 4N_2O = 2CO + CO_2 + 4N_2.$$

To maintain thermal equilibrium and accelerate the above reactions, the operating temperature is maintained in the gas generator by adding oxygen:

$$2CN_4 + O_2 = 2CO + 4N_2;$$

$$C_2N_4 + O_2 = 2CO + 2N_2.$$

The various fuels produced through pyrolysis—including vapors, gases, and solid carbon-rich coke (charcoal) – possess a lower total combustion energy compared to the original biomass. However, they are characterized by greater versatility in their applications.

The primary factor influencing the results of thermal decomposition of the fuel is temperature. As the temperature increases, the yield of combustible gas rises, while the yields of tar and pyrogenic water decrease, along with a reduction in semi-coke production. When the temperature remains constant, increasing the pressure within the gas generator extends the residence time of the gas in the equipment, which enhances the intensity of secondary reactions in the vapor-gas phase and boosts the heat transfer coefficient between the fuel and the gas.

The products of pyrolysis—including resin vapors, acetic acid, hydrogen, carbon dioxide, and coke—are suitable for combustion. The combustion processes can be described using chemical equations that illustrate the proportions and interactions of the various substances involved.

$$C+O_2=CO_2+33{,}190MJ/kg;$$

$$H_2+1/2O_2=H_2O+10{,}780MJ/m^3;$$

$$CO+1/2O_2=CO_2+23{,}9MJ/kg;$$

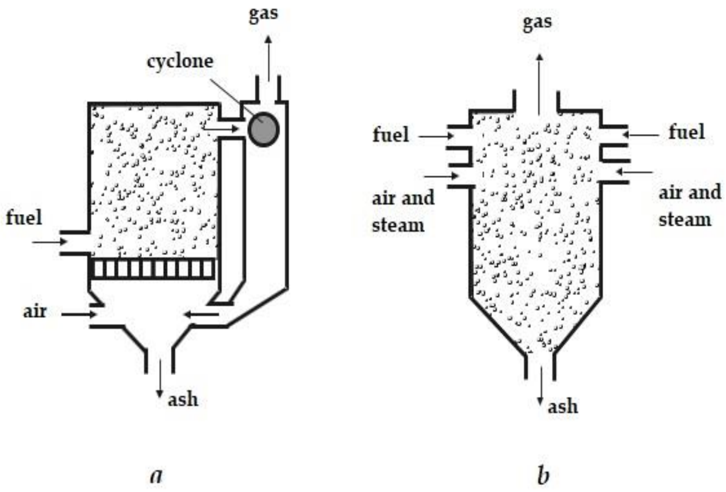
$$CH_4+2O_2=CO_2+2H_2O+35{,}76MJ/m^3;$$

$$C_2H_4(\text{этилен})+3O_2=2CO_2+2H_2O+58{,}967MJ/m^3.$$

3.3 Fluidized bed gasification

In addition to the layered solid fuel gasification methods previously described, the fluidized bed gasification process is commonly employed (figure 3.3). This process operates on the principle that air is introduced at a specific velocity beneath a layer of fuel particles resting on a grid. As the air flows upward, it causes the fuel layer to become agitated, resembling a boiling liquid.

Figure 3.3 (a) illustrates the configuration of a gas generator unit with a rotating liquid bed. In this gasifier, the fuel particles are suspended in an upward-moving gas stream. This phenomenon occurs when the gas pressure acting on the particles counterbalances their gravitational force. Unlike stratified gasifiers, fluidized bed gasifiers do not exhibit zoning due to the vigorous mixing of fuel particles with hot air. Consequently, the entire volume of fuel is maintained at a consistent temperature of 900-1000 °C. Although the chemical reactions during fluidized bed gasification are similar to those in fixed bed gasification, they occur with significantly greater intensity [19].



a - with circulation; b - in the coolant flow

Figure 3.3 - Liquid bed gasification process

Another promising gasification technique involves the gasification of pulverized fuel within a cooling stream, such as steam (figure 3.3(b)). This method combines high process intensity with broad control over the gasifier's output. The elevated intensity is attributed to an increased reaction surface area, the application of high temperatures, and hydrodynamic factors.

Various types of solids, as well as liquid products and suspensions, can serve as coolants in this process. However, there are some drawbacks to this method, including incomplete combustion of dust particles, a significant amount of ash present in the generated gas, the high costs associated with preparing solid fuel, and challenges related to installing a fuel supply device (such as a spray system) inside the reactor. Despite these disadvantages, this technique is regarded as a progressive approach to fuel gasification.

3.4 Other thermochemical fuel processing methods

Fuel undergoes chemical processing to generate synthetic liquid fuel, which is a complex mixture of hydrocarbons sourced from non-petroleum feedstocks. The primary distinction between the chemical compositions of biomass and oil lies in their hydrogen-to-carbon ratios, which are approximately 0.5-0.7 for biomass and around 1.2 for oil. To convert biomass into synthetic liquid fuel, it is essential to remove ash, liquefy the solid organic matter, enrich it with hydrogen, and extract oxygen, nitrogen, and sulfur in the form of H_2O, NH_3, and H_2S. Let's examine some of the significant examples.

Production of Methyl Alcohol: Methyl alcohol (methanol) is a toxic liquid produced through a catalytic reaction between H_2 and CO at a temperature of 330 °C and a pressure of 15 MPa.:

$$2H_2 + CO = CH_3OH.$$

Hydrogen H_2 and carbon monoxide CO are components of synthetic gas that can be obtained from biomass gasification. Methanol can be used as a substitute for petrol with a calorific value of 23 MJ/kg.

Treatment of biomass with organic solvents at high temperature and pressure

Wood is liquefied under high pressure in a solution of carbon monoxide and aqueous alkali:

$$C_nH_mO + CO = C_nH_m + CO_2.$$

The liquid products are then upgraded using industrial petroleum hydro treating catalysts.

Conversion of generator gas into synthetic liquid fuel

In the 1920s, F. Fischer and G. Tropsch were the first to uncover that hydrocarbons are produced from a mixture of carbon monoxide (CO) and hydrogen (H_2) using metal catalysts, specifically iron and cobalt, under pressure. This reaction yields water when a cobalt catalyst is used, while carbon dioxide is released when an iron catalyst is employed.

Hydrogenation

Shredded, decomposed, or digested biomass, such as manure, is subjected to heating at approximately 600 °C under a pressure of around 5 MPa in a hydrogen atmosphere. The process produces combustible gases, primarily methane (CH_4) and ethane (C_2H_5), which release about 6 MJ of energy per kilogram of dry feedstock when burned.

Hydrogenation with CO and steam

The process is similar to the previous one, but heating takes place in an atmosphere of CO and water vapour at a temperature of 400 °C and a pressure of 5 MPa. The reaction products are gas and synthetic oil, which can be used as fuel. The corresponding reactions take place in the presence of a catalyst:

$$CO + H_2O = CO_2 + H_2;$$

$$C_n\,(H_2O)_n + (n+1)H_2 \rightarrow nH_2O + H(CH_2)n\,H\ .$$

The latter reaction describes the conversion of carbohydrates into petroleum-like hydrocarbons. The energy conversion efficiency of this process is approximately 65 %.

4 Material and heat balances of thermal installations

Recycling units with diverse operating principles and designs are employed to harness energy from secondary energy sources. These units can be categorized into specialized and universal systems. Given that secondary energy sources encompass mediums like gas and steam along with water, universal boilers and boiler units can be classified as cogeneration systems. The primary aim of these systems is typically large-scale electricity generation.

Specialized, narrow-purpose plants include:

- waste heat boilers;
- economizers;
- heat pumps;
- heat exchange units;
- absorption chillers;
- water heaters;
- evaporative cooling units;
- turbogenerators, etc.

To ensure the effective operation of such units, a comprehensive array of auxiliary equipment is necessary to connect the system to fuel sources. For instance, a recovery unit may require a dedicated compressor station to facilitate secondary energy sources in conjunction with a gas pipeline. Additionally, systems for cooling, filtration, heating, and pressure regulation may be needed, depending on the specific characteristics of the resource.

During the design and operation of recovery units, it is essential to analyze the efficiency of heat utilization within energy and heat technology units, as well as to regulate heat energy and fuel use. To achieve this, several methods based on creating material and heat balances for heat and mass transfer devices are employed.

4.1 Heat balances of thermal technological units

Standardizing the consumption of heat, fuel, and electricity is essential for establishing a scientifically grounded plan to optimize their usage. The primary goal of standardization is to develop and implement effective consumption measures in production that promote the economical use of fuel and energy resources.

The principle behind creating a heat balance for any energy or thermal technology installation is based on the equality of input and output components. When preparing a heat balance, it is crucial to identify the boundaries of heat entering and leaving the installation. This balance can be constructed for the entire installation or for specific components [22].

A common approach to determining the energy cost associated with producing a particular type of product involves calculating the hourly heat or electricity consumption using the following heat balance equation:

$$Q_1 + Q_2 + \ldots + Q_i = Q'_1 + Q'_2 + \ldots + Q'_n \cdot \tag{4.1}$$

The left side of equation (4.1) represents the total amount of heat entering the unit from various energy sources, while the right side illustrates the heat leaving the unit.

Equation (4.1) provides the fundamental definition of the heat balance, indicating how much heat has entered the unit through an imaginary boundary and how much has exited through that same boundary. The heat balance equation, expressed as a percentage for a heat and mass transfer unit, takes the following form:

$$100\% = \frac{Q'_1}{\sum_1^n Q_n} \cdot 100\% + \frac{Q'_2}{\sum_1^n Q_n} \cdot 100\% + \cdots + \frac{Q'_n}{\sum_1^n Q_n} \cdot 100\% =$$
$$= q'_1 + q'_2 + \cdots + q'_n \tag{4.2}$$

where Q_1, Q_2,..., Q_n– sources of heat input to the plant, kJ/h;

Q'_1, Q'_2, …, Q'_n– heat losses by the plant, kJ/h.

The efficiency of the power plant can be expressed through the ratio of useful heat input Q_{useful} to the total heat input Q_{inp}

$$\eta = \frac{Q_{usefull}}{Q_{inp}} \cdot 100\% \tag{4.3}$$

For a boiler unit, useful heat is the heat used for feed water heating, steam generation and superheating

$$Q_{usefull} = D_c\left(i'' - i_{fw}\right) \tag{4.4}$$

where Dc – boiler unit capacity, kg/h;

i'' - enthalpy of superheated steam, kJ/kg;

i_{fw} - enthalpy of feed water, kJ/kg;

To heat the material without changing its phase state, the useful heat input is calculated by the formula

$$Q_{usefull} = G_m \cdot c_m(t_1 - t_o), \tag{4.5}$$

where G_m is the capacity of heat and mass transfer unit, kg/h;
c_m - heat capacity of the material, kJ/(kg·°C);
t_o, t_1 - initial and final temperatures of the material, ºC.
For gaseous media the useful heat is equal to

$$Q_{usefull} = L \cdot (i_1 - i_o), \tag{4.6}$$

where L - mass flow rate of gaseous medium, kg/h;
i_0, i_1- initial and final enthalpies of the medium, kJ/kg.
The input heat is calculated by the formula

$$\mathrm{Q_{inp}} = B_f \cdot Q_d = B_f\left(Q_l^w + c_f \cdot t_f + \alpha \cdot V_a^o \cdot c_a \cdot t_a\right), \tag{4.7}$$

where B_f - fuel consumption, kg/h;
Q_d – design heat of combustion of fuel, kJ/kg;
Q^w_l – lower heat of combustion of fuel, kJ/kg;
c_f– fuel heat capacity, kJ/(kg·°C);
t_f– fuel temperature, °C;
α – air excess ratio.

The most common method in industry is to estimate the heat energy consumption based on the heat cost per unit of product. The equation then takes the form

$$\frac{Q_1}{G_m} + \frac{Q_2}{G_m} + \cdots + \frac{Q_i}{G_m} = \frac{\acute{Q}_1}{G_m} + \frac{\acute{Q}_2}{G_m} + \cdots + \frac{\acute{Q}_\iota}{G_m}, \tag{4.9}$$

where G_m is the capacity of the heat and mass exchange plant for the output product, kg/h.

The same equation expressed in terms of specific heat consumption per unit of output product

$$q_1 + q_2 + \cdots + q_i = q'_1 + q'_2 + \cdots + q'_i, \frac{kJ}{kg}. \tag{4.9}$$

For drying plants, it is characteristic to estimate the efficiency of their operation by the specific heat consumption related to the hourly flow of evaporated moisture. The equation in this case takes the form

$$\frac{Q_1}{M} + \frac{Q_2}{M} + \cdots + \frac{Q_n}{M} = \frac{\acute{Q}_1}{M} + \frac{\acute{Q}_2}{M} + \cdots + \frac{\acute{Q}_n}{M}, \tag{4.10}$$

where $Q_1, Q_2, \ldots, Q_n$ – heat balance input items, kJ/h

$Q'_1, Q'_2, \ldots, Q'_n$ – consumption items of the heat balance, kJ/h;

M – moisture evaporation rate in the dryer, kg/h.

4.2 Evaluating the efficiency of thermal equipment

For thermal process equipment, the coefficient of performance (COP), which is the ratio of useful heat output to total heat input, can be employed to assess efficiency.

Utilizing the heat balance equation, we can express the efficiency of the thermal equipment as follows: [23]

$$\eta = \frac{Q_{usefull}}{\sum_1^n Q_{incom}} \cdot 100\% == \frac{(Q_1+Q_2+\cdots+Q_n)-(Q'_1+Q'_2+\cdots+Q'_n)}{\sum_1^n Q_{incom}} \cdot 100\%. \quad (4.11)$$

If the thermal design of the plant incorporates heat recovery equipment, efficiency can be enhanced by minimizing heat losses to the environment.

Analyzing the heat balance of the power or thermal plant allows for the development of engineering measures aimed at reducing heat losses and reintroducing a portion of the residual heat energy back into the plant's heat cycle.

These calculations typically result in the determination of fuel efficiency, denoted as ΔB, which is calculated using the following formula:

$$\Delta B = \frac{\Delta Q}{Q_l^w \cdot \eta_i}, \text{ kg/h}, \quad (4.12)$$

where ΔQ – the thermal energy savings due to the introduction of energy saving technologies, kJ/h;

Q^w_l – lower heat of combustion of fuel, kJ/kg;

η_i – the efficiency of thermal energy production.

For fuel energy and heat technology appliances, the efficiency of fuel combustion is represented by the fuel utilization factor under specific conditions. This coefficient is defined as the ratio of the maximum amount of heat utilized to the total heat released during combustion.

$$\eta_{fe} = \frac{Q_l^w + Q_{ph.f} + Q_{ph.a} - Q_{fg}}{Q_l^w + Q_{ph.f} + Q_{ph.a}} \cdot 100\%, \quad (4.13)$$

where Q^w_l – lower heat of combustion of fuel, kJ/kg;

Q_{pha} – physical heat of air, kJ/kg;

Q_{phf} – physical heat of fuel, kJ/kg;

Q_{fg} – heat of flue gases, kJ/kg, calculation see in [24].

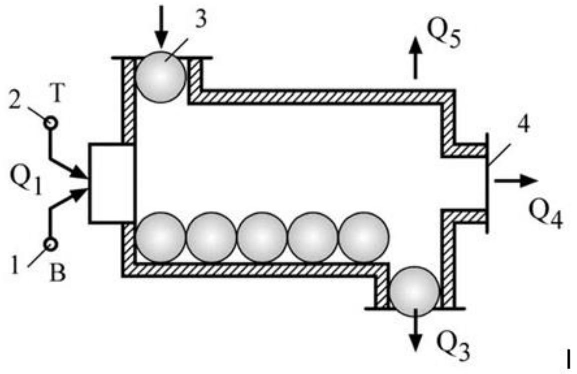
To assess the energy efficiency of industrial plants, specific fuel consumption is often used, which is equal to the ratio of fuel consumption B_f to the capacity of the plant G_p

$$b_f = \frac{B_f}{G_p}.$$

For steam turbine plants, the fuel consumption $B_f$is related to the generated electrical energy N_e

$$b_e = \frac{B_f}{N_e}.$$

Figure 4.1 presents a diagram illustrating the distribution of heat flows for heating workpieces within a heat and mass transfer unit. An example of the unit's operation demonstrates the calculation of heat utilization indicators [23].



1– air supply; 2 – fuel supply; 3 – workpieces; 4 – exhaust gases

Figure 4.1 – Diagram of a heat and mass transfer unit for heating products

The heat balance equation for this unit is as follows

$$Q_1 + Q_2 = Q_3 + Q_4 + Q_5, \text{кJ/h},$$

where Q_1– heat entering the working chamber with fuel;

Q_2– heat entering the working chamber with material;

Q_3– heat losses with material;

Q_4– heat losses with exhaust gases;

Q_5– heat lost to the environment.

Technological efficiency for a given plant is equal to the ratio of the heat used to heat the product to the heat supplied to the plant.

$$\eta_{\text{Т}} = \frac{Q_3 - Q_2}{Q_2 + Q_1} \cdot 100\% \; .$$

The energy efficiency is the ratio of the useful heat of the products of combustion to the total amount of heat supplied to the plant

$$\eta_{\text{э}} = \frac{Q_1 - Q_4}{Q_2 + Q_1} \cdot 100\% \; .$$

Relative flue gas losses are the ratio of flue gas heat losses to total heat input to the plant

$$q_4 = \frac{Q_4}{Q_2 + Q_1} \cdot 100\%.$$

Relative loss with heated material is the ratio of heat loss with heated material to the total heat input to the plant

$$q_3 = \frac{Q_3}{Q_2 + Q_1} \cdot 100\%.$$

Relative heat loss to the environment is the ratio of heat lost to the environment through the plant walls to the total heat entering the plant

$$q_5 = \frac{Q_5}{Q_2 + Q_1} \cdot 100\%.$$

4.3 Saving energy in industrial furnaces

4.3.1 Classification of furnaces

A furnace is a high-temperature heat treatment device in which heat is generated and transferred to the material being heat treated to give it the desired physical, mechanical or chemical properties [23], [25].

Natural gas, solid or liquid fuels, and electricity are utilized to generate high temperatures in the working chamber. Given the extensive use of furnaces across industries, power generation, and residential applications, approximately 60 % of the country's fuel and energy resources are consumed by furnaces. Therefore, the efficient use of fuel is crucial for the nation's economy.

Furnace systems consist of several components, including a working chamber where thermal energy is produced and transferred to the material being processed, as well as burners, nozzles, regenerators, recuperators, fume extractors, fans, and other equipment. Furnaces can be categorized as industrial or domestic and are classified by their purpose, such as melting, heating, roasting, drying, or baking. They can also be distinguished based on the type of heating, with flame and flameless furnaces being the two primary types.

Furnaces are classified according to their technological purpose:

- melting (blast furnace, foundry, glass melting, etc.);
- heating furnaces (thermal, forging, process, etc.);
- kilns (lime kilns, cement kilns, kilns for firing porcelain and clay products),
- furnaces for the chemical industry (for the production of Sulphur dioxide, etc.).

According to structural and thermal characteristics:

- tunnel furnaces;
- chamber and multi-chamber furnaces;
- ring furnaces;
- shaft furnaces;
- rotary drum furnaces, etc.

According to the method of heating the material

- flameless ovens;
- furnaces;
- electric.

According to the type of work:

- continuous action;
- periodic action.

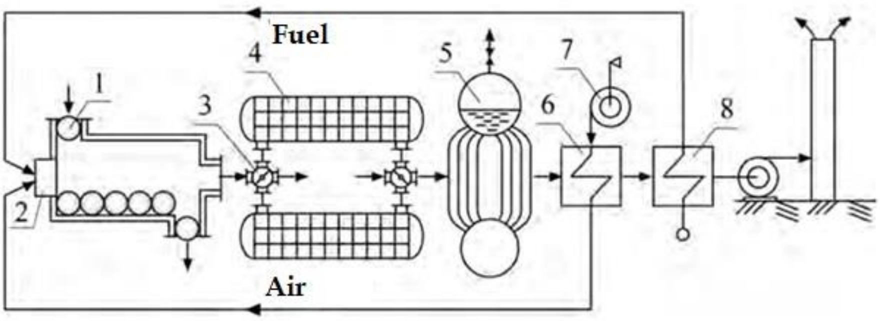
By heat recovery method:

- regenerative furnaces;
- recuperative furnaces.

According to the type of fuel used:

- fuel oil;
- gas;
- for solid fuel.

Figure 4.2 illustrates the diagram of the furnace installation. This setup facilitates energy savings by optimizing heat production within the working chamber and transferring it to the material. It includes components such as regenerators, waste heat boilers, and heat exchangers for heating gaseous fuel and incoming air [23].



1 – heated workpieces in the working chamber; 2 – burner; 3 – flap valve; 4 – regenerative air heater; 5 – heat recovery boiler; 6 – air heater; 7 – fan; 8 – fuel heater.

Figure 4.2 – Energy saving scheme for combustion products:

4.3.2 Blast Furnaces

Blast furnaces are designed to extract iron from ore-bearing materials by melting them in a reducing environment at elevated temperatures.

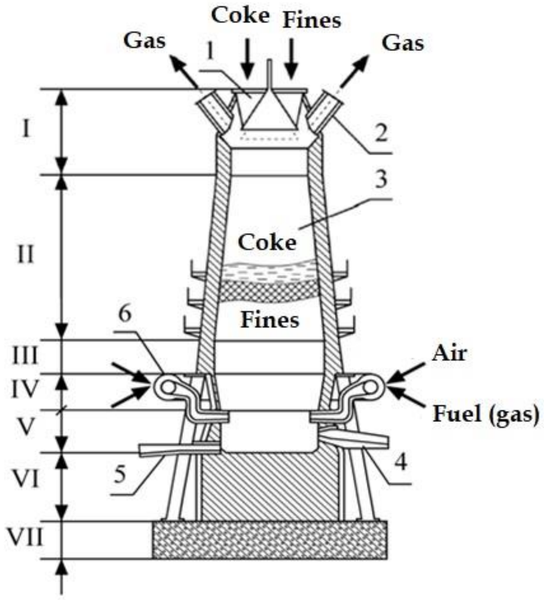
Cast iron is an alloy of iron and carbon, typically containing 2-4 % carbon. If the carbon content is below this range, the alloy is classified as steel, while a content above this level classifies it as cast iron.

A blast furnace serves as a continuous high-temperature thermal processing unit that utilizes various forms of energy, including coke, natural gas, compressed air, high-temperature combustion air, and electricity. The furnace itself is a shaft where the charge, consisting of iron ore sinter, pellets, coke, and fluxes, is introduced. Heated air, along with liquid, gas, or powdered fuel, is injected from below through nozzles (see figure 4.3). [23]

The reduction of iron from oxides in a blast furnace takes place in two ways:

- CO and H_2 gases - indirect reduction;
- solid carbon - direct regeneration.

The indirect redox reaction of iron oxides occurs with a positive heat effect, while the reduction reaction of iron with carbon involves significant heat absorption.



1– charging mouth; 2 – blast furnace gas outlet; 3 – coke and charge layers; 4 – slag tuyere; 5 – iron tuyere; 6 –tuyere; I – neck; II – shaft; III – steam; IV –houlders; V – bell; VI – foundation; VII – base.

Figure 4.3 – Schematic diagram of a blast furnace

At a temperature of 1000 °C, hot carbon also generates carbon dioxide (CO_2) and water vapor (H_2O), resulting in a substantial negative heat effect. To establish a reducing environment within the furnace shaft, the combustion of coke is conducted with a limited supply of air ($\alpha < 1.0$).

Heat balance of a blast furnace

The approximate heat balance of a blast furnace plant is as follows

$$Q_{ch} + Q_{coke} + Q_{ng} + Q_{ph.a} + Q_{ex} = Q_{ci} + Q_{sl} + Q_{env} + Q_{gg} + Q_{fl.g} + Q_{end}.$$

The left side of this equation represents the heat input into the blast furnace (heat extraction), while the right side indicates the amount of heat that is removed from the furnace unit (output components of the heat balance). Figure 4.4 presents a diagram of the blast furnace plant illustrating the heat flows [23].

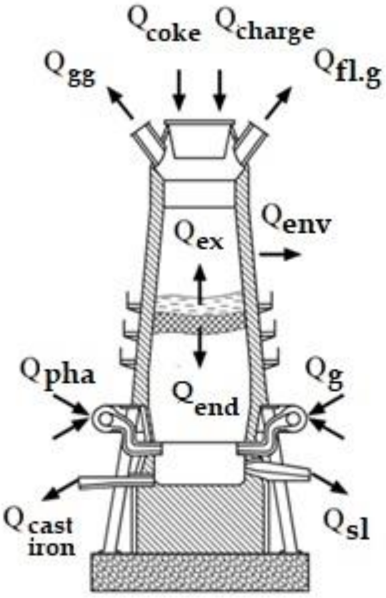


Figure 4.4 - Diagram of blast furnace plant with heat flows

Heat input

Heat introduced into the furnace with the charge

$$Q_{ch} = G_{ch} \cdot c_{ch} \cdot t_{ch}, \text{ kJ/kg} \tag{4.14}$$

where G_{ch} is the mass flow rate of the charge entering the furnace, kg/h;

c_{ch} is the average heat capacity of the composite materials, kJ/(kg·°C);

$$c_{ch} = \frac{m_1 c_1 + m_2 c_2 + \cdots + m_n c_n}{m_1 + m_2 + \cdots + m_n},$$

where m_1, $m_{2,}$ …, m_n – mass flow rates of the components forming the mixture, kg/h;

c_1, $c_{2,}$…,c_n – heat capacities of the respective components, kJ/(kg·°C)..

Heat released in the blast furnace shaft during coke combustion

$$Q_{coke} = Q^{coke} \cdot B_{coke}, \tag{4.15}$$

where B_{coke} - coke mass flow rate, kg/h;

$Q^{(coke)}$is the heat of coke combustion, kJ/kg.

The balance tests show that most of the heat is released during coke combustion in the blast furnace shaft (62%).

Heat entering the furnace with heated air for coke combustion

$$Q_{ph.a}^{coke} = \alpha \cdot V_a^o \cdot \rho_a \cdot t_a \cdot B_{coke} \cdot c_p,$$

where α – air excess ratio, α = 0.5-0.6;

V_a^o– theoretical air flow rate for coke combustion, m^3/kg;

c_p – heat capacity of air, kJ/(kg·°C);

ρ_a – air density, kg/m^3, ρ_a =1.293-273/(273+ t_a);

t_a – temperature of blowing air, t_a = 1100÷1200 °C.

Heat brought into the kiln by physical heat and released during the combustion of natural gas

$$Q_g = B_g \cdot \left(Q_g^w + c_g t_g\right),$$

where B_g– the gaseous fuel consumption, kg/h;

$Q^w{}_g$– the lower heat of combustion of the gaseous fuel, kJ/kg;

c_g– the heat capacity of the gas fuel, kJ/(kg·°C);

t_g– the gas fuel temperature, t_t = 1100-1200 °C.

With sufficient accuracy it is possible to accept $Q^w{}_g$ = (0.10-0.12) Q_{coke}.

Heat released by chemical reactions with positive thermal effect

$$Q_{ex} = G_{ch} \cdot q_{ex},$$

where q_{ex} - specific heat released by exothermic reactions, kJ/kg.

Heat output

Heat removed from the furnace with the molten iron (5.7%)

$$Q_{\mathrm{ci}} = G_{ci} \cdot c_{ci} \cdot t_{ci},$$

where G_{ci}– the average hourly productivity of the blast furnace, kg/h;

c_{ci}– heat capacity of liquid cast iron, kJ/(kg·°C);

t_{ci}– temperature of molten cast iron, t_{pi} = 1450-1520 °C.

Heat removed from the furnace by the liquid slag (3.0 % of the total)

$$Q_{sl} = G_{sl} \cdot c_{sl} \cdot t_{sl},$$

where G_{sl}– average hourly slag output from the melting chamber, kg/h;

c_{sl}– heat capacity of solid slag, c_{sl} = 0.18 kJ/(kg·°C);

t_{sl}– temperature of liquid slag, t_{sl}= 1450-1520 °C.

Heat loss to the environment, including when cooling the furnace with water or air

$$Q_{env} = \sum_{i=1}^{n} k_i \cdot F_i \cdot \Delta t_i + G_a c_a (t_{a1} - t_{a2}),$$

where k_i – heat transfer coefficient, kJ/(m^2·°C·h);

G_a, c_a – flow rate and heat capacity of the cooled agent, kg/h;

t_{a2} , t_{a1} – final and initial temperatures of the cooled agent, °C.

It is recommended to calculate heat losses to the environment in distinct sections, as both the temperature and thickness of the lining (heat exchange surface) vary with height.

For the sake of approximate calculations, it is estimated that heat losses to the environment account for 8-10 % of the heat generated from coke combustion.

$$Q_{env} = (0.08 \div 0.10) Q_{coke}.$$

The majority of heat loss from the blast furnace occurs through the grate gas, accounting for 42.4 %. This loss encompasses the total heat effects resulting from the combustion of carbon monoxide, hydrogen, and hydrocarbons (which indicates incomplete combustion), as well as the thermal energy of the combustion products.

Chemical heat carried away with the grate gas

$$Q_{gg} = B_{coke} \left[1 + \frac{(0.1-0.12) Q_l^{coke}}{Q_l^g}\right] \times \left(q_{CO} V_{CO} + q_{H_2} V_{H_2} + q_{C_m H_n} V_{C_m H_n}\right),$$

where B_{coke}– hourly coke consumption, kg/h;

q_{CO} – heat of combustion of carbon monoxide, q_{CO} = 127.6 kJ/m^3;

V_{CO} – volume of CO formed during combustion of stoker gas, m^3;

q_{H2} – heat effect of hydrogen combustion, q_{H2} = 107.7 kJ/m^3;

V_{H2} – volume of H_2 formed during combustion of flue gas, m^3;

q_{CmHn} – heat effect of hydrocarbon combustion, q_{CmHn} = 107.7 kJ/m^3;

V_{CmHn} – volume of C_mH_n formed during combustion of colostrum gas, m^3;

Q_l^{coke} – the lowest heat of coke combustion, kJ/kg;

Q_l^g –the lower heat of combustion of gaseous fuel, kJ/kg.

The use of gaseous fuel in blast furnaces in this formula is represented by the second summand.

The approximate composition of the furnace gas, in %, is as follows $V_{CO2} = 10.5$; $V_{CO} = 28$; $V_{H2} = 2.7$; $V_{CH4} = 0.3$; $V_{N2} = 58.5$.Calorific value of the dry grate gas $Q_d = 3972$ kJ/m^3.

Physical heat of flue gas leaving the blast furnace

$$Q_{fl.g} = \left\{B_{coke}\left[V_g^{o(coke)} + (1-\alpha)V_a^{o(coke)}\right] + B_g\left[V_g^{o(g)} + (1-\alpha)V_a^{o(g)}\right]\right\} \times c_{fl.g} t_{fl.g},$$

where B_{coke}– hourly coke consumption, kg/h;

B_g– gaseous fuel consumption, kg/h;

$V_g^{o(coke)}$– theoretical volume of combustion products during coke combustion, m^3/kg;

$V_a^{o(coke)}$– theoretical air consumption required for coke combustion, m^3/kg;

α – excess air coefficient;

$V_g^{o(g)}$– theoretical volume of combustion products of gaseous fuel, m^3/kg;

$V_a^{o(g)}$ – theoretical air flow rate required to burn gaseous fuel,m^3/kg;

$c_{fl.g}$– blast furnace gas heat capacity, kJ/(kg·°C).

Heat used for endothermic reactions

$$Q_{end} = \sum_{1}^{n}\left(G_{ore} q_{end} + G_g q_g\right),$$

where G_{ore} - ore mass flow rate, kg/h;

q_{end} - specific heat of endothermic reaction, kJ/kg

G_{cp} - mass flow of combustion products, kg/h;

q_g- specific heat of endothermic reactions of gaseous substances, kJ/kg.

Next, the established conditions for the input and output elements should be incorporated into the heat balance equation (4.14). The parameter of interest must then be determined, which is often either the output of the blast furnace unit or the fuel consumption required for a specific output. The relative cost of the fuel necessary to produce one ton of cast iron is then calculated. This calculated data is compared with actual data, discrepancies are analyzed, and strategies are developed to reduce heat and fuel consumption.

Additionally, the efficiency of the blast furnace is assessed, defined as the ratio of useful heat to waste heat. The useful heat in the blast furnace comprises the heat used for heating and melting the charge.

4.4 Material balance of heat engineering plants

The material balance is the equilibrium of the masses of materials entering and leaving the plant. It is used to determine the consumption of raw materials (primary materials), fuels and the yield of the finished product [26].

General material balance formula

$$\sum M_{inp} = \sum M_{out}.$$

For example, the material balance can be written in the following form for a technological process carried out by chemical transformations:

$$M_{tr} + M_f + M_a = M_{tp} + M_{tw} + M_{pg} + M_{cp,}$$

where M_{tr} - mass of technological raw materials (charge);
M_f- mass of fuel;
M_a - mass of air;
M_{tp} - mass of technological product;
M_{tw} - mass of technological waste (slag);
M_{pg} - mass of process gases (gaseous products of chemical transformations);
M_{cp} - mass of fuel combustion products.

Process waste consists of slag, scale, and leachates, while waste gases include process gases and products of fuel combustion.

For batch operations, the material balance is calculated per unit of production, whereas for continuous processes, it is determined per unit of time (such as hours or seconds).

5 Use of high-temperature thermal secondary energy resources

5.1 Sources of high and medium temperature thermal waste

The main carriers and aggregate sources of high and medium temperature secondary energy resources in industrial enterprises:

- boiler plants;
- technological heating devices, furnaces;
- radiant heat losses on heated surfaces of equipment;
- radiant heat wastes from heated products;
- residues of fuel combustion before release into the atmosphere;
- exhaust gases from compressors, gas turbines, piston engines [28].

Below are several examples of secondary heat energy sources and their applications:

1. Heat from flue gases: The potential and effectiveness of utilizing this heat depend on the gas temperature, with its usefulness increasing as the temperature rises.
2. Heat contained in released steam: The feasibility of harnessing this heat depends not only on the steam parameters but also on the ability to utilize the latent heat of vaporization during condensation.
3. Heat from heated process water: This heat can be applied to produce cold in situations where temperatures are sufficiently high (medium and high potential heat).
4. Heat from products exiting the technological unit: The potential for utilizing this heat type relies on its temperature and the cooling limits dictated by the requirements of the technological process.

5.1.1 Sources of high temperature secondary energy resources in metallurgy and engineering.

Heat waste of metallurgical enterprises has the greatest potential.

Sources of high-temperature secondary energy resources in metallurgy

- hot gases from industrial furnaces (temperature = 1000 °C);
- heat of combustion products of martensitic furnaces (12.5 GJ/t of steel) and heating furnaces (0.8 GJ/t of rolled steel);
- heat of materials (t > 1000 °C) (molten metal, coke and slag from industrial furnaces (1 GJ/t liquid cast iron; 1.2 GJ/t liquid steel; 0.8 GJ/t liquid slag; 12 GJ/t coke; 0.6) GJ/t agglomerate);
- hot gases from combustion engines (g = 600 °C) [21].

Waste heat from engineering activities: (a) waste gases; (b) heating and thermal furnaces and domes; (c) waste from forges and presses.

5.1.2 Sources of high-temperature secondary energy resources in the oil refining and petrochemical industries

The reserves of thermal secondary energy resources in the petrochemical, oil refining, and gas industries are substantial. For instance, the flue gas temperature in pyrite burning furnaces ranges from approximately 650 to 900 °C, while in process gas generators it ranges from 250 to 1100 °C, and in tube furnaces used for oil and fuel oil processing, it falls between 400 and 600 °C. Typically, these gases are directed to waste heat boilers for the generation of process and power steam [21].

The thermal secondary energy resources in the oil refining and petrochemical sectors are primarily determined by the enthalpy of the gases emitted from various pieces of equipment. The total production of thermal secondary energy resources in the industry amounts to millions of tons of equivalent fuel annually, with their current utilization rate around 50%.

5.1.3 Sources of high temperature secondary energy in the chemical industry

In the chemical industry, the most energy-intensive processes include the production of ammonia, chemical fibers, synthetic resins, soda, phosphorus, and methanol, collectively accounting for over 70 % of the electricity consumption and more than half of the heat used across the entire sector. The production of thermal secondary energy resources in the overall industry is significant, exceeding 1 million cubic meters per year.

These thermal secondary energy resources primarily meet the heating requirements of specific industries. For instance, renewable energy sources supply over 26 % of the heat demand in the nitrogen sector and more than 11 % in the soda industry.

However, the industrial utilization of these secondary energy resources does not yet meet contemporary standards. In the most energy-intensive sectors, the current utilization rate is approximately 37 %. This relatively low level of usage can be attributed to technological facilities not being fully equipped with existing recycling technologies. In some instances, effective use is hindered by the absence of the necessary technical resources. Overall, the adoption of secondary energy resources in the chemical and petrochemical industries is satisfactory, with utilization exceeding 80 %.

5.1.4 Sources of high-temperature secondary energy resources in the construction materials industry

In the building materials industry, heat gas secondary energy resources are generated in the following cases

- combustion of cement clinker, lime, ceramic products;
- production of glass, bricks, refractories, thermal insulation, reinforced concrete and other products.

Heat losses can reach 40-50 %.

The building materials industry is characterized by the following units - sources of secondary energy resources

- rotary kilns for cement and lime;
- glass melting furnaces;
- expanded clay kilns;
- furnaces for firing ceramic products;
- autoclaves;
- steam chambers for reinforced concrete products,
- steam and hot water boilers;
- compressors.

Overall, the secondary energy resources in this industry are estimated to amount to several million tons of standard fuel. The most effective sources of secondary energy in the building materials sector include exhaust gases from cement clinker furnaces, which operate at temperatures between 1000 and 1100 °C.

Typically, a significant portion of secondary energy resources is generated during specific technological processes such as clinker burning and glass melting, resulting in outputs like exhaust gases, thermal radiation, and contaminated condensate from exhaust steam. In most instances, these secondary energy resources encompass both high and medium potential.

Within the building materials sector, the production of cement, lime, and glass is the most energy-intensive, with energy consumption exceeding 1 million cubic meters, accounting for approximately 70 % of the total energy used in the building industry.

5.1.5 Sources of Heat Secondary Energy Resources in the Food Industry

Companies in the food industry are significant consumers of fuel and energy resources, making the issue of conserving heat and electricity particularly pressing. The most energy-intensive sectors within this industry include sugar production, oil and ghee extraction, alcohol manufacturing, and vegetable drying, among others.

The heat secondary energy resources generated by food industry enterprises can be categorized into the following groups:

- heat from waste gases and liquids (i.e. heat from the flue gases of boilers and ovens, heat contained in water, waste from distilleries, etc.);
- waste steam heat from steam power plants and secondary steam from heat-using units (evaporators, rectifiers, dryers, self-evaporating steam);
- heat contained in products and production wastes (this group includes heat from boiler slag, hot pulp from sugar factories, hot bread, sugar, etc.; this group may also include heated air released from hot shops).

Sugar production is highly energy-intensive, with the primary components of secondary energy resources including steam heat from vacuum equipment, self-evaporating steam (from boiler deaerators, saturators, and sulphitators), condensate collectors, process solutions, boiler exhaust gases, condensates, barometric water, blowdown water, pulp press water, pulp heat, and heated air from industrial facilities.

In alcohol production, secondary heat sources include thermal energy from the curd column, secondary curd, by-products (such as alcohol, fusel oil, yeast, and the ether aldehyde fraction), condenser heat, wastewater, secondary steam, and heat from yeast dryers, as well as lye water, cooling water in condensers and refrigerators, heated air from industrial spaces, and residual gases in the boiler, along with blowdown water. Distilleries that are equipped with secondary gas evaporators benefit from additional sources of steam heat, condensate in the evaporators, and barometric water in the condenser.

In brewing operations, secondary energy resources consist of waste steam heat from mash tuns, as well as heat from condensers, cooling water, dryers, and boiler exhaust.

For the bakery, confectionery, and starch industries, secondary energy resources include heat from condensates, secondary steam from vacuum equipment and coils, barometric water, secondary steam from evaporation units, industrial products, and exhaust gases from ovens, dryers, and boilers.

Finally, in the oil and gas extraction industries, secondary heat energy resources are derived from the heat of condensates and cooling water, by-products, heat from waste incineration, and heat from the exhaust gases of dryers and boilers.

In the canning industry, secondary heat energy resources comprise heat derived from secondary steam generated by evaporation units and vacuum equipment, as well as barometric and cooling water, condensate, semi-finished and finished products, and heat from exhaust gases produced by dryers and boilers.

5.2 Methods of heat utilization in industry

5.2.1 General principle of secondary thermal energy use

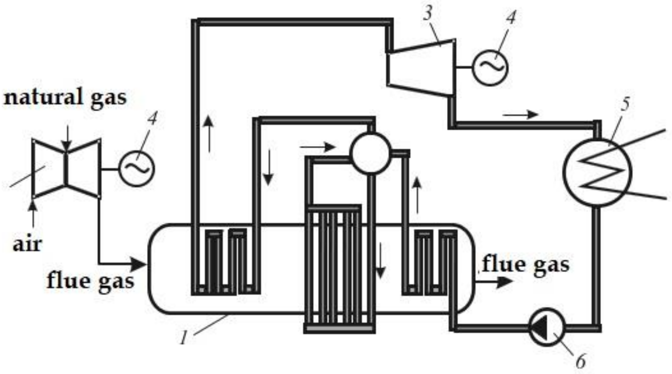
5.2.1.1 Use of flue gas heat

Two types of flue gas installations can be distinguished:

- energy (gas turbine plant)
- technological (thermal furnaces, calcination, etc.).

An important characteristic of flue gases is the presence of polydisperse particles, which can lead to contamination of the surfaces of heat utilizers.

Flue gases from natural gas-fired gas turbines (figure 5.1) do not contain liquid and solid impurities [29].



1 – HRSG; 2 – gas turbine unit; 3 – steam turbine; 4 – generator; 5 – condenser; 6 – circulation pump.

Figure 5.1 – Combined cycle with HRSG

For the use of thermal energy from flue gases

- boilers with a temperature higher than 450 ºC and a flue gas flow rate higher than 5000 m^3/h;
- heat exchangers.

5.2.1.2 Chemical heat recovery from waste gases

Typically, in high-temperature thermal plants operating at temperatures between 800 and 1100 ºC, the heat from flue gases is initially utilized for the regenerative heating of the combustion air, while the remaining heat is directed to other heat recovery devices. A significant drawback of the method that recovers heat from spent flue gases by heating the blast air is the challenge of achieving deep heat regeneration. Although raising the air temperature above the optimal level can yield positive energy benefits, the low heat transfer coefficients and pressure conditions significantly diminish the economic viability of this approach. Furthermore, pre-heating fuel before combustion has not seen widespread application in the industry due to the soot generated by methane cracking reactions when hydrocarbon fuels are heated, which can accumulate on heat exchanger surfaces.

One potential solution to enhance heat recovery efficiency after high-temperature thermal plants is the implementation of thermochemical heat recovery systems that utilize flue gases.

The core concept of thermochemical heat regeneration from spent flue gases involves utilizing their physical heat for the preliminary endothermic treatment of primary fuel. This process allows the primary fuel to acquire additional chemically bound heat and reach a higher temperature. The increased chemically bound and physical heat, along with the heat from the preheated combustion air, is then transferred to the furnace's working chamber. This not only raises the temperature of the process but also reduces the specific fuel consumption.

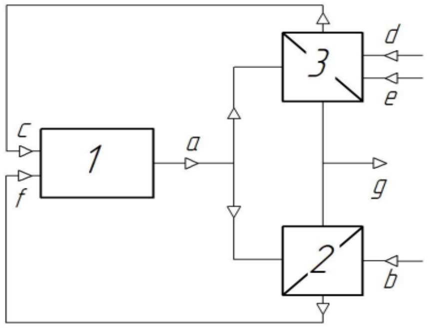
One approach to thermochemical regeneration is the steam reforming of methane. The steam reforming mechanism consists of a series of reactions that absorb and release heat. Based on chemical kinetic studies, the following reactions are anticipated to take place:

$$\mathrm{CH4 + H2O \leftrightarrow CO + 3H2} - 206{,}1\ \mathrm{kJ/mol};$$

$$\mathrm{CH4 + 2H2O \leftrightarrow CO2 + 4H2} - 165{,}1\ \mathrm{kJ/mol},$$

$$\mathrm{CO + H2O \leftrightarrow CO2 + 3H2} + 41{,}2\ \mathrm{kJ/mol}.$$

The scheme shown in figure 5.2 is one of the options for using thermochemical heat recovery of flue gas heat after a high-temperature unit [30].



1 – high temperature unit; 2 – recuperative air heater; 3 – steam conversion reactor; a – flue gas exhaust; b – cold air; c – converter gas; d – steam; e – fuel; f – hot air; g – flue gas exhaust.

Figure 5.2 – Schematic diagram of a high temperature unit with thermochemical recovery of flue gas heat by steam conversion of methane.

After the unit 1, the flue gases (a) are divided into two streams. The first stream is directed to the regenerative air heater 2, where the cold air (b) is heated to hot air temperature (f). The second stream is fed to a steam conversion reactor 3, where methane (e) is oxidized with steam (d) to produce a converted gas (c).

5.2.2 Methods of heat recovery in metallurgy

5.2.2.1 Use of secondary heat energy resources from blast furnace production. The approximate heat balance of blast furnace production is as follows (table 5.1).

Table 5.1 – Heat balance of blast furnace [3]

Heat input	Heat consumption
Heat of coke (Q_c ~ 73%)	Heat used for technology: heating, melting, recovery, etc. (Q_{tech} ~ 30%)
Heat of coke substitutes: natural gas, coal dust, fuel oil, etc. (Q_{ks}~ 12%)	Heat of liquid pig iron (Q_{pi} ~ 6%)
Heat of high temperature air blast (Q_{ab} ~ 13%)	Heat of liquid slag (Q_{sl}~ 5%)
Heat of exothermic reactions, e.g. slag formation reactions (Q_{ex}~ 2%)	Chemical energy of the blast furnace gas (Q_{fg}~ 44%)
	Physical heat of blast furnace gas (Q_{fgph}~ 4%)
	Heat of cooling of furnace structural elements (Q_{cool}~ 4%)
	Other heat consumption and losses (Q_{los}~ 7%)
100 %	100 %

In terms of heat balance consumption, the blast furnace process serves as a source of secondary heat energy, contributing to 19 % of the total heat consumption. This includes approximately 6 % from liquid iron, 5 % from slag, 4 % from the physical blast furnace gas, and another 4 % from the cooling heat of the blast furnace's structural elements [3].

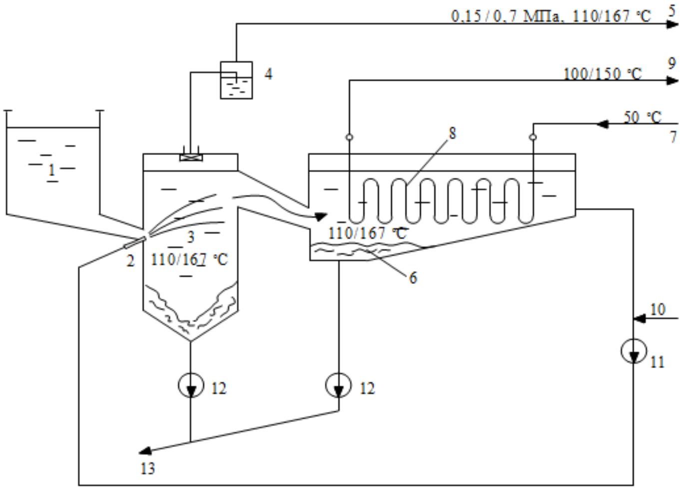
Use of heat of cast iron

The physical heat of cast iron, which has an outlet temperature ranging from 1350 to 1400 °C, is utilized in steel melting by transferring the liquid cast iron into steel melting units such as martens, converters, and electric furnaces. Depending on the conversion rate to commercial pig iron, companies can leverage 50-90 % of the heat from the liquid pig iron in their steelmaking processes.

Use of slag heat

The specific yield of slag ranges from 0.6 to 0.8 tons per ton of cast iron at a blast furnace outlet temperature of 1450-1550 °C, making slag heat a significant source of thermal energy.

The utilization of slag heat is influenced by the granulation method employed, which can either be water or air granulation. Granulated slag is commonly used as a construction material. In the case of water granulation, the heat from the slag is harnessed to produce steam or heated water in thermal systems (see figure 5.2) [3].



1 – slag reservoir; 2 – nozzle for water supply for granulation; 3 – granulator, which also performs the function of contact steam generator and primary settling tank of granulated slag; 4 –barbotage steam cleaning of Sulphur; 5 – steam supply pipe of the heating system; 6 – secondary settling tank of granulated slag, which also performs the function of network heating; 7 – heating network return pipe; 8 – heating network heating surfaces; 9 – heating network feed pipe; 10 – water additive to compensate for evaporation and water losses; 11 – circulating pump; 12 – slag mixture transport bagger pumps; 13 – slag mixture delivery to storage.

Figure 5.2 – Schematic diagram of blast furnace slag heat recovery with water granulation [3]

The liquid slag flows by gravity into the third granulator, where it is sprayed and granulated in a water stream within the second granulator. This granulation process occurs alongside boiling water.

Following desulphurization, the generated steam enters the steam supply pipe of the heating system. The pressure within the granulator is maintained at either 0.15 or 0.7 MPa, resulting in the production of saturated steam at a temperature of 167 °C.

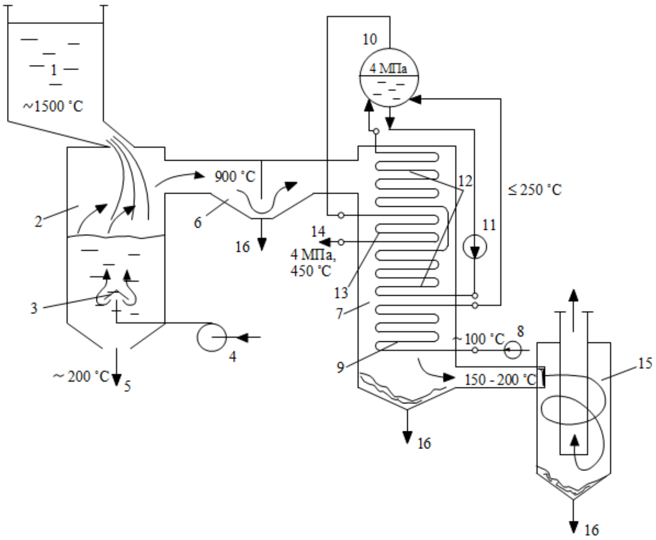
The mains water is then heated in the secondary condenser to temperatures of 110 °C or 150 °C, depending on the temperature of the water received from the primary condenser. This system enables significant fuel savings by reducing the amount of fuel consumed in the boilers during the heating season.

Disadvantages:

- seasonal nature of the use of the heat obtained during the slag heat treatment;

- sulphuric acid corrosion of the installation structures and heating surfaces of the line heater due to the transfer of Sulphur compounds from the slag to the water;
- the need for thorough cleaning of the steam from Sulphur compounds;
- the need for periodic inspection and cleaning of the installation piping from fine slag contamination.

Air granulation uses the heat from the heated air produced by slag granulation to produce steam in a recovery boiler (figure 5.3) [3].



1 – slag accumulator; 2 – air granulator shaft; 3 – air distribution device; 4 – blower; 5 – granulated slag outlet; 6 – dust removal chamber; 7 – heat recovery boiler including positions 8–13; 8 – feed pump; 9 – economizer; 10 – separator drum; 11 – circulation pump; 12 – evaporative heating surfaces; 13 – steam super heater; 14 – superheated steam outlet; 15 – dust removal cyclone; 16 – fine slag removal

Figure 5.3 – Schematic diagram of heat recovery from blast furnace slag by air granulation [3]

Liquid slag descends by gravity into shaft 2 of the air pelletizer, where it is pelletized through a counter-flow of air. The granulated slag at the bottom of the shaft is cooled in layers.

Once it enters the dust settling chamber 6 and proceeds to the recovery boiler 7, the air, heated to 900 °C during the slag granulation process, transfers its heat to the air cooled to 150-200 °C, facilitating steam production in the boiler.

A key advantage of this unit over the previous one is its ability to generate steam energy parameters that can be utilized in a thermal power plant for electricity generation via turbogenerators.

Disadvantages:

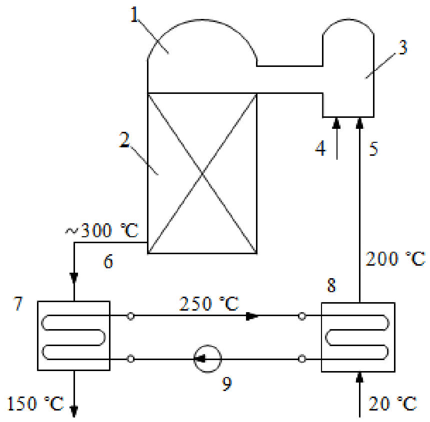
- abrasive wear of installation elements and heating surfaces of the waste heat boiler due to air pollution with slag dust;
- sulphuric acid corrosion of the rear heating surfaces of the waste heat boiler (Sulphur compounds in the slag are partially released into the air during granulation);
- the need for additional air cleaning after the dust settling cyclone.

Use of waste heat from blast furnace heaters

The heat of waste gases from blast furnace heaters with an output temperature of 150 ÷ 350 °C can be used in two ways

- for the water of heating networks in heat supply systems (heat recovery);
- to heat the air used for fuel combustion when heating the nozzle of the air heater (heat recovery).

Using intercooled heat exchangers for air heating is a highly efficient solution. This approach enables a compact arrangement of the heat exchangers, eliminating the need for large enclosures for air intake and exhaust (figure 5.4).



1 – blast furnace air heater; 2 – air heater nozzle; 3 – remote furnace; 4 and 5 – gas and air supply; 6 – exhaust gas outlet; 7 – intermediate coolant heat exchanger; 8 – intermediate coolant cooling heat exchanger; 9 – intermediate coolant circulating pump

Figure 5.4 – Scheme for the use of heat from the waste gases of blast furnaces [3]

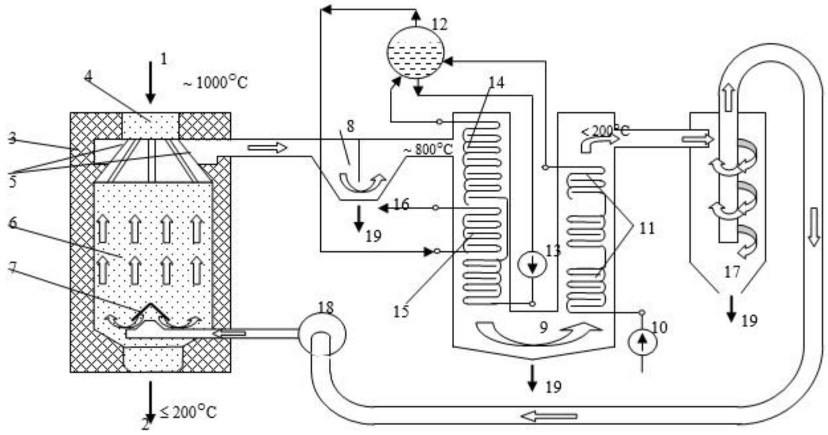
Water, oil, and organic compounds (such as diphenyl, diphenyl oxide, and dutherm) serve as intermediate coolants. Heating air to 200 °C results in fuel savings of 4-5 % in blast furnace heaters. When using blast furnace gas as fuel, it is beneficial to preheat the gas.

5.2.2.2 Use of thermal energy resources from coke production

Use of heat from hot coke

The use of heat from hot coke is associated with coke quenching (cooling) and is possible with dry quenching, which has the following advantages over wet (water) quenching.

- The quality of the coke is significantly improved due to the absence of cracking and coke hydration. In dry quenching, the isothermal effect makes the coke porous and gas permeable, increasing the reactivity of the coke.
- There is no water consumption for coke irrigation and consequently no toxic waste water (water consumption for wet quenching is 4-5 m^3/t coke).
- No toxic fumes are released into the atmosphere.
- Steam energy parameters can be obtained (4 MPa at the rate of 0.4 t/t of coke).The heat from the hot coke is used in dry coke quenching units, see figure 5.5 [30].



1 – red-hot coke feed; 2 – cooled coke outlet; 3 – dry quenching chamber, which includes; 4 – pre-chamber for receiving hot coke; 5 – inclined gas ducts for gas outlet; 6 – dry quenching zone; 7 – gas supply and distribution device; 8 – dust removal chamber; 9 – heat recovery boiler (items 10-16); 10 – feed pump; 11 –economizer; 12 – separator drum; 13 – circulation pump; 14 – evaporator heating surfaces; 15 – steam super heater; 16 – superheated steam outlet; 17 – ash removal cyclone; 18 – cooling gas recirculation exhaust; 19 – coke fines and dust removal

Figure 5.5 – Schematic diagram of dry coke quenching plant [30]

In HRSGs of dry coke quenching plant steam is produced with parameters:$p_n \cong$ 4 МПа и $t_{ПП} \cong 400$ °C.

The steam capacity of the dry coke quenching plant is determined by the following formula

$$D_{DCQP} = \frac{\eta_{HRSG} \cdot Q_{cg}}{\left(i' - i_{fw}\right) \cdot (1 + q) + r}, \tag{5.1}$$

where η_{HRSG}– thermal efficiency of the HRSG;

$i^{/}$ – enthalpy of feed water at saturation temperature according to the pressure in the HRSG drum;

i_{fw}– enthalpy of feed water at the economizer inlet;

q – value (in fractions of one unit);

r– heat of vapour formation according to the pressure in the drum;

Q_{cg}–heat of circulating cooling gas:

$$Q_{cg} = V_{cg} \cdot i_{cg} = V_{cg} \cdot c_{cg} \cdot t_{cg}, \tag{5.2}$$

where Q_{cg} is the flow rate of circulating gas (exhauster capacity);

$i_{cg}, c_{cg,} t_{cg}$–enthalpy, heat capacity and temperature of circulating gas at the inlet to the HRSG;

$$i_{cg} = c_{cg} \cdot t_{cg}. \tag{5.3}$$

Operating problems of dry coke extinguishing system:

- coke fumes;
- the risk of explosion, which is eliminated by adjusting the gas content by adding an inert gas, such as nitrogen;
- abrasive wear of USTK gas pipes and boiler heating surfaces due to gas contamination with coke dust;
- sulphuric acid corrosion of boiler heating surfaces.

Utilization of the physical heat of direct coke gas and fuel gas combustion products

The thermal energy of direct coke gas, with a temperature of approximately 650 ºC, is harnessed by incorporating various heating surfaces along the gas flow path:

- The gas temperature is reduced from 650 ºC to 400 ºC by installing evaporative heating surfaces in the risers.

- In the gas collectors, the gas temperature is further lowered from 400 ºC to 80 ºC through the use of evaporative heating surfaces and water heating packages.
- The temperature is then decreased from 80 ºC to 20 ºC by heating reagents used for gas purification in the primary cooling rooms, such as soda water for gas desulphurization.

Additionally, the combustion products from the fuel gas can be utilized for:

- Heating the air used to ventilate coal cars and to warm coal tower gates during winter.
- Heating the network water in the heating system.
- Preheating the coal charge before it is loaded into the coke ovens. Preheating the coal charge to temperatures between 200-250 ºC can result in fuel savings of 10-15 % and reduce coking time by up to 30 % [3].

5.2.2.3 Utilization of the Thermal DER of Open Hearth Steelmaking

The approximate heat balance of the open hearth furnace in the scrap ore process is shown in table 5.2.

Table 5.2 – Heat balance of the open hearth furnace [3]

Heat input	**Heat consumption**
Heat of liquid iron (Q_i ~ 10 %) Heat of fuel (Q_f ~ 50 %) Heat of heated air (Q_{ha} ~ 25 %) Heat of exothermic reactions of oxidation of pig iron impurities (Q_{ex}~15 %)	Heat of liquid steel (Q_{st}~ 20 %) Heat of slag (Q_{sl}~ 5 %) Heat of endothermic reactions related to steelmaking technology (Q_{end}~ 10 %) Heat of waste gases (Q_{wg}~ 45 %) Heat of the coolant of the furnace structure elements (Q_{cool}~ 10 %) Heat losses (Q_{loss} ~ 10 %)
100 %	100 %

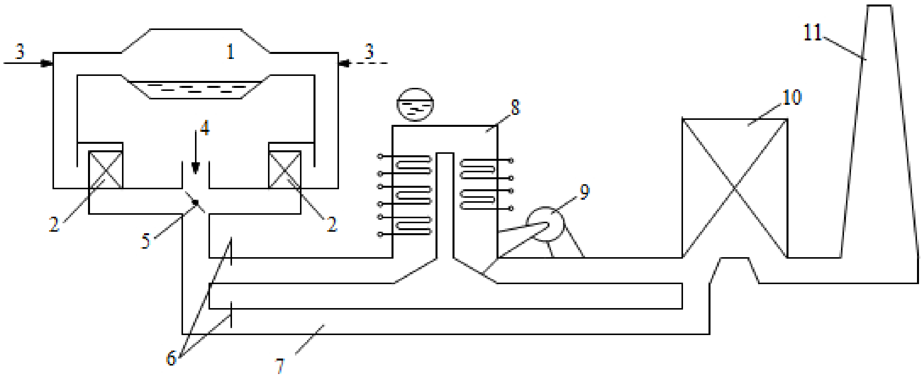
The consumption section of the heat balances indicates that the scrap-ore process is a significant source of thermal energy recovery, contributing approximately 90 % of the heat in this section (including heat from steel, slag, waste gases, and the coolers of furnace structural elements).

After the melting and finishing processes, the waste gases are utilized to heat the charge. Any heat deficit during the heating and melting of the charge is compensated by additional fuel combustion using a gas-oxygen tuyere.

Use of flue gas heat

The heat from flue gases produced by Martin stoves is frequently employed to heat air in regenerators. The temperature of the exhaust gases after passing through the regenerators ranges from 500 to 900 °C. This heat is then utilized in waste heat boilers (as shown in figure 5.6) [31].

Water-tube convective recovery boilers are set up behind open-hearth furnaces. The steam generated has the following parameters: pressure of up to 4.5 MPa and a temperature of superheated steam not exceeding 450 °C. The specific steam capacity is approximately 0.4 tons of steam per ton of steel produced.



1 – open-hearth furnace; 2 – regenerators; 3 – fuel supply; 4 – air supply; 5 – flap valve; 6 – baffles; 7 – bypass gas duct; 8 – heat recovery boiler; 9 – smoke pump; 10 – gas cleaning; 11 – flue pipe

Figure 5.6 – Scheme of the placement of the HRSG on the exhaust gas duct of an open hearth furnace

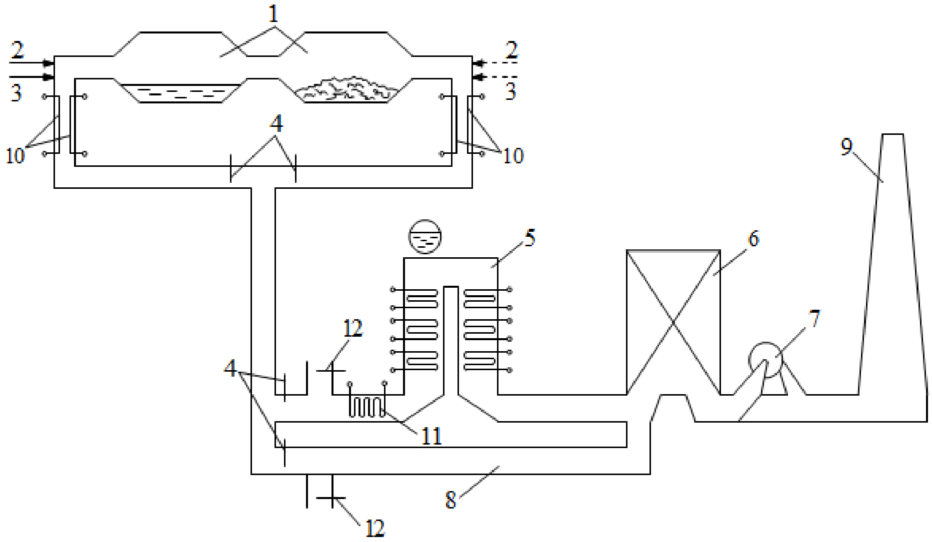
The installation of waste heat recovery boilers behind open-hearth furnaces lowers the temperature of waste gases to between 150 and 200 °C. This allows for the implementation of a smoke evacuator, facilitates forced draught, and enhances the productivity of the furnace.

Utilizing waste gases from electric arc steel furnaces with serial heat recovery steam generators (HRSGs) presents several challenges:

1. Reducing Waste Gas Temperature: The waste gas temperature behind arc steelmaking furnaces ranges from 1400 to 1500 °C, making the direct use of standard water-tube HRSGs unfeasible.

2. CO Afterburning: The concentration of carbon monoxide (CO) in the waste gases from arc steelmaking furnaces is significantly higher than that in the waste gases from open-hearth furnaces due to more intensive oxygen purging.

A possible solution to these issues is depicted in the schematic arrangement of HRSG placement behind the arc steelmaking furnaces. (figure 5.7).



1 – steelmaking baths; 2 and 3 – fuel and air supply; 4 – furnace channels and gas ducts; 5 – HRSG; 6 – gas cleaning; 7 – smoke pump; 8 – bypass gas duct; 9 – chimney; 10 – radiating heating surfaces made in the form of screens of vertical gas ducts of arc steelmaking furnaces; 11 – pre-injected evaporating heating surfaces; 12 – valve for air supply for the purpose of CO afterburning.

Figure 5.7 – Scheme of HRSG placement on the gas exhaust duct of arc steelmaking furnaces

Flue gas cooling is accomplished by installing radiation shields in the vertical gas ducts of electric arc furnaces, along with a pre-cooled section of evaporative heating surfaces. Carbon monoxide (CO) post-combustion is facilitated by drawing in air through valve 12.

5.2.3 Methods of processing high temperature ferrous metals in the building materials industry

The majority of secondary energy resources in this sector are utilized for preheating the primary raw material mix in the dry clinker production process. Heating can be achieved through several methods, including: a) decarbonizing the batch by 30-40 % to temperatures of 800-850 °C in a cyclone heat exchanger using flue gases; and b) utilizing conveyor machines such as Lepol furnaces.

By eliminating endothermic decarbonization processes, which account for up to 60 % of the heat required for clinker production, there can be a significant reduction in fuel consumption, decreasing from 5200-6700 kJ/kg (wet method) to 3000-4200 kJ/kg of clinker. Additionally, this improvement results in a doubling of kiln productivity, allowing for the implementation of shorter units.

Another significant source of renewable energy in building materials production is the gases generated from lime kilns. These gases primarily consist of combustion products from fuel and byproducts from the decomposition of limestone. When rotary kilns are employed, their productivity reaches 2500-3000 m^3/t at temperatures ranging from 750 to 800 °C.

To reduce fuel consumption and effectively utilize the heat from flue gases, burners (such as shaft, staged, or cyclone burners) are installed behind the rotary kilns, where the material lumps are sent for combustion. The material is then transferred to the kiln at temperatures ranging from 500 to 700 °C before being moved to the drum cooler. This configuration decreases the heat consumption for burning from 5900-7300 kJ/kg to 4600-5000 kJ/kg of lime.

Lime produced using another advanced incineration method, such as a fluidized bed furnace, is transferred to a cooler where it is chilled using air before being stored. The heated air from the cooler is directed to the gas burner. Additionally, it is well-known that the heat from the exhaust gases of clay kilns is utilized for heating and ventilating industrial facilities. This installation also enhances working conditions for employees in the clay storage and transport tunnels.

5.2.4 Use of flue gas heat in the production boiler

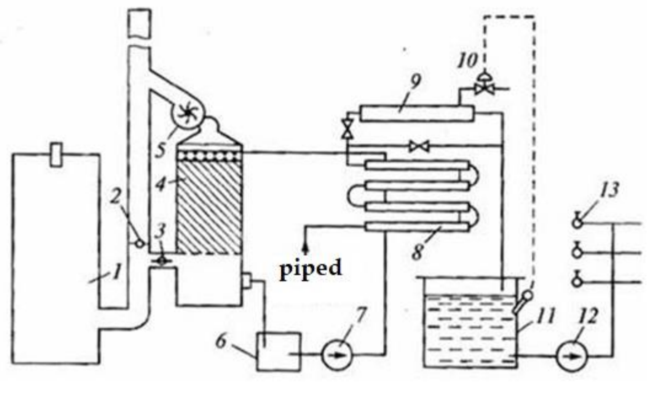
Example

One of the workshops is heated by a boiler room featuring three MZK-7 steam boilers, each with a capacity of 1 ton per hour. These boilers are equipped with burners designed for low-pressure natural gas, with fuel oil as a backup. The boiler design allows for operation under pressure and utilizes individual fans for each unit. The combustion products are discharged through separate metal chimneys with the aid of pressure boosting.

To harness the thermal energy from the flue gases for the boiler's hot water supply and heating needs, a heat recovery unit with a contact economizer has been designed and installed 3 meters above the boiler (see figure 5.8). A Ts13-50 No. 3 exhaust fan (operating at 1440 rpm) is responsible for venting the boiler through the economizer. The boiler can operate both with and without the recovery unit by utilizing control dampers. When the economizer is turned off, damper 3 is closed and damper 2 is open. Conversely, when the economizer is activated, damper 2 closes, damper 3 opens, and exhaust fan 5 engages, allowing the gases from boiler 1 to flow into the economizer 4.

The system operates as follows: Gases from boiler 1 enter the lower section of economizer 4, where they flow through the nozzle layer before being discharged into the chimney. Heated water from the sprayer is directed by nozzles to the nozzle layer, where it then falls into a trough. From the trough, the water is transported through a transfer pipe to the intermediate tank 6, and subsequently sent to the water/water heat exchanger 8. The cooled water is pumped back to the economizer via circulation pump 7, passing through the sprayer. The cold water in the pipeline is channeled to heat exchanger 8, where it is warmed before being sent to the hot water tank 11. From there, the heated water is pumped through pump 12 to the shower 13.

Tests have indicated that the efficiency of the MZK-7 boilers increases from 82 % to 93 % when using the contact economizer (calculated based on the higher heating value of the fuel combustion). However, a significant drawback of the installation was noted: during operation, very low velocities of the heated water in the pipes (ranging from 0.05 to 0.09 m/s) were observed, particularly in the space between the pipes, where the speed was even lower (between 0.01 and 0.014 m/s) [32].



1 – boiler; 2, 3 – dampers; 4 – economizer; 5 – fan; 6 – tank; 7 – pump; 8 – heat exchanger; 9 – steam and water boiler; 10 – regulating valve; 11 – hot water tank; 12 – pump; 13 – showers

Figure 5.8 – Heat recovery system with contact economizer

To address this issue, the heat recovery unit is equipped with sectional water-to-water heat exchangers that meet the necessary specifications: a sectional pipe diameter of 57/50 mm, a length of 4 meters, a sectional heating surface area of 0.75 m^2, and a total of 7 sections.

The new system allows for two-stage heating of the tap water within the water-to-water heat exchangers 8 and the steam-to-water boilers 9.

During testing of this upgraded system, it was discovered that water flowing through the water-to-water heat exchangers at a rate of 2.4 m^3/h was heated to temperatures ranging from 44 to 45 °C, and the unit achieved an impressive efficiency of 95 % (based on the higher heating value of the primary fuel combustion). If higher temperatures (between 50 and 60 °C) are needed, the steam-to-water boiler can be utilized for further heating. The steam supplied to the boiler is regulated by control valve 10, which adjusts based on a pulse signal related to the water temperature in the tank.

For industrial showers, a standard water temperature of 37 °C is sufficient, indicating that the water-to-water heat exchangers alone can adequately heat the water. If hotter water is necessary, it can be heated in the steam-to-water boiler following the water-to-water heat exchangers. This approach allows steam to contribute a small portion of the useful heating power when the water is heated to 50 °C.

6 Use of low temperature secondary energy sources

6.1 Main sources of low temperature heat and possibilities for their use

The previously discussed sources of secondary energy resources (SER) were characterized by high temperature levels. However, a considerable number of SERs exist with relatively low temperatures. These include gases from industrial and power plants with temperatures below 300 °C, ventilation emissions (ranging from 15 to 25 °C), waste steam heat, and ambient air. Additionally, there are heat sources from condensed media, such as heated and recycled water (25-40 °C), high-temperature liquids (40-70 °C), and natural bodies of water like reservoirs, rivers, lakes, and seas (with average temperatures of 5-25 °C). Underground water typically has temperatures between 10-15 °C, while soil temperatures range from 5-10 °C, among others [23].The temperature ranges for the use of lower heat are shown in figure 6.1.

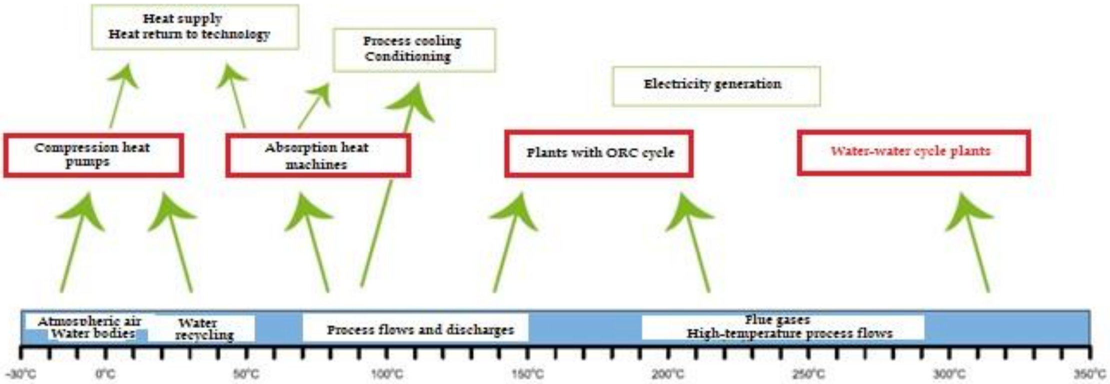


Figure 6.1 –The temperature ranges for the use of lower heat [23]

The main carriers and primary units of low-temperature energy and energy resources in industrial enterprises:

- boiler plants (with exhaust gases, slag and environmental damage);
- technological heating devices;
- convective heat wastes from heated surfaces of equipment;
- convective heat wastes from heated products;
- fuel combustion residues before release into the atmosphere;
- exhaust gases from compressors, gas turbines, piston engines;
- water for cooling systems of technological equipment, air compressors, internal combustion engines

- petrochemical and gas processing enterprises, for example, are characterized by the consumption of flue gases from technological furnaces, waste steam from distillation columns, vacuum systems, heaters and product stream heat.

How can this heat be utilized? The answer depends on your company's specific needs and goals. There are various options available:

1) Utilizing the heat for heating, water pre-treatment, or pre-deaeration for industrial systems.

2) Returning waste heat to the technological cycle for reuse in production processes.

3) Employing inexpensive fuel sources to heat remote facilities.

4) Purchasing electricity from external suppliers to lower costs or to reserve electricity for internal use.

Here are some examples of low-temperature thermal verification energy resource (VER) sources and their potential applications:

1) Heat from Flue Gases: The feasibility and effectiveness of utilizing this heat depend on the gas temperature, which increases its potential use as the temperature rises.

2) Heat Contained in Waste Steam: The applicability of this heat is determined by the steam parameters; additionally, the latent heat of vaporization can be harnessed during condensation.

3) Convective and Radiative Heat Loss: This typically involves low-grade heat lost through the external surfaces of process equipment, which can be repurposed for heating and producing hot water.

4) Heat Energy from Cooling Water: This can be effectively utilized by installing heat exchangers to warm fresh water for various applications.

5) Low-Quality Heat from Heated Process Water: This heat can be converted into usable energy by employing heat pumps.

6) Heat from Products Exiting the Process Plant: The usability of this heat is contingent on temperature and cooling capacity, aligned with process requirements.

7) Heat from Liquid and Gaseous Effluents: For effluents that are highly polluted, the utility of this heat is often low, particularly if specialized alloys are required for heat exchanger surfaces.

Additionally, thermal energy is a by-product generated by the operation of various equipment in energy supply systems and the energy consumption of buildings and structures (e.g., electrical substations, air conditioning systems). This excess heat is often released into the environment, but it can be captured, stored, and utilized for heating and ventilation systems in residential and commercial buildings.

Technical and economic analyses indicate that projects aimed at harnessing by-products from the primary systems for heating purposes in the domestic sector are financially attractive for potential investors. Furthermore, utilizing this waste heat contributes to a reduction in pollutant emissions, such as CO_2 and NO_x.

Benefits of utilizing less heat include:

1) Decreased fuel costs, leading to a reduction in the primary production of heat or electricity.

2) Lower expenses for purchasing water needed for technological processes, as well as for treating and heating water to meet required temperatures.

3) Diminished costs associated with additional water use for circulation purposes, such as evaporation in cooling towers.

4) A reduction in CO_2 and nitrous oxide emissions as a result of decreased fuel consumption. .

6.2 Sources of low temperature secondary energy resources in metallurgy and engineering

6.2.1 Sources of low-temperature secondary energy resources in metallurgy and engineering include:

- Heated chilled water (at 95 °C) and cooling steam generated from industrial furnaces through evaporation (0.1 tons per ton of cast iron and 0.2 tons per ton of martensitic steel).
- Heated cooling water from internal combustion engines (with temperatures below 100 °C).
- Steam or heated water produced from the coolers of structural components within the machinery.
- Contaminated water drainage (with temperatures below 100 °C) [23].

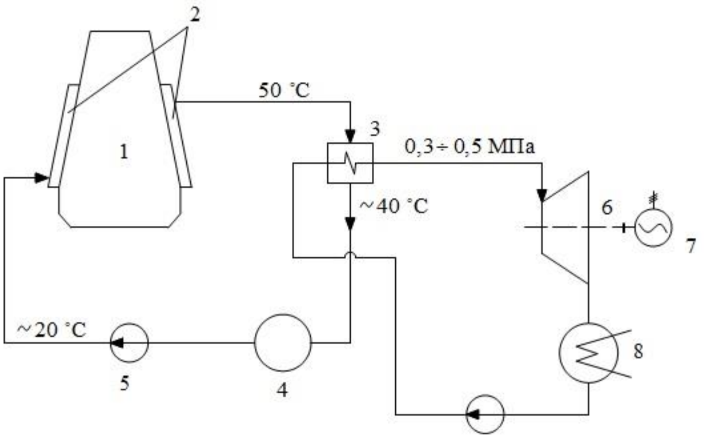
One of the dependable sources of low-grade heat is industrial steam waste, with the majority generated during the operation of forging equipment in manufacturing facilities. It's important to note that the efficiency of these mechanisms is relatively low, and the amount of steam consumed can reach 85-90 % of what is provided to them. The steam typically operates at a pressure of 0.20-0.25 MPa and an enthalpy ranging from 2510 to 2720 kJ/kg.

The preferred approach for utilizing the energy from this released steam is to transfer it directly to the working fluid, be it a heated medium or a turbogenerator. This method allows for at least some of the heat to be supplied to consumers for heating and ventilation, or it can be harnessed to generate electricity via steam turbines.

6.2.2 Use of heat from the cooling of the structural elements of the blast furnace

The utilization of heat from the cooling of structural elements of the blast furnace is influenced by the cooling method employed, whether it be water cooling or evaporative cooling [33].

In the case of water cooling, the heat from water heated to 50-55 °C can be harnessed to generate electricity in steam power plants that use low-boiling liquids, such as Freon, which has a boiling point ranging from 24 to 30 °C (figure 6.2) [3].



1 – blast furnace; 2 – blast furnace shaft coolers; 3 – freon evaporator; 4 – cooling device of the recycling water supply system (cooling tower); 5 – circulation pump of the recycling system; 6 – Freon turbine; 7 – electric generator; 8 – freon condenser; 9 – freon pump

Figure 6.2 – Schematic diagram of the plant for the recovery of water cooling heat from the blast furnace

The installation shown in figure 6.2 contains Freon turbo generators with a power of 2÷10 thousand kW. Freon pressure at the turbine inlet is 0.3÷0.5 MPa.

Advantages of the installation:

- high operational reliability due to low Freon pressure and temperature;
- the possibility of producing electricity directly in the blast furnace shop and using it for the shop's own needs.

Disadvantages:

- low energy efficiency of a steam power plant, its efficiency is determined by the product:

$$\eta_{plant} = \eta_{eva} \cdot \eta_t \cdot \eta_{ir} \cdot \eta_{em},$$

where $\eta_{eva}$is the thermal efficiency of the freon evaporator, $\eta_{eva} = 0.33$;

η_t is the thermal efficiency of the cycle, $\eta_t = 0.30$;

η_{ir} is the internal relative efficiency of the turbine, $\eta_{ir} = 0.85$;

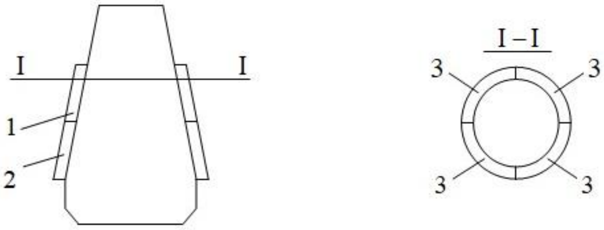
η_{em} is the electromechanical efficiency of the turbogenerator, $\eta_{em} = 0.98$.

$$\eta_{plant} = 0.33 \cdot 0.30 \cdot 0.85 \cdot 0.98 = 0.08 = 8\%;$$

- negative environmental impact of Freon (formation of ozone holes in the atmosphere).

In evaporative cooling, the cooling heat is derived in the form of saturated water vapor. Let's examine the evaporative cooling system used in blast furnace refrigerators, which is responsible for removing the majority of the cooling heat.

To ensure reliable circulation, blast furnace refrigerators are segmented into zones based on height (upper and lower) and further divided into sections around the perimeter (ranging from 2 to 4 sections).

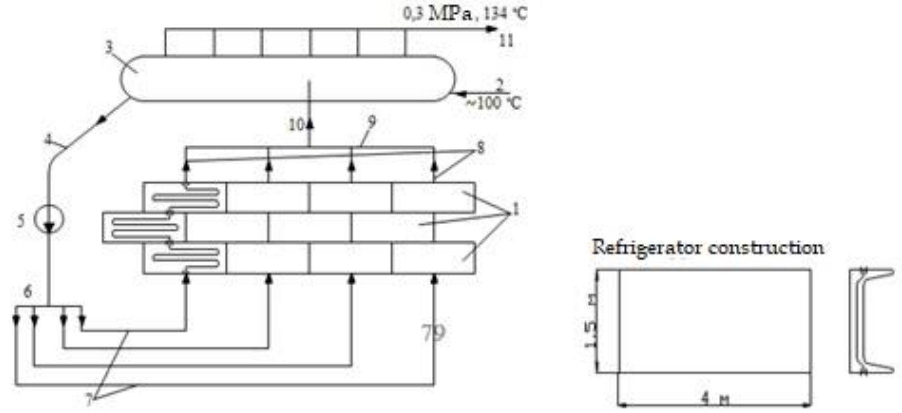


1– upper zone; 2 – lower zone; 3 – sections

Figure 6.3 - Diagram of the refrigerator sections [33]

Each section is equipped with an autonomous evaporative cooling system (figure 6.4).

Blast furnace coolers are constructed from cast iron, featuring heating surface tubes integrated into the casting. When stacked on top of one another, these coolers create an autonomous circuit (see figure 6.1).



1 – blast furnace shaft coolers; 2 – feed water supply; 3 – separator drum; 4 – downpipe; 5 – circulation pump; 6 – downpipe collector; 7 – individual supply pipes; 8 – individual discharge pipes; 9 – lift pipe collector; 10 – lift pipe; 11 – saturated steam outlet

Figure 6.4 – Diagram of the evaporative cooling system of the cooler section of the blast furnace shaft [33]

The low steam pressure, ranging from 0.2 to 0.3 MPa, is a limitation of the evaporative cooling system used in blast furnace coolers, which restricts their application. Additionally, the operation of the evaporative cooling system allows for an evaluation of the uniformity of the thermal regime within the furnace.

6.3 Low-grade heat sources in the manufacture of building products

Many process units, including compressors, rotary kilns, and glass melting furnaces, require artificial cooling based on their operating conditions. This cooling generates low-grade energy resources, such as ventilation emissions and industrial as well as domestic wastewater.

At the Langfurt cement plant in Germany, a Rankine cycle has been implemented to generate electricity by recovering heat from the cooling air of the clinker cooler. In this facility, the air from the clinker cooler, which has a temperature of 275 °C and a volume of 150,000 m^3/h, is cleaned before being directed to the waste heat boiler. Most of the heat is transferred to oil using a conventional tubular heat exchanger. As a result, the air temperature decreases to approximately 125 °C, while the oil is heated to 230 °C before entering the unit where the Rankine cycle takes place.

A notable characteristic of the plant is the circulation of pentane, which has a boiling point of 36.1 °C. In a counterflow configuration with liquid oil, pentane heats up to 162 °C and vaporizes (with a vapor pressure of approximately 19 atm). During the expansion phase, the pentane drives a two-stage turbine that is connected to a standard generator (690 V, 50 Hz). The turbine has a power output of 1.1 MW, and the capital investment for this system is DM 7164. The company anticipates that the Rankine cycle will fulfill up to 12 % of its electricity requirements in the future.

6.4 Characteristics of the use of low-grade heat

6.4.1 Use of Rankine and Kalina cycles

The characteristics of utilizing low-grade heat are linked to its application in power plants that use low-boiling refrigerants, heat pumps, economizers, heat exchangers, and chillers. Units employing low-boiling refrigerants are commonly utilized, typically consisting of organic substances (such as "cold" steam or those used in Rankine cycles).

To illustrate the operating principle of the system, consider Freon as a low-boiling refrigerant. In this scenario, steam with a pressure of no more than 0.12-0.20 MPa is employed in the unit’s heating circuit to heat Freon to temperatures between 70-85 °C, which corresponds to a final steam pressure of 1.4-1.6 MPa. The Freon vapor is then directed to the turbine. In addition to generating electricity, the unit also produces heating steam condensate. Calculations indicate that the cost of electricity generated at such a plant is three times lower than that of a thermal power plant. In Germany, organically cooled steam turbine units are widely used for producing mechanical and electrical energy, with capacities ranging from 50 to 800 kW. In Japan, units capable of producing up to 3000 kW operate using "cold" steam.

The Kalina cycle is also implemented internationally, utilizing a water-ammonia mixture that serves as a low-boiling refrigerant fed to the turbine blades. In Japan, the capacity of a waste-to-energy plant was enhanced by 20 %, reaching 4 MW. Similarly, in California (USA), the adoption of the Kalina cycle led to an increase in electricity production from 3.7 MW to 6.5 MW.

6.4.2 Use of heat pumps

Heat pumps demonstrate high efficiency when utilizing low-quality heat. They are engineered to elevate the temperature of the working fluid from levels that are unsuitable for a particular application to a sufficient level for that purpose. This often involves increasing the vapor pressure of the working fluid to raise the condensation temperature. By raising it above the boiling point of the working fluid at atmospheric pressure, it allows for evaporation (boiling). This process aligns with the second law of thermodynamics, which states that heat flows spontaneously from a hotter body to a cooler one.

In a heat pump, compression energy is therefore employed to elevate the condensation temperature of the working fluid beyond its boiling point at normal pressure, resulting in an energy-efficient process. The working principle of a compression heat pump is illustrated in figure 6.4, representing one of the most common types.

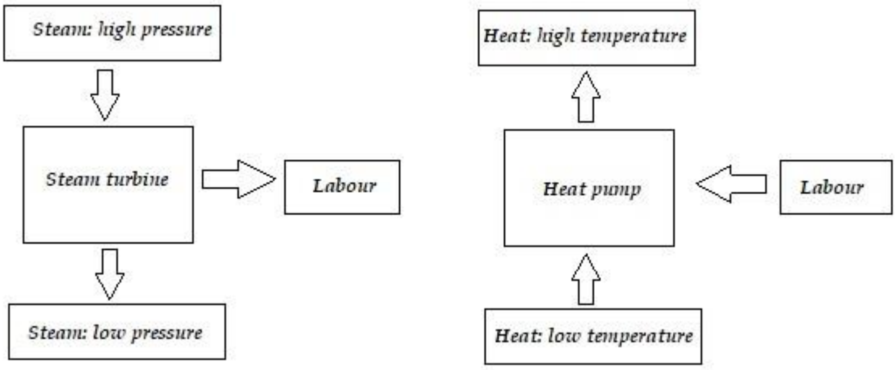


Figure 6.4 – Comparison of the principles of operation of the heat engine cycle and the heat pump cycle

Waste heat energy is transferred to the working fluid within the evaporator, resulting in the boiling and evaporation of the refrigerant. In the compressor, the vapor pressure increases, leading to a corresponding rise in temperature. The working vapor then condenses in the condenser, releasing heat to the surrounding environment.

The primary factor influencing the efficiency of the heat pump is the temperature difference between the evaporation and condensation processes of the working fluid. Through the operation of heat pump units, 1 kW/h of external electrical energy is consumed, which can yield 3-6 kW/h of high-potential thermal energy.

Currently, the four most developed countries – ion fuel units in this manner, resulting in savings of around 220 million tons of fuel equivalent each year.

There are three types of heat pumps:

- compression,
- sorption
- thermoelectric.

An expert evaluation conducted by the International Technical Committee on Heat Pumps indicated that the primary type of system to be adopted is the compression heat pump. In this system (as illustrated in figure 6.5), the compressor takes in low-boiling vapors of a working fluid, such as Freon, from the evaporator and compresses them [34].

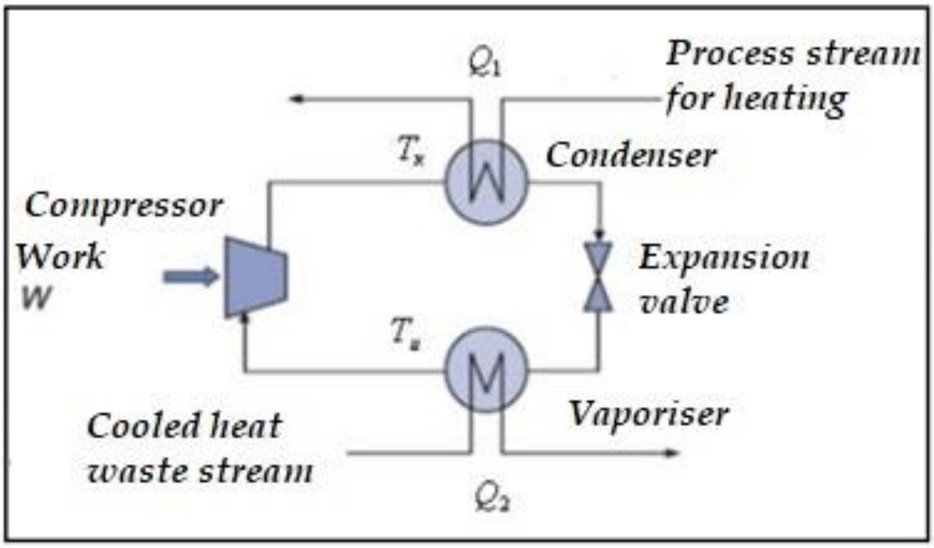


Figure 6.5 – Operating principle of a compression heat pump

The compression process leads to an increase in both temperature and vapor pressure. The compressed vapor then flows into the condenser, where it transfers heat to another refrigerant, such as water, which is subsequently utilized in the hot water supply system. Since the condensation temperature of the compressed gas exceeds the boiling point of the working fluid at ambient pressure, the condensate is routed to the evaporator through the control valve. This cycle enables the continuous operation of the heat pump.

In the figure, Q_2 represents the input energy from thermal waste; T_c is the condensation temperature of the working fluid; Te is the evaporation temperature of the working fluid; W is the work performed by the compressor to compress the working fluid; and Q_1 is the heat produced by the heat pump

$$Q_1=Q_2+W.$$

The efficiency of a heat pump is characterized by its coefficient of performance

$$COP = \frac{Q_1}{W} - 1.$$

Research has demonstrated that the efficiency of heat pumps in batch processes is greater than in continuous processes. Heat pumps can utilize various low-grade heat sources, such as waste air, wastewater from hot water supply systems, and both industrial and domestic water. The recovered heat can then be transferred to either water (in water-to-water heat pumps) or air (in air-to-air heat pumps).

For instance, air-to-air heat pumps are commonly employed in heating and ventilation systems. Additionally, the heat from low-temperature gases is effectively harnessed in economizers. These devices are designed to preheat water (before it enters the boiler of a heating plant) or air (prior to entering the furnace) using the heat generated from the condensation of flue gases that exit the steam boiler and are cooled below the dew point temperature.

To facilitate this process, special designs such as surface and contact economizers are utilized, increasing the degree of flue gas regeneration – particularly for those with high humidity – by 20-40 %.

In air conditioning and ventilation systems, heat recovery from exhaust air can be achieved using various types of heat exchangers, including rotary regenerative coolers and intercoolers. Intercooler heat exchangers primarily consist of heat pipes. As illustrated in the figure, exhaust gases pass over the hot end of the heat pipe, causing a liquid, such as deuterium, to vaporize. The resulting vapor then travels to the cold end of the pipe, where it transfers heat to a heated medium, such as air, causing the vapor to cool and condense. The condensate subsequently enters an annular opening filled with a porous, capillary-structured material, which can include wicks, metal fibers, or other fillers. Capillary pressure forces the condensate back into the heating zone once the mass is saturated. Notably, the operation of the pipe is gravity-independent, allowing it to be installed in any orientation.

Heat pipes come in various shapes and sizes, with internal diameters ranging from a few millimeters to 10-15 cm and lengths of 2-3 meters. For instance, facilities in Japan have been developed to utilize heat from the exhaust gases of blast furnaces to preheat the air entering burners. When the gas temperature reaches 230 °C, the air can be heated up to 180 °C.

Beyond metallurgy, heat pipes find applications across several industries, including energy, engineering, electronics, chemicals, and agriculture. They are particularly sought after in the temperature range of 50-250 °C, where they can operate effectively without the need for expensive materials and coolants.

Example. Use of heat pumps in drying processes

Heat pumps are extensively used for the humidification and drying of various materials, such as wood. In this context, warm, humid air from the dryer serves as the heat source for a closed-loop heat pump, which transfers this heat to incoming fresh air.

The drying of wood occurs within an enclosed environment, where heated air is circulated through the wood material. In steam-heated kilns, fresh air is warmed by steam before being introduced into the dryer. This hot air evaporates the moisture from the wood and releases it into the atmosphere. Figure 6.6 illustrates the operation of a closed-cycle mechanical (compression) heat pump utilized for drying wood materials. [27].

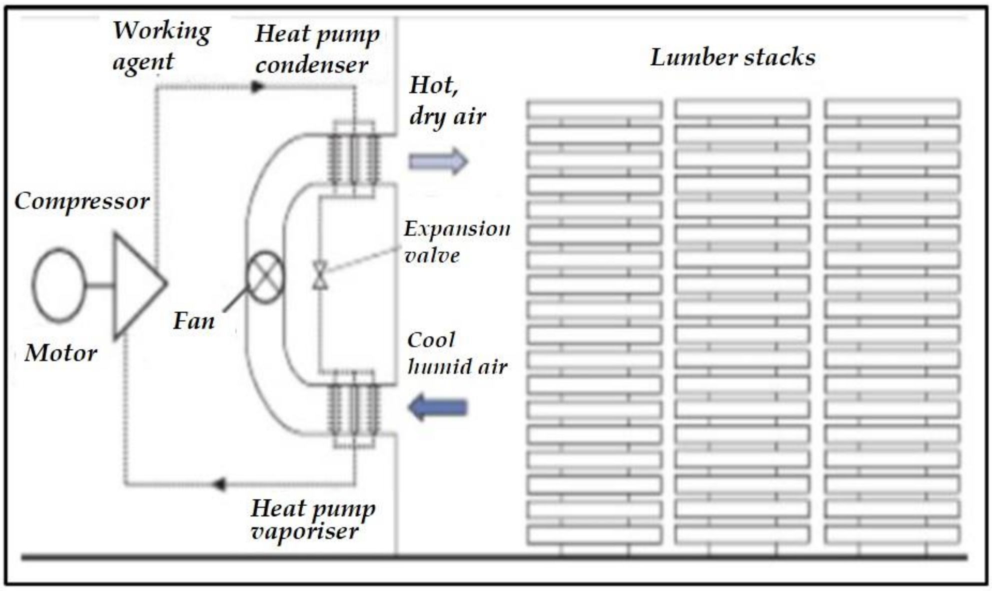


Figure 6.6 – Principle scheme of application of closed cycle heat pump for heating of air for drying of sawn timber [27]

Humid air from the kiln flows through the evaporator of the heat pump, where it is cooled, leading to the condensation of moisture in the air. In the compressor, the compressed material releases heat to fresh air, which then warms the air being used in the dryer. Consequently, the electricity costs for operating a heat pump are significantly lower than the costs associated with steam used in a kiln that does not incorporate a heat pump.

6.4.3 Cold production from low temperature heat

Low-temperature SER heat can also be effectively utilized for refrigeration production. Unlike a heat pump, which extracts heat from the refrigerant and transfers it to a higher temperature level, a chiller removes heat from the refrigerated compartment and discharges it into the environment.

Chillers help to balance seasonal fluctuations in the use of renewable energy sources, as the reduction in heat demand for district heating during the summer is compensated for by an increased requirement for cooling. This cooling is provided in the form of chilled water, typically maintained at a temperature of 5-7 °C. The chilling process employs dust-free flue gas at a temperature of 300 °C, steam at a pressure of 0.13-0.15 MPa, and hot water at a temperature of 130 °C.

6.5 Heat recovery from flue gases of boiler units

The primary factor influencing the efficiency of a boiler unit is the temperature of the flue gases. Heat losses through the flue gases constitute a substantial portion of the total heat losses, which also include losses arising from chemical and mechanical combustion of the fuel, physical heat losses due to slag, and heat dissipated to the environment via external cooling.

These losses significantly affect the boiler's performance and reduce its overall efficiency. Therefore, lower flue gas temperatures correlate with higher boiler efficiency.

The optimal flue gas temperature for various fuel types and boiler operating conditions is established during the initial design phase based on technical and economic analyses. Traditionally, maximizing the use of flue gas heat has involved enlarging the size of the convective heating surfaces as well as the rear surfaces, such as water economizers and regenerative air heaters. Regardless of the implementation of heat recovery technologies and equipment, current regulatory documentation stipulates that flue gas temperatures should remain within a specific range.

- 120-180 °C for solid fuel boilers (depending on fuel moisture and boiler operating parameters),
- 120-160 °C for boilers using fuel oil (depending on the Sulphur content),
- 120-130 °C for natural gas boilers [35].

The indicated values are determined taking into account environmental safety factors, but are primarily based on the requirements for performance and durability of the equipment.

Thus, the minimum limit is set to eliminate the risk of condensation in the convective part of the boiler and further along the flue (in the chimney and the flue).

However, there is no need to sacrifice heat to the atmosphere instead of useful work to prevent corrosion.

Corrosion. Eliminating the risks

Corrosion poses a significant threat to the safe operation of a boiler unit and greatly shortens its service life. When flue gases are cooled to or below the dew point temperature, water vapor condenses along with nitrogen oxides (NO_x) and sulfur oxides (SO_x). These compounds react with water to form acids that can be highly corrosive to the internal surfaces of the boiler. The dew point temperature of these acids can change depending on the type of fuel being burned, as can the composition of the acids that are deposited as condensate. However, the outcome remains consistent: corrosion occurs.

Flue gases from natural gas boilers contain the following main combustion products

- watervapour (H_2O),
- carbon dioxide (CO_2)
- carbon dioxide (CO),
- unburned combustible hydrocarbons C_nH_m.

The last two issues arise when fuel combustion is incomplete or when the combustion parameters are not properly adjusted. Due to the high nitrogen content in atmospheric air, combustion products include nitrogen oxides, namely NO and NO_2, collectively referred to as NO_x. These compounds are detrimental to both the environment and human health. When nitrogen oxides react with water, they produce corrosive nitric acid.

The combustion of fuel oil and coal also results in the formation of sulfur oxides (SO_x). The negative environmental effects of these compounds are well-documented and indisputable. The acidic condensate that forms from their interaction with water leads to sulfur-induced corrosion of heating surfaces.

Traditionally, the temperature of the flue gases is set to protect the equipment from acid deposits on the boiler's heating surfaces. Additionally, this temperature must facilitate the condensation of NOx and SO_x outside the gas path, safeguarding not only the boiler itself but also the chimney and flue gases from corrosion. While certain standards exist to limit permissible concentrations of nitrogen and sulfur oxides, these measures do not prevent the accumulation of these combustion products in the Earth's atmosphere, ultimately resulting in acid rain.

Furthermore, the sulfur content in fuel oil and coal, along with the emission of unburned solid fuel particles (including ash), imposes additional requirements for flue gas treatment. Implementing gas cleaning systems significantly complicates and increases the cost of the flue gas heat recovery process, rendering such measures economically unattractive and often impractical.

In certain instances, local authorities mandate a minimum flue gas temperature at the top of the stack to ensure effective gas dispersion and prevent visible smoke. Additionally, some companies may voluntarily implement such practices to enhance their public image, as visible smoke is often associated with pollution, while its absence is perceived as an indicator of clean production.

Consequently, under specific weather conditions, companies may intentionally heat flue gases before releasing them into the atmosphere. By understanding the composition of flue gases from a natural gas-fired boiler (as discussed in detail earlier), it becomes evident that the white "smoke" emitted from the chimney – when the combustion parameters are properly set – is primarily water vapor generated from the combustion of natural gas in the boiler's furnace.

Combating corrosion necessitates the use of materials resistant to its detrimental effects (such materials are available and can be utilized in installations that use gas, oil products, and even waste as fuel) as well as the implementation of systems for the collection, treatment, and disposal of acid condensate.

Technology

Implementing a series of measures to lower the temperature of flue gases after leaving the boiler, primarily by utilizing the heat generated by the boiler itself, leads to improved efficiency for the entire system, including the boiler unit in operation.

The essence of these solutions is as follows: a heat exchanger is installed in the chimney prior to the stack, allowing it to absorb heat from the flue gases using a coolant (e.g., water). This water can serve as an end-cooler that requires direct heating or as an intermediary that transfers heat to another circuit via additional heat exchangers. A schematic diagram illustrating this setup is shown in figure 6.6.

The resulting condensate is collected directly in a new heat exchanger made from corrosion-resistant materials. This is accomplished by carefully maintaining the flue gas moisture inside the heat exchanger above the dew point temperature. By doing so, both the sensible heat of the flue gases and the latent heat of condensation from the contained water vapor are effectively utilized. The design of the device must ensure that it does not create excessive aerodynamic resistance, thereby preserving optimal operating conditions for the boiler unit.

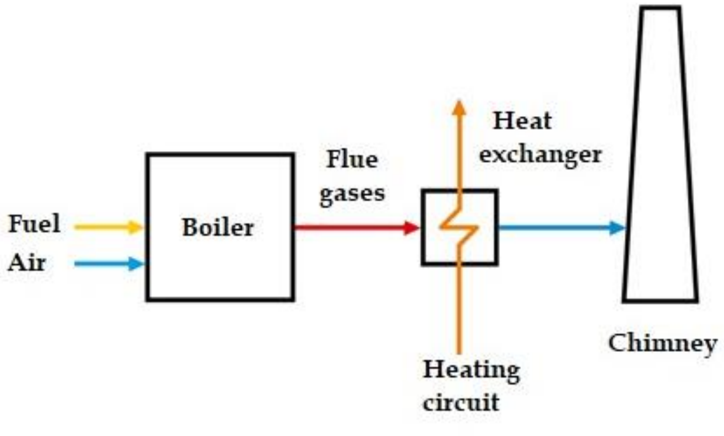


Figure 6.7 – Principal scheme of flue gas heat utilization in a boiler house

The design of the heat exchanger can take the form of a conventional recuperative heat exchanger, where heat is transferred from gases to liquids through a partition. Alternatively, it may be a contact heat exchanger, where flue gases come into direct contact with water that is sprayed into their flow via nozzles. To address the challenge of acid condensate in a recuperative heat exchanger, it is essential to implement a system for its collection and neutralization. In a contact heat exchanger, a slightly different approach is applied, akin to the periodic cleaning of a circulating water supply system: as the acidity of the circulating liquid increases, a portion of it is routed to a storage tank, where it undergoes treatment with reagents before the water is either discharged into the drainage system or returned to the process cycle.

Some applications of flue gas energy may be constrained by discrepancies between the gas temperatures and the specific inlet temperature requirements of the energy-consuming process. Nevertheless, even in seemingly challenging situations, innovative solutions based on advanced technologies and equipment have been developed.

Innovative solutions utilizing heat pumps are frequently employed globally as a key component in enhancing the efficiency of flue gas heat recovery processes. In specific sectors, such as bioenergy, these solutions are implemented in the majority of operational boilers.

In this context, additional savings in primary energy resources are realized through the use of more reliable and technologically advanced absorption heat pumps, which operate using heat instead of electricity (often harnessing unused waste heat), as opposed to traditional steam compression electric machines that are largely unnecessary in most industries. The absorption of heat from an external heating source activates the internal cycle of the heat pumps, enabling the conversion and transfer of the available temperature potential of the flue gases to a higher temperature environment.

Result

1) The cooling of boiler flue gases with such solutions can be quite extensive, reducing temperatures from an initial 120-130 °C down to 30 °C or even 20 °C.

2) The heat recovered is adequate for heating water for chemical treatment, cleaning, hot water supply, and even for use in the heating network.

3) Fuel savings can range from 5-10%, while the efficiency of the boiler unit can increase by 2-3 % [35].

The implementation of the described technology addresses multiple issues simultaneously:

- Maximizing the effective utilization of the heat from flue gases, including the latent heat of condensation from water vapor.
- Reducing emissions of NO_x and SO_x into the atmosphere.
- Generating an additional resource in the form of purified water, which can be beneficially used in various applications, such as filling heating networks and other water systems.
- Mitigating smoke visibility, either significantly or entirely eliminating it.

Experience indicates that the suitability of such solutions primarily depends on the following factors:

- The ability to effectively utilize the heat present in the flue gases.
- The duration of time that the thermal energy can be used.
- The cost of energy resources for the enterprise.

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- The cost of energy resources for the enterprise.
- Whether the levels of NO_x and SO_x emissions exceed permissible limits, along with the strictness of local environmental regulations.
- The method of condensate neutralization and the potential for its subsequent use. Whether the levels of NO_x and SO_x emissions exceed permissible limits, along with the strictness of local environmental regulations.
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6.6 Basic tasks in the design and operation of low energy heat recovery systems

1) Linking existing sources of low-quality heat with consumers, while considering the specific needs of each enterprise and ensuring the project's

economic viability, presents a complex engineering challenge. To address this issue, the development of a recycling system should follow these steps:

2) Conducting a pre-project study of the energy system, which includes data collection and the compilation of energy balances, as well as instrumental research;

3) Modeling technological processes of equipment that results in maximum energy loss through methods such as mathematical modeling and pinch analysis;

4) Analyzing resource limitations regarding the utilization of low-quality heat, and exploring options to identify optimal solutions;

5) Evaluating economic constraints and conducting a technical and economic analysis for the implementation of low-grade heat recovery specific to the given enterprise.

The design and operational characteristics of low-grade heat recovery systems typically involve the use of low-boiling refrigerants, effectively categorizing them as "refrigeration" technologies.

7 Use of secondary thermal energy sources in enterprises. Waste heat boilers

7.1 Description and classification of waste heat boilers

7.1.1 Characteristics of waste heat boilers

Waste heat boilers are designed for the production of steam (both saturated and superheated) and hot water. They can be categorized into technological boilers and energy boilers, with the latter primarily receiving heat from gas turbine units.

Technological waste heat boilers are commonly utilized in the metallurgical industry, where they capture heat from flue gases emitted by steel melting furnaces, heating wells, and other furnaces used for melting coconut and copper. Additionally, they are employed in the chemical industry, particularly in processes such as the production of sulfuric acid and synthetic rubber, as well as in the construction materials sector, including cement and glass manufacturing.

Key features of the equipment include:

1) The absence of a combustion device or combustion chamber when heat is derived from other thermal processes. A furnace is included only if the working environment contains a chemical component that requires combustion for heat generation.

2) The presence of micro-impurities in the flue gases, such as dust, unburned fuel, and metal particles, depending on the specific technology employed. As a result, waste heat boilers are typically equipped with at least two compartments, including gas turbine chambers and a bypass channel with a valve to regulate operating parameters. This bypass assists the heat exchanger in achieving efficient heat transfer and minimizes the risk of accidents caused by excessive temperature and erosion stresses in extreme operational conditions. The working elements and materials are made from specialized steel grades to enhance durability.

3) The boiler structure is sealed, and the evaporation coils are enclosed in a single circuit that aligns with the gas path to the chimney, utilizing a circulation pump for efficient operation.

4) The boiler body is constructed from steel sheets that are 15 to 20 mm thick, ensuring reliable performance in environments that experience high pressure and elevated temperature levels.

5) To protect gas surfaces from wear, special X17 steel pipe sleeves are typically used. The design of the heat recovery steam generator (HRSG) must also provide a sealed unit.

6) Evaporation elements are installed within the boiler chimneys, contributing to the overall circulation circuit.

7) Waste gases resulting from technological processes contain dust and other corrosive substances that must be removed before entering the boiler. Powerful cyclones and electric filters are used for this purpose, although these alone cannot guarantee complete purification of the gas environment.

8) Dust tends to settle unevenly on the heating surfaces, which impairs heat transfer and may lead to coil misalignment due to inconsistent heating. The presence of compounds such as Ca, Na, and S in the flue gases contributes to the formation of hard deposits on these surfaces, accelerates corrosion within the evaporation circuit, and negatively impacts the conductivity of the media. To address these challenges, modern heat recovery steam generators (HRSGs) are typically equipped with a flue gas combustion furnace.

In a standard waste heat boiler, you will find: 1) a drum; 2) an evaporator without a superheater; and 3) a water economizer.

The efficiency of the heat exchanger is influenced by three key factors: the temperature of the gas entering the boiler, the volume of the gas, and the method of supplying secondary energy resources. Depending on the amount of fuel burned in the furnace and the temperature of the flue gases exiting the furnace (ranging from 400 to 1200 °C), the steam production of waste heat boilers can vary widely from 2 to 40 tons per hour. Furthermore, depending on the consumption requirements, the steam pressure can range from 0.2 to 4 MPa, with steam temperatures capable of being superheated to between 420 and 470 °C.

Requirements for waste heat boilers:

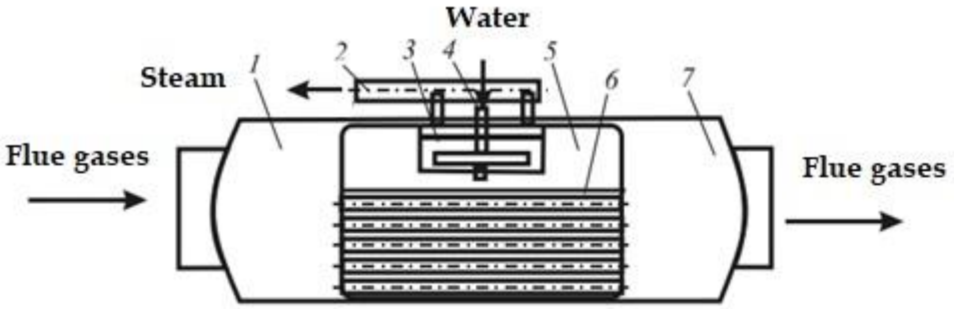
- compactness;
- efficient heat transfer of streams;
- ability to work in low-quality water;
- cleaning drums and pipes from salt deposits, and gas pipes from ash.

7.1.2 Classification of waste heat boilers

According to the design, waste heat boilers are divided into:

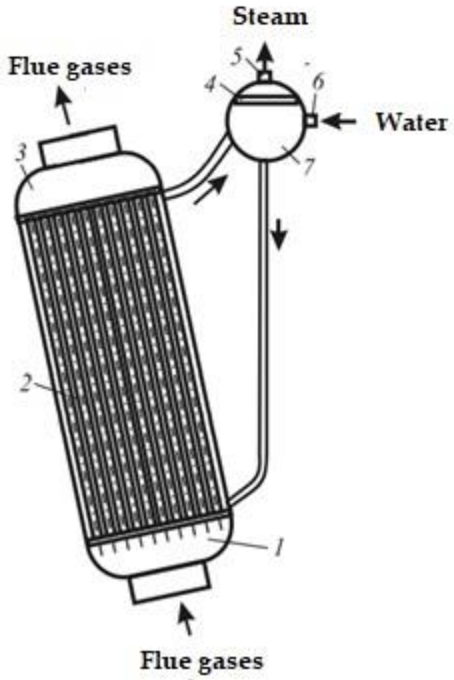
- for gas pipelines - to obtain saturated ($p = 1.4$ MPa) and superheated steam ($p = 1.6$ MPa);
- water tube - for producing superheated steam ($p = 1.8–4.5$ MPa).

By construction, gas tube boilers are divided into horizontal (figure 7.1) and vertical (figure 7.2).



1 – inlet gas chamber; 2 –vapour outlet; 3 – separation device; 4 – water inlet; 5 – drum; 6 – evaporating surface; 7 – outlet gas chamber

Figure 7.1 –Gas-tube horizontal heat recovery boiler



1 – inlet chamber; 2 – evaporating surface; 3 – outlet chamber; 4 – separator; 5 –vapour outlet; 6 – water inlet; 7 – drum

Figure 7.2 – Gas-tube vertical heat recovery boiler

The main disadvantages of gas pipe heating boilers include:

- low coefficient of heat utilization of gases emitted from technological facilities (50–60 %).
- high specific metal consumption for steam production (up to 8 kg/(kg·h)).

- the lower pressure limit of the generated steam due to the presence of a large diameter drum (only 1.5–2.0 MPa),
- limited passage of exhaust gases - no more than 30-40 thousand m^3/h.
- the internal surfaces of pipes and gas pipe boilers are quickly covered with slag, so it is necessary to clean the pipes often.

Advantages of gas tube boilers:

- special laying is not required;
- characterized by high gas density;
- ease of preparation, installation, maintenance;
- reduction of feed water requirements;
- slight pressure fluctuations with non-uniform steam flow.

For low-power units (not more than 7.5 t/h), it is recommended to use gas pipe boilers, especially if the heating gases have high pressure or contain explosive or toxic components.

Depending on the design, water pipe boilers are also divided into horizontal and vertical.

Advantages of water pipe boilers:

- increase in steam pressure;
- increase of the heating surface without increasing the dimensions;
- the vertical location of the pipes, which makes it easier to clean them from sludge.

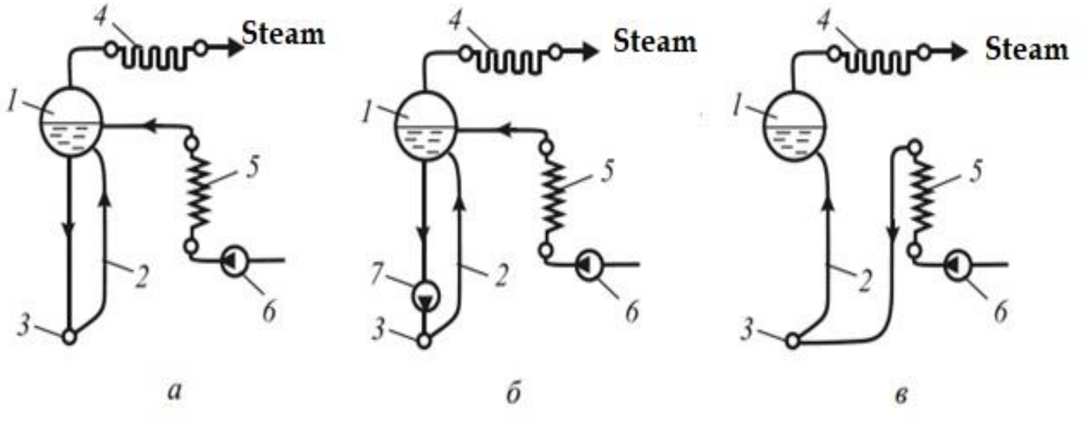
Disadvantages:

- covers a large area;
- unreliable circulation of steam-water mixture.

Due to their advantages, water pipe heating boilers are widely distributed.

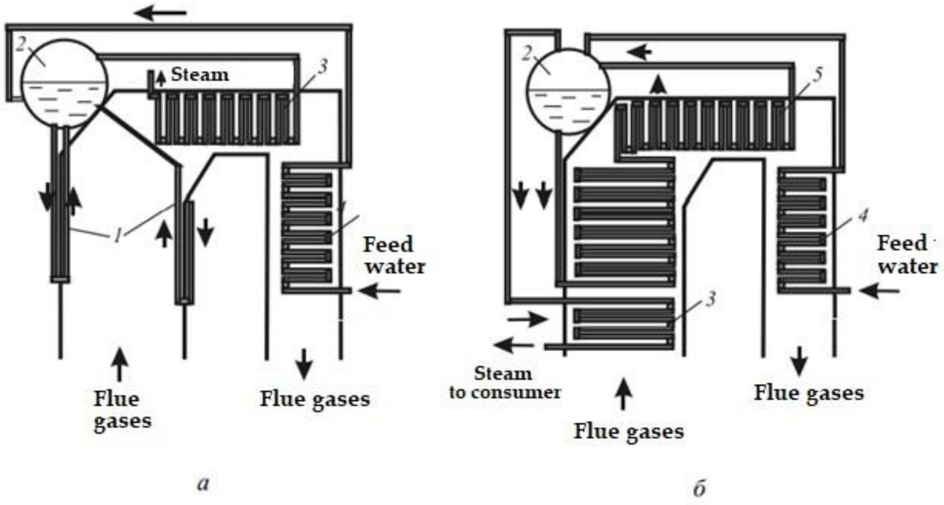
Water-tube boilers are categorized based on their water circulation principles into four types: natural circulation (figure 7.3, a), forced circulation (figure 7.3, b), mixed circulation, and direct flow (figure 7.3, c). Boilers featuring natural circulation are primarily utilized in furnaces operating at flue gas temperatures between 800 and 1000 °C or higher. This is due to the need to ensure reliable circulation under these conditions.

Circulation rate for boilers with natural circulation (figure 7.4) varies from 10 to 60 [23].



a – natural; b – forced; c – direct flow; 1 – drum; 2 – evaporating surfaces; 3 – bottom collector; 4 – steam super heater; 5 –economizer; 6 – feed pump; 7 – circulation pump

Figure 7.3 – Scheme of water circulation in water-tube waste heat boilers



1 – radiation evaporator; 2 – drum; 3 – steam super heater; 4 –economizer, 5 – convective evaporator

Figure 7.4 – Water-tube drum П-shaped heat recovery boiler with natural circulation with radiation (a) and convective (b) evaporator surfaces

7.2 Working principle of waste heat boilers

The operation of waste heat boilers is determined by the configuration used for producing secondary energy resources and the movement of gases within the system – either through pipes or in the inter-pipe space. In gas pipeline utilizers, the secondary energy carrier flows either vertically or horizontally within the gas space. These units are typically installed within the operational circuit of low-energy-efficient furnaces, such as those in Martin furnaces.

The operational principle of gas pipe heating boilers is as follows:

1. Hot gases at a temperature of 1200 ºC from the furnace travel along the gas-air path to the inlet of the flue pipe of the waste heat boiler, where W-heating surfaces including strip screens and convective steam superheaters are located.
2. Water that absorbs heat from the exhaust gases is heated and moves as a steam-water mixture through natural circulation; steam pressure can reach up to 4.5 MPa with a temperature of 440 ºC. The total capacity of such waste heat boilers can reach up to 10 MW. To ensure a consistent load, these boilers are equipped with a pre-burner box that operates with a gas nozzle.

In water-tube heating boilers, secondary energy resources are conveyed through the inter-pipe space, while heated water circulates within the pipes. The operation of these waste heat boilers relies on the repeated forced circulation of the coolant in the water circuit.

The evaporator element consists of parallel sections, which minimizes the resistance of the fluid and enables the use of lower-capacity pumps for water circulation. The arrangement of this type of boiler can be either horizontal or vertical, depending on the specific layout of the facility.

Combined heat and power plants (figure 7.5) utilize heat from turbine gases as a secondary energy resource. The steam generated is employed for heating water in the boiler heating system or for fulfilling the technical requirements of the industrial facility. Typically, these are single-circuit forced circulation boilers [22].

7.3 Heat exchange elements of a waste heat boiler

The primary heat exchange components of a waste heat boiler include the evaporation sections, a superheater, and an economizer [3]. Waste heat boilers are categorized based on the type of evaporation surface in the heat exchanger as follows:

- Convective boilers with natural and forced circulation, operating at flue gas temperatures ranging from 450 to 1200 °C.
- Radiant convective boilers with natural circulation, functioning at flue gas temperatures between 1200 and 1600 °C.

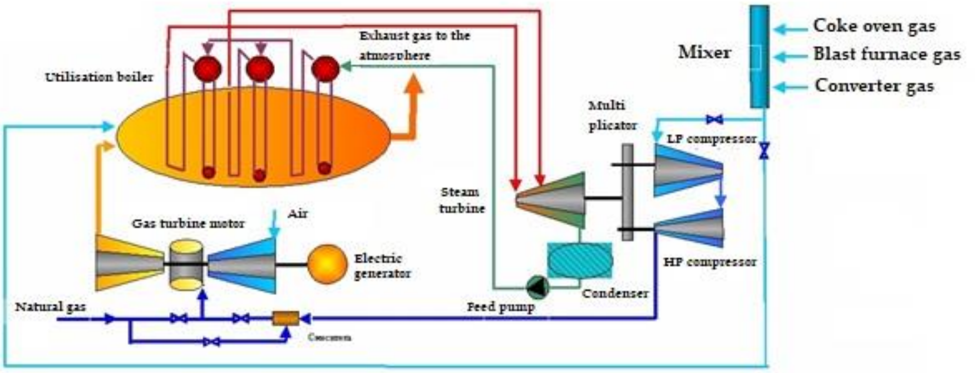
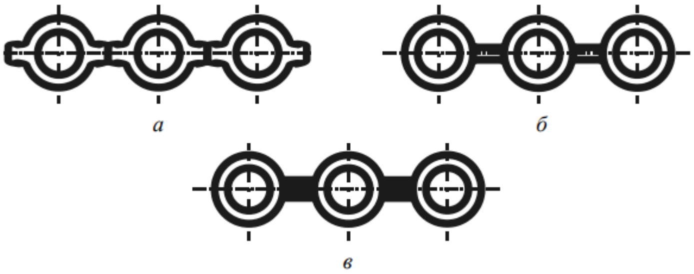


Figure 7.5 – Cogeneration unit [22]

At elevated gas temperatures (above 900 °C), waste heat boilers are equipped with radiant (screen) heating surfaces (figure 7.4, a). For gas temperatures below 900 °C, waste heat boilers primarily utilize convective surfaces, which are composed entirely of coils (figure 7.4, b) [36].

The radiant sections of the evaporator consist of parallel tubes that are mounted on the boiler walls and connected to a collector. Screen types are classified into gas-tight and gas-impermeable categories (figure 7.6). The use of fully welded membrane screens has proven to be the optimal solution for ensuring the tightness of the boilers, leading to their widespread adoption and use.



a– from finned tubes; b – with welded ribs of rectangular cross-section; c – with metal cladding between tubes

Figure 7.6 –Gas-tight screen of evaporator radiation section

Fully welded gas-tight (membrane) screens offer several advantages, including:

- complete prevention of air intake;
- reduced thermal inertia of the boiler unit, enhancing its maneuverability;
- decreased installation work associated with assembly, particularly the insulation of the screens;

- lower weight of the screen surfaces, which in turn reduces the weight and cost of insulation materials.

The superheater is a crucial component of modern waste heat boilers, designed specifically to superheat steam. In contemporary waste heat boilers, superheaters are positioned in areas with high gas temperatures to achieve optimal superheating. A convective superheater is typically located at the top of the gas tube. Superheaters can be classified as vertical or horizontal, depending on the arrangement of the tubes.

Advantages of vertical superheaters:

- Installation is generally easier and more cost-effective.

Disadvantages:

- risk of salt accumulation at the bottom, which may lead to pipe burn;
- potential formation of water plugs when the waste heat boiler is turned off.

Steam superheaters are categorized into different designs based on the type of heat exchange: direct flow (figure 7.6, a), counter flow (figure 7.7, b), and mixed flow (figure 7.7, c). [3, 36].

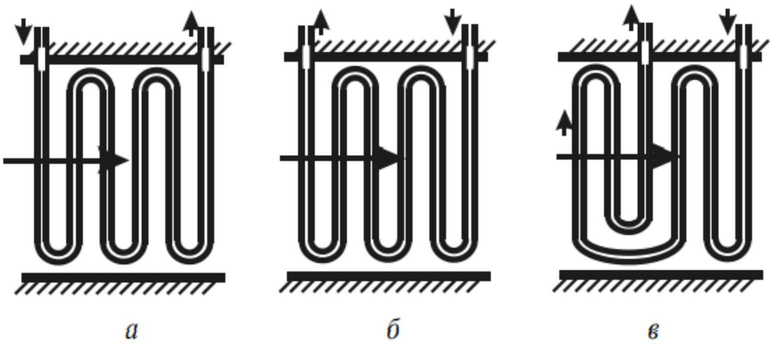


Figure 7.7 – Direct flow (a), countercurrent (b) and mixed (c) schemes of steam super heater connection to the gas path

In terms of heat transfer efficiency, the counterflow arrangement is the most effective as it creates a significant temperature gradient between the flue gas and the steam. However, this design also subjects the coil outlet to the highest thermal loads, which can result in wall temperatures that require the use of more expensive high alloy steels. Consequently, when implementing a counterflow system, the cost of the heating surface is significantly increased due to the need for these premium materials, and mixed-flow circuits are often used instead. This results in a 'hidden' loop (figure 7.7, c).

During operation, the temperature of the superheated steam can fluctuate beyond acceptable limits. Factors affecting the temperature of the superheated steam include the steam flow rate, the temperature of the feed water, the characteristics of the combustion products and the fouling of the screen surfaces and the superheater

The following types of superheated steam temperature control are used:

- steam (surface disinfectants, injectable);
- gas (gas recirculation, bypass).

Heaters are installed (figure 7.8): behind the super heater, in front of the heater, in the section.

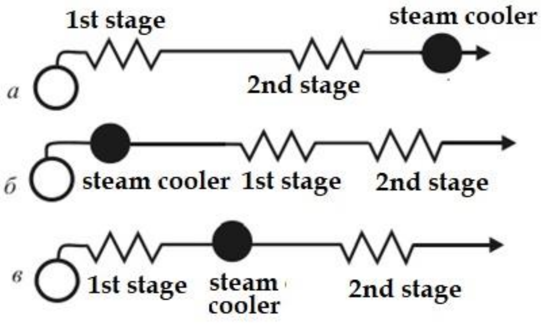
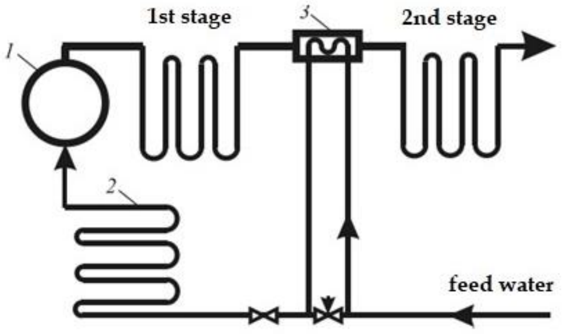


Figure 7.8 –Schemes of steam cooler installation in the super heater and graph of steam temperature change

The primary drawback of surface steam coolers is their inertia. This inertia is marked by a notable delay of approximately 5-7 minutes in the temperature adjustment of the superheated steam when there is a change in the boiler's operating mode. Typically, water is supplied to the surface steam cooler from the feed line.

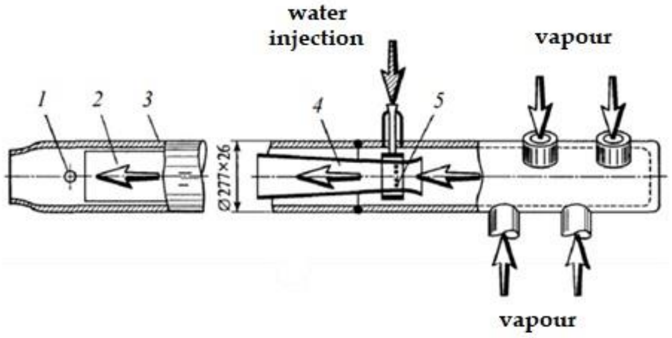
The connection diagram of the surface steam cooler is shown in figure 7.9.



1– drum; 2 – economizer; 3 – steam cooler

Figure 7.9 – Diagram showing the installation of a surface steam cooler in a steam super heater

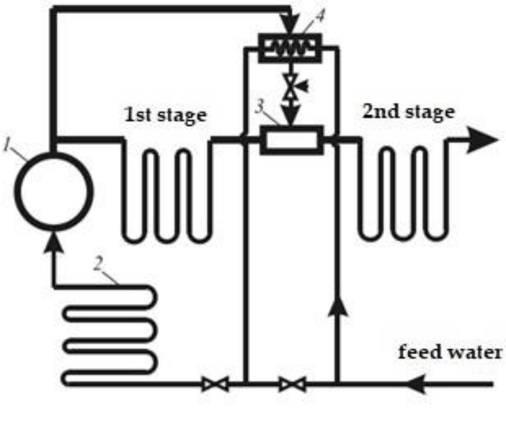
In the injection superheater (figure 7.10), cooling water enters the superheater pipe through several openings around the nozzle. The water is then sprayed into the jacket, which consists of a diffuser and a protective cylinder that shields the housing from splashing water. This design helps prevent cracks in the housing metal that can occur due to rapid temperature changes. The finely atomized water droplets mix with the superheated steam, absorbing heat and transforming into steam, which results in the cooling of the overall steam mixture.



1 – thermocouple; 2 – cylinder; 3 – housing; 4 – diffuser; 5 – holes for water supply to the diffuser

Figure 7.10 –Injection type steam cooler

To ensure that the level of impurities in the injected water does not exceed the level of impurities in the steam, the water supply to the injection steam cooler is usually taken from the saturated steam condenser (figure 7.11).



1 – drum; 2 –economizer; 3 – steam cooler; 4 – condenser

Figure 7.11 – Schematic diagram of a surface steam cooler incorporated into a steam super heater

7.4 Combined operation of waste heat boilers with air heaters

The heat from flue gases can be utilized to preheat the combustion air supplied to the process furnace. Since the volumetric flow rate of combustion air is approximately 30 % lower than that of the flue gases, and due to the low efficiency of heat exchange between the gases, an air heater alone cannot efficiently utilize the heat from the flue gases. Therefore, a waste heat boiler is typically installed downstream of the furnace, alongside the air heater. Various configurations exist for connecting the air heater and the waste heat boiler, including primary, secondary, and combined schemes.

In the primary scheme (figure 7.12), the air heater is positioned after the process furnace, followed by the waste heat boiler. In this arrangement, the thermal efficiency of both devices is relatively low: the air heater suffers from a low heat transfer coefficient for air, while the waste heat boiler operates at reduced effectiveness due to the lower temperatures of the cooled flue gases it receives. Consequently, this initial configuration results in a less efficient utilization of flue gas heat.

However, this scheme is employed when the objective is to achieve higher temperatures in the process furnace by more effectively heating the combustion air.

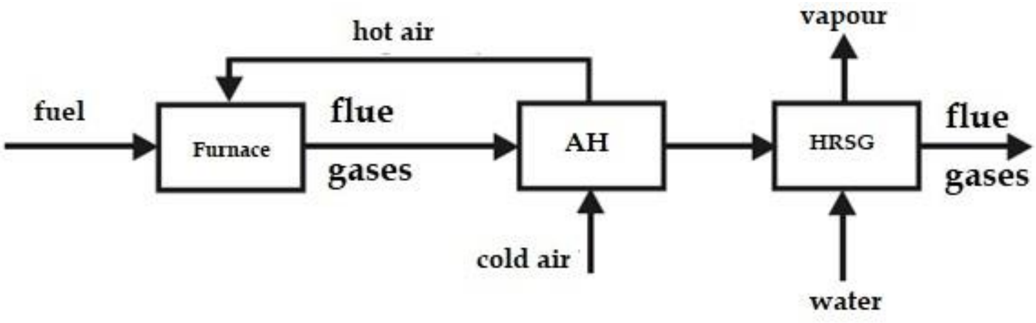


Figure 7.12 – Diagram of the primary circuit of the air heater and connection of the HRSG [37]

The secondary scheme (figure 7.13) makes more efficient use of the flue gas heat (deeper cooling of the flue gases). This scheme is used when it is not necessary to heat the air to high temperatures [37].

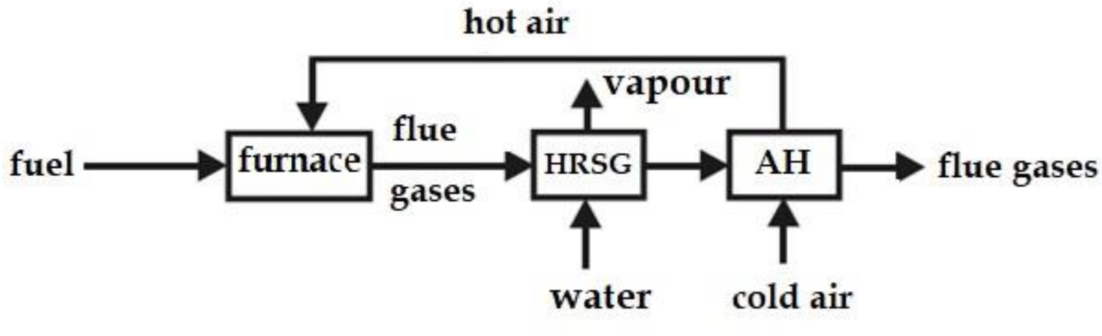


Figure 7.13 – Secondary scheme of air heater and HRSG connection

The combined system depicted in Figure 7.14, featuring two air heaters – one located after the process furnace and the other after the heat recovery steam generator (HRSG) – is more intricate. This arrangement serves as a compromise between primary and secondary heating. It enables both high combustion air temperatures and substantial cooling of the flue gases; however, it comes at a higher cost [37].

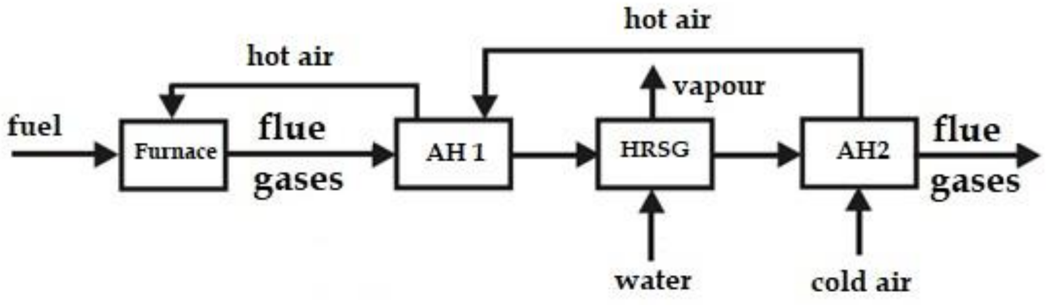
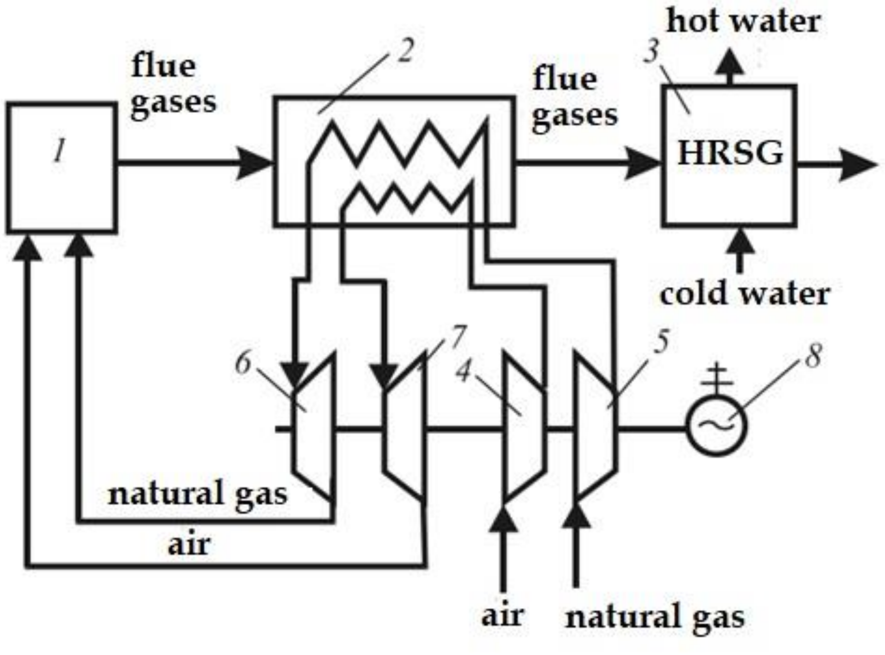


Figure 7.14 – Combined diagram of air heater and heat recovery steam generator start-up [37]

7.5 Use of flue gas energy for mechanical and electrical power generation

Flue gas heat from industrial furnaces can be used by gas turbines integrated in the gas path (figure 7.15) to generate electricity and to supply gas and air to the furnace.



1 – furnace; 2 – heat exchanger; 3 – heat recovery boiler; 4, 5 – compressors; 6, 7 – gas turbines; 8 – electric generator.

Figure 7.15 – Scheme of flue gas energy utilization for power generation and gas and air supply to the furnace [38]

Typically, a heat recovery boiler (3) is positioned after the heat exchangers (2) of gas turbine units to maximize the utilization of flue gas heat, as the flue gas temperature remains relatively high (around 450-500 °C). Compressors (4) and (5) deliver natural gas and air to the heat exchangers (2), where they are warmed by the flue gas heat. The heated gas and air are subsequently supplied to turbines (6) and (7), which power the compressors and the electric generator (8). This approach effectively addresses the challenge of supplying fuel and air to the combustion chamber (1) while concurrently generating energy by leveraging secondary thermal energy resources..

8 Use of secondary overpressure energy resources

The most common secondary overpressure energy source for industrial facilities is super-atmospheric gas, typically steam. However, the following issues may restrict the use of gas for operational purposes: 1) the gas pressure may exceed the required level; 2) the gas pressure may be insufficient for the needs.

In the first case, the potential energy of the excess pressure can be used by pressure energy conversion systems:

- turbines (conversion of potential pressure energy into mechanical energy);
- vortex tubes (conversion of potential pressure energy into thermal energy);
- wave expanders-compressors (transfer of potential pressure energy from one medium to another) [1].

In a second embodiment, devices for increasing the pressure of the gas can be used.

8.1 Utilization by Steam Turbines

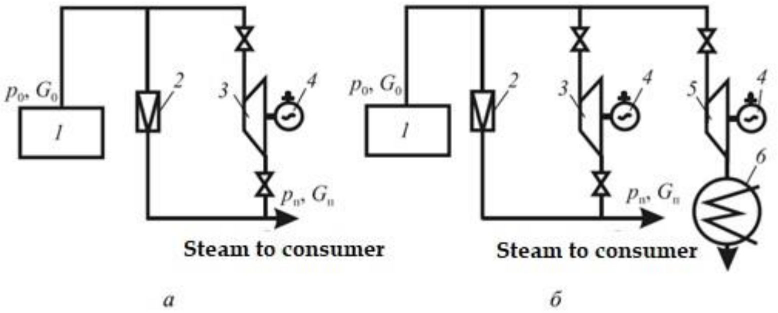
8.1.1 Utilization of the overpressure energy of the hot steam

Currently, the majority of boiler houses equipped with steam boilers throttle fresh steam from a pressure of 1.3 MPa or higher down to a range of 0.3-0.6 MPa. In this process, the potential energy from the steam pressure is irretrievably lost.

Installing steam back-pressure turbines in these facilities would allow for the recovery of this energy, transforming it into mechanical (electrical) energy primarily for the company’s internal use. Preliminary estimates indicate that power losses resulting from throttling in boiler houses reach approximately 240 MW, which is about 4 % of the total installed capacity of the power system.

The configuration of the back-pressure turbine connection is illustrated in Figure 8.1, a. Steam with initial parameters p_o, t_o is sourced from boiler 1 and directed to turbine 3, where it is expanded to a steam pressure of $p = 0.4$-1.8 MPa for industrial applications. During peak heat load periods, if the steam flow needed by the consumer exceeds what the turbine can handle, the consumer will receive additional steam from the Reduction and Cooling Unit (RCU) 2. This unit also provides steam to the consumer during turbine shutdowns [40].

Essentially, the reduction of steam pressure to the levels required for production occurs within a back-pressure turbine. The mechanical energy produced from the rotation of the turbine shaft, or the electrical energy generated by the attached generator, is a by-product of this process, requiring only a small additional amount of fuel consumption (about 4-7 % of the initial level).



1 – steam boiler; 2 – reduction and cooling unit; 3 – backpressure turbine; 4 – generator; 5 – condensing turbine

Figure 8.1 – Scheme of connection of backpressure turbine-generator set to boiler house steam piping

Typically, the thermal energy of steam in the enterprise's energy systems is utilized almost entirely, including the heat released during condensation (formation of steam). However, in power stations, this condensation heat is irreversibly lost to the environment. The condensate from the heater is returned to the boilers, resulting in minimal heat loss.

Therefore, losses in such a facility primarily stem from steam and condensate leakage, friction in bearings, losses in the generator, and thermal losses in the turbine and steam lines. The efficiency of these turbine units ranges from 90-95 %, meaning that only 5-10 % of the steam heat is lost from the boiler. Consequently, the specific fuel consumption for combined heat and power production is approximately b = 150-160 g/kWh, which is half that of a condensing power plant.

Clearly, a back-pressure turbine should only be installed if all the steam passing through it can be fully utilized for production purposes. It is inefficient to vent excess steam to the atmosphere, resulting in a loss of thermal energy. Therefore, the plant's steam demand must always be equal to or slightly exceed the steam flow through the turbine.

In manufacturing processes, steam pressures should generally remain constant, despite potential fluctuations in consumption. As such, the turbine's load (the amount of electricity generated) is entirely dependent on and varies with the production demand for steam heating. This mode of operation is referred to as "heat schedule operation," in contrast to "electric schedule operation," where turbine load is dictated by electricity needs.

In scenarios where a plant experiences highly variable steam consumption – depending on the time of day or season – relying on a single back-pressure turbine becomes impractical. This is because the turbine may need to operate partially or fully with exhaust gas to meet electricity demands. Consequently, a condenser turbine is often installed in parallel with the back-pressure turbine (figure 8.1, b), allowing for adjustable load based on electricity requirements.

The reconstruction of boilers through the installation of back-pressure turbines represents the sole option for integrating power generation equipment into coal-fired boilers, as well as natural gas-fired boilers. This is particularly true in cases where it is not feasible to install internal combustion engines or gas turbines due to fire and environmental safety regulations.

The use of small-scale CHP has the following advantages

- efficiency - efficient production of electricity;
- reliability - producing your own electricity increases the reliability of the boiler;
- reduced energy consumption - electrical and thermal energy is transported over short distances, reducing the cost of installing transformers and pumping stations;
- possibility of more efficient use of burnt fuel;
- flexibility in the choice of fuel and emission of harmful substances in comparison with traditional boilers allows solving environmental problems.

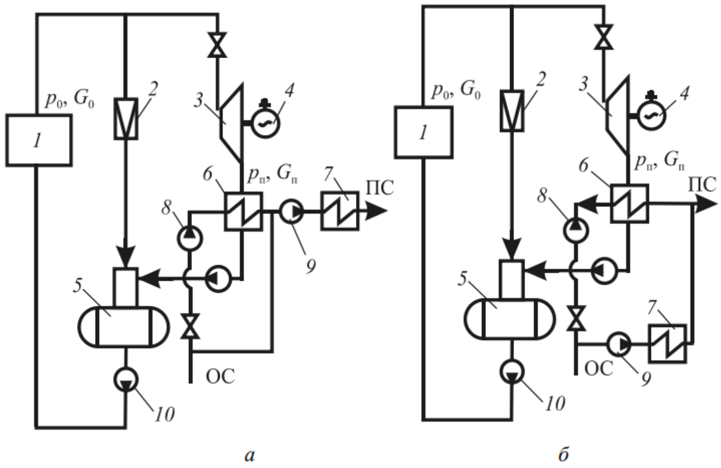
In addition to the advantages, there are also some disadvantages:

- the installation of backpressure turbines is only possible in boiler plants with steam boilers;
- relatively high noise of the turboset;
- short lifetime and overhaul period compared to boiler plants.

For closed heat supply systems, series or parallel heat circuits of small thermal power stations can be proposed (figure 8.2).

Figure 8.2 (a) illustrates the thermal scheme for the sequential connection of a small combined heat and power (CHP) plant to the steam section of a boiler featuring atmospheric deaerators. It also shows the arrangement of the entire flow of steam-water heaters, alongside the line water and condensate pumps, in the machine room of the steam turbine unit. This configuration is preferred because it allows for the maintenance of the temperature schedule necessary for regulating the heat load of the heating system. In this setup, all return water from the heat pipe flows through the heat exchangers of the small CHP.

Figure 8.2 (b) depicts the thermal diagram for the parallel connection of small thermal power plants with atmospheric deaerators to the steam section of the boiler. This arrangement is designed for a closed heating system that incorporates a steam turbine unit, with line water and steam-water heaters located in the machine room [41].



1 − steam boiler; 2 − boiler house reduction and cooling unit; 3 − steam turbine; 4 − electric generator; 5 − feed atmospheric degasser; 6 − network water steam heater; 7 − hot water boiler; 8 − condensate pump; 9 − network pump; 10 − feed pump; SP, RP − heat network supply and return pipes

Figure 8.2 − Thermal scheme of a mini thermal power plant with series (a) and parallel (b) connection of network water heaters

This setup does not necessitate the installation of additional network pumps. However, the capacity of the heat source is limited due to the inability to significantly alter the flow rate of the network water in the supply line of the heating network.

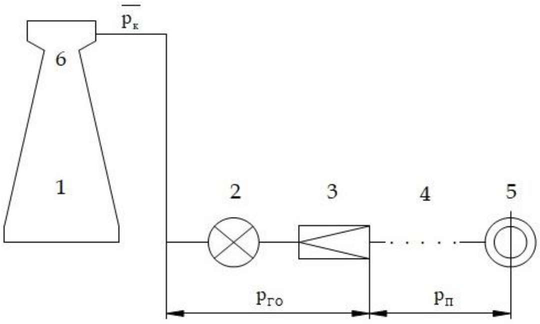
The same scheme can also serve as a backup for an open heat supply system. When transitioning to a closed heat supply system, the heat exchangers for the mains and make-up water will be cooled using mains water to maintain the nominal steam flow rate through the turbine.

The diversity of scheme designs implemented in practice allows for an optimal selection of the thermal scheme that aligns with the specific operational conditions of the boiler house, ensuring efficient and flexible operation of the mini thermal power plant.

8.2 Gas turbine utilization

Use of blast furnace gas overpressure

The blast furnace gas pressure at the furnace grates pk is 0.18 ÷ 0.34 MPa (average value =0.26 MPa), at foreign furnaces $p_k \leq 0.5$ MPa. Taking into account the pressure required for cleaning, transport and use of the blast furnace gas, the consumers have an unrealized overpressure (figure 8.3) [3].



1 − blast furnace; 2 − gas cleaning; 3 − throttle group for maintaining the set pressure on the grate 6; 4 − factory gas pipeline; 5 − consumer.

Figure 8.3 − Blast furnace gas flow diagram [3]

The unrealized overpressure will be, according to the blast furnace gas pressure balance, as follows:

$$p_{over}= p_к – (p_{gp}+ p_c)= 0.26 - (0.02+0.01)=0.23 \text{ МПа},$$

where p_{gp}– loss of pressure at the gas purification plant (p_{gr}=0.02 MPa);

p_c – the pressure required to transport the blast furnace gas to the consumer and to use the gas at the consumer (p_c=0.01 MPa).

Unused blast-furnace overpressure is harnessed to generate electricity in uncompressed gas-fired turbines. Before the blast furnace gas is introduced into the uncompressed gas turbines, it needs to be heated to a temperature range of 250 to 600 °C after undergoing wet cleaning.

The lower limit ensures that the gas exits the turbine at a temperature between 60 and 80 °C, preventing moisture condensation and avoiding the freezing of the turbine components in case of negative gas temperatures. The upper limit is determined by the thermal resistance of the steels that are economically viable for manufacturing the rotors of turbines in this class.

Depending on the method of blast furnace gas heating gas utilization uncompressed gas turbines (GUUGT) are divided into 3 groups:

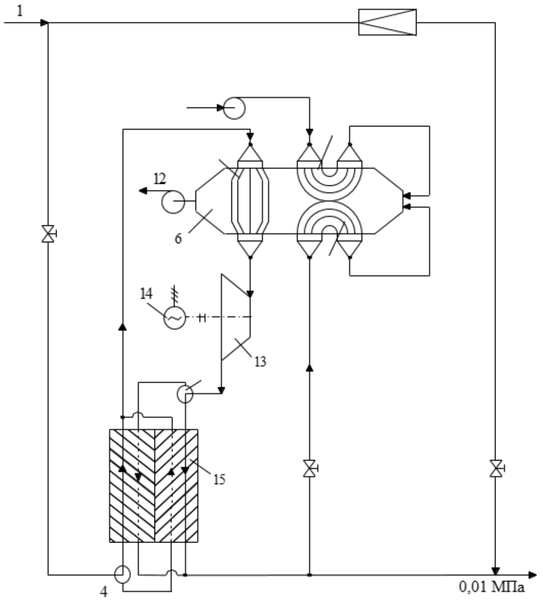
1) with two-stage regenerative and recuperative heating: GUUGT -6 (6-installed turbine generator capacity, MW);

2) with blast furnace gas heating by mixing it with high-temperature combustion products: GUUGT -8 and GUUGT -12;

3) without heating, by applying dry methods of blast furnace gas cleaning, for example, in metal-ceramic or fabric filters, which excludes gas

saturation with moisture and, consequently, excludes moisture condensation during gas cooling in turbines.

Let's examine the fundamental scheme for utilizing uncompressed gas turbines with two-stage regenerative and recuperative heating of blast furnace gas (see figure 8.3).



1 − blast furnace gas pipeline from gas cleaning; 2 − throttle group designed to maintain appropriate pressure on the blast furnace grate; 3 − low pressure blast furnace gas pipeline (factory gas pipeline); 4 − high pressure blast furnace gas flip valve; 5 − regenerative heat exchanger; 6 − complex recuperator including positions 7-12; 7 − combustion chamber; 8 − recuperator for heating of high pressure blast furnace gas; 9 − recuperator for heating of low pressure blast furnace gas used for heating of the complex recuperator; 10 - recuperator for heating of air used for combustion of low pressure blast furnace gas; 11 − blast fan; 12 − exhauster for removal of combustion products; 13 − gas turbine; 14 − electric generator; 15 − flip valve for low pressure blast furnace gas

Figure 8.3 − Schematic diagram of two-stage regenerative and recuperative blast furnace gas heating unit [42]

After undergoing gas cleaning, the high-pressure blast furnace gas enters the heated section of the nozzle of the regenerative heat exchanger (5), where it is heated to a temperature between 200 and 300 °C. The gas then flows into the heater (8) of the complex recuperator (6), where its temperature is elevated to 600 °C. The pressure loss during the heating process is approximately 0.01 MPa, allowing the gas to enter the gas turbine (13) with parameters of 0.22 MPa and 600 °C [42].

Following expansion in the turbine, the parameters of the blast furnace gas are: pressure – 0.02 MPa and temperature - approximately 300 °C. The heat from the blast furnace gas after the turbine is utilized to heat the regenerator nozzle. Subsequently, the gas, with a pressure of 0.01 MPa and a temperature of up to 100 °C, is directed to the plant gas pipeline.

The alternating operation of the regenerator nozzles in heating and cooling modes is facilitated by bypass valves 4 and 15.

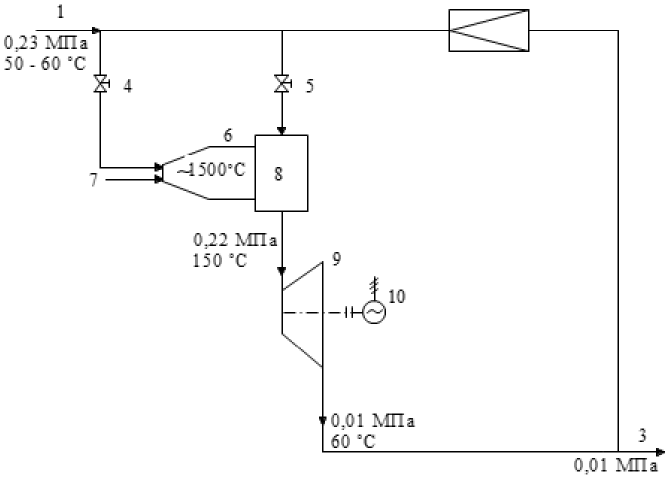
Disadvantages of the GUUGT *-6:*

- bulky due to the presence of a regenerative heat exchanger which requires limited gas velocities (up to 1 m/s) for normal operation, increasing the volume of the heat exchanger;

- high capital and operating costs due to the use of two types of heat exchangers and the large volume of equipment;

- consumption (combustion) of blast furnace gas for servicing the GUUGT.

The principle scheme of the GUUGT using a mixed heat exchanger is shown in figure 8.4 [42].



1 – blast furnace gas pipeline from gas cleaning; 2 – throttle group; 3 – low-pressure blast furnace gas pipeline (factory gas pipeline); 4 – blast furnace gas supply for combustion; 5 – blast furnace gas supply for mixing; 6 – combustion chamber; 7 – compressed air supply; 8 – mixing chamber; 9 – gas turbine; 10 – electric generator

Figure 8.4 – Principal scheme of the gas turbine with blast furnace gas heating by mixing with high-temperature combustion products [42]

Advantages over the GUUGT *-6:*

- simplicity, compactness of the equipment and therefore significantly lower investment costs;
- more efficient use of excess gas pressure due to the absence of heat exchangers causing gas pressure losses.

Disadvantage: reduction of the heat of combustion of blast furnace gas due to ballasting with combustion products.

8.3 Use of energy from natural gas overpressure

After leaving the pumping stations, natural gas is transported over long distances via pipelines at pressures ranging from 7.0 to 7.5 MPa. Upon entering the distribution systems of cities and large industrial facilities, it is necessary to significantly reduce this pressure from the main gas lines to the burners of gas appliances. This process includes two stages of gas pressure reduction: Stage 1 involves gas distribution stations (GDS) that are positioned along the branch from the gas main, where the gas pressure is reduced to 1.2 MPa. Stage 2 consists of gas regulating stations (GRS) found at production plants, where the pressure is further decreased to levels appropriate for operational conditions. This reduction in gas pressure occurs through pressure relief valves, representing a direct loss of potential flow energy.

By using expander-generator units instead of conventional throttling devices, it becomes possible to generate electricity by harnessing excess gas pressure. An expander-generator unit comprises an expander, a generator, heat exchange equipment, and control and regulation systems for operating parameters. Within the expander, the energy from the gas flow is converted into mechanical work, resulting in a reduction in gas pressure and temperature. This mechanical energy can then be transformed into electrical energy by a generator connected to the expander.

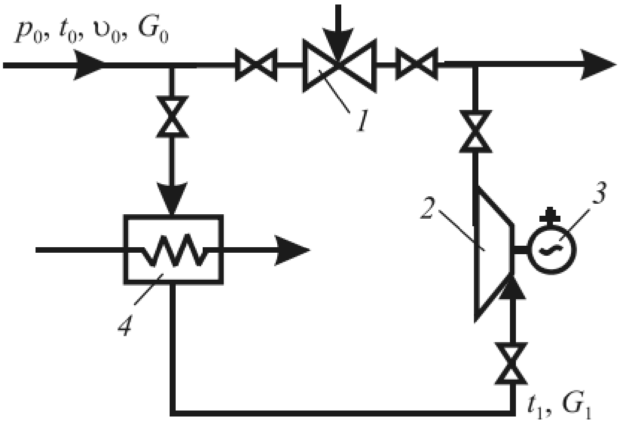
Moreover, during the adiabatic expansion of gas, the temperature of the working fluid significantly decreases as external work is released. The extent of this temperature reduction is determined by the ratio of the pressures at the inlet and outlet of the expansion machine (expander). Calculations indicate that when gas pressure is reduced from 1.2 to 0.3 MPa, its temperature drops by 50 to 60 °C, depending on the gas composition and the efficiency of the expander. If the pressure drop ratio increases to 6 (from 1.8 to 0.3 MPa), the temperature difference can rise to 70 to 80 °C. Assuming that the gas temperature at the inlet to the machine is 20 °C, the outlet temperature after expansion would be between 30 and 40 °C in the first case and between 50 and 60 °C in the second. Consequently, as the pressure of natural gas decreases, condensation can occur downstream of the expander, leading to suboptimal performance and accelerated wear of conventional gas turbine expanders.

This problem can be solved in two ways:

1) by preheating the natural gas to a temperature that prevents condensate formation after expansion;

2) using expansion machines (expanders) that provide efficient and reliable operation under these conditions.

Figure 8.5 illustrates the process of utilizing the overpressure of natural gas with preheating. Natural gas from the high-pressure pipeline passes through the control valve and then through heater 4 before expanding in turbine 2. After transferring its energy to turbine 2, the gas flows through the low-pressure pipeline to the consumer. The power generated by the turbine is converted into electrical energy by generator 3.

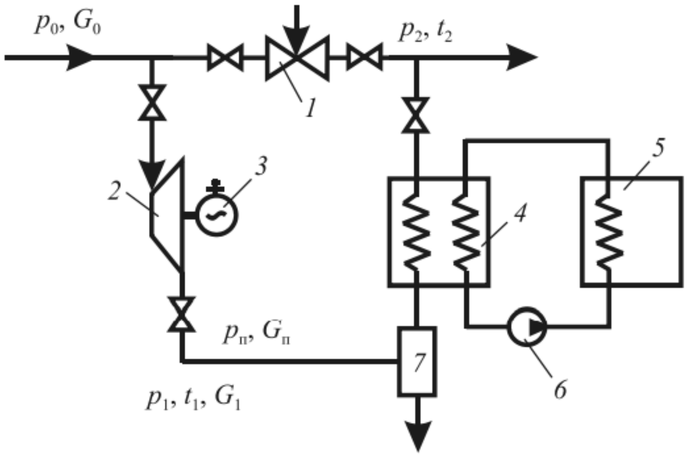


1 - GDS reducing valve; 2 - turboexpander; 3 - electric generator; 4 - heat exchanger

Figure 8.5 - Schematic diagram of a detander-generator unit with preheating

Natural gas is heated in four heaters to prevent the condensation of moisture and heavy fractions, such as hydrates, propane, and butane, which can compromise turbine reliability. To ensure this, the gas temperature behind the turbine must be maintained at a minimum of 5 °C. Additionally, it should not exceed the maximum allowable temperature of 40 °C to ensure the reliable functioning of the heat-insulating and anti-corrosion coatings of the gas pipeline. Heating the gas raises its internal energy, which in turn enhances the power of the turbocharger and improves its efficiency. Specifically, increasing the gas temperature from 0 °C to 80 °C can boost the power of the turboexpander by 30 to 35 %.

A drawback of this system is that it requires burning a portion of the natural gas to generate hot water for heat exchanger 4. This issue can be mitigated by using a heat pump unit to heat the gas before it enters the expander, utilizing some of the electricity generated by generator 3. In this scenario, only the potential pressure energy and low potential energy of the transported natural gas are harnessed for the proper functioning of the expander-generator unit. The low potential energy can come from secondary energy resources or ambient heat. Therefore, it appears beneficial to utilize the overpressure of natural gas in conjunction with a refrigeration chamber. (figure 8.6).



1 - reducing valve of GDS; 2 - screw detander; 3 - electric generator; 4 - heat exchanger; 5 - refrigerating chamber; 6 - circulation pump; 7 - separator

Figure 8.6 - Schematic diagram of a detander-generator unit with a refrigeration chamber

To implement this scheme, you need expansion machines (expanders) that meet specific requirements:

- high degree of gas expansion, reliable and efficient operation in variable modes;
- resistance to possible condensation and hydrate formation during expмansion.

These requirements are fully met by screw expanders, which belong to the class of bulky machines such as piston expanders. Unlike piston units, screw units have a rotary movement of the working parts, they do not have a gas distribution mechanism and there is no "dead volume".

8.4 Pressurization (compression) of waste steam

In numerous industries, a significant amount of low-pressure exhaust or secondary steam is released from various steam-utilizing systems, with parameters that are not suitable for further utilization in process equipment. However, by employing mechanical or thermal heat exchangers, it is possible to enhance the pressure of the exhaust steam, facilitating its subsequent use and leading to substantial savings in heat and fuel.

The pressure of the exhaust steam can be increased using several methods: mechanical (via electric drives or steam turbines), injection, and thermochemical processes.

Mechanical compression is one approach. Piston compressors are generally not utilized for increasing vapor pressure, as their size would need to be substantial to accommodate the large specific volumes of low-pressure vapor, resulting in considerable energy consumption during idle periods. For smaller capacities (up to 0.7 m^3/s), rotary compressors can be employed. For larger capacities, turbo-compressors powered by steam turbines or electric motors are utilized.

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A. K. Kinzhibekova

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