Строительные материалы и изделия
Construction Materials and Products

journal homepage: https://bstu-journals.ru

ISSN 2618-7183

DOI: 10.58224/2618-7183-2026-9-4-5

Improving the efficiency of steam condensation from combined-cycle gas mixtures in shell-and-tube condensers during CO_2 capture in cement plants

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Abstract. The article discusses the processes of heat exchange during the condensation of vapors from combined-cycle gas mixtures containing a significant amount of non-condensing gases and solid impurities. The original design of a horizontal shell-and-tube condenser with profiled fins providing rupture and dispersion of the condensate film is presented. A quantitative assessment of the effectiveness of the proposed apparatus was carried out in relation to the conditions of a cement plant (capacity of 1.0 million tons of cement per year). It is shown that the introduction of oxygen combustion of fuel with subsequent condensation of water vapor makes it possible to reduce the volume of exhaust gases by 54.6%, increase the mass fraction of co_2 in the stream to 94.8% and reduce carbon dioxide emissions by 0.83 tons of co_2 per ton of cement produced. The optimal angle of inclination of the fins distribution strips is 5°, at which the degree of condensation reaches 95.1%, and the heat transfer coefficient is 260 $W/(m^2 \cdot K)$. The proposed design makes it possible to reduce the metal consumption of the condenser by 12-15% compared to smooth-tube analogues without increasing hydraulic resistance.
Keywords: heat exchange, condenser, combined-cycle mixture, co_2 capture, cement clinker, finning, heat exchange intensification, film condensation, heat transfer coefficient, gas utilization, cement industry, energy efficiency, environmental safety

Please cite this article as: Golubev V.G., Syrlybekkyzy S., Taizhanova L., Nurbayeva F.K., Fediuk G.R., Fediuk R.S., Nesterenko N.G., Kerimbekova Z.M. Improving the efficiency of steam condensation from combined-cycle gas mixtures in shell-and-tube condensers during CO_2 capture in cement plants. Construction Materials and Products. 2026. 9 (4). 5. DOI: 10.58224/2618-7183-2026-9-4-5

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Received April 18, 2026; Received in revised form June 20, 2026; Accepted July 21, 2026

1. INTRODUCTION

Heat exchange processes play a fundamental role in modern technology, being the basis for the implementation of a wide range of technological operations in various industries. They are used everywhere where it is necessary to heat or cool the medium for its treatment and heat recovery. The importance of heat exchange processes cannot be overestimated: the efficiency of power plants, chemical reactors, air conditioning and refrigeration systems directly depends on the perfection of the heat exchangers used [1-3]. Heat exchange processes are particularly widely used in the chemical, oil refining, energy, construction, metallurgical and food industries. In the chemical industry, heat exchange equipment accounts for 15-18% of the total equipment by weight and cost, and up to 50% in the oil refining industry. A condenser is a heat exchanger in which vapors of a working substance (refrigerating agent or technological product) are cooled and condensed by heating a coolant – cooling water or air.

The problem of increasing the energy efficiency of industrial enterprises is becoming particularly relevant in the context of global climate challenges. The Intergovernmental Panel on Climate Change (IPCC) has repeatedly stressed that anthropogenic greenhouse gas emissions are the main cause of the observed global warming [4]. According to the IPCC, in order to limit the increase in the global average temperature to 2.0-2.4 °C by 2050, global co_2 emissions must be reduced by at least 50% compared to the level of 2000 [4]. The cement industry is one of the largest industrial sources of carbon dioxide emissions. According to the Global Cement and Concrete Association (GCCA), the cement sector accounts for about 5-8% of global anthropogenic CO_2 emissions [5, 6]. At the same time, cement production is characterized by specific features: approximately 60% of emissions are technological (decarbonization of limestone during clinker firing), which makes traditional methods of reducing emissions by increasing energy efficiency insufficiently effective [4, 5]. According to the IPCC Tier 1 methodology, 0.52 tons of CO_2 are formed during the production of 1 ton of clinker only due to the chemical decomposition reaction of calcium carbonate [4].

In the field of industrial construction, a condensing heat exchanger is widely used as a heat exchanger for the production of cement clinker using a wet method. It receives a mixture of fuel combustion products and moisture evaporated at the clinker firing stage. However, a very global problem is the increase in the degree of CO_2 capture from the exhaust gases of cement kilns in the light of the development of measures to reduce carbon dioxide emissions in the construction industry [5, 7]. Modern research shows that Carbon Capture, Utilization and Storage (CCUS) technologies are considered as a key tool for decarbonization of the cement industry. By the middle of the century, CCUS is expected to provide up to 36% of the total emissions reduction in the sector, which is equivalent to approximately 1.37 billion tons of CO_2 per year [5].

One of the promising approaches to CO_2 capture is the technology of fuel combustion in an oxygen environment (oxyfuel combustion). When CO_2 is captured using this method, the fuel is burned not in air, but in oxygen, which ensures a concentration of CO_2 in the exhaust gases of the order of 80% with the remainder being water vapor [8]. Oxyfuel technology is a combination of the combustion of fuel in an oxygen-rich atmosphere and the subsequent condensation of water vapor to produce an almost pure stream of CO_2. In the technology of capture with combustion of fuel in oxygen, an air separation unit (ASU) is required to produce oxygen, the technological scheme of which is shown in Figure 1. If gorenje oxygen is gorenje, the temperature in the combustion zone will rise to an unacceptably high level, so it is necessary to regulate the temperature regime by returning part of the exhaust gas back to the combustion zone [8-10]. The efficiency of CO_2 capture technologies is largely determined by the efficiency of heat exchange equipment. As shown in a study on the optimization of heat exchangers for CO_2 capture plants [1, 11, 12], the choice of the type of heat exchanger and its design parameters has a significant impact on both capital costs and operating costs. In particular, it was found that plate heat exchangers (PHE) demonstrate better economic and environmental performance compared to traditional shell-and-tube heat exchangers (STHX), reducing the cost of co_2 capture by up to 16% for a cement plant and up to 34% when using excess heat [1, 13, 14]. The optimal minimum temperature approach for plate heat exchangers is 4-7 °C [1].

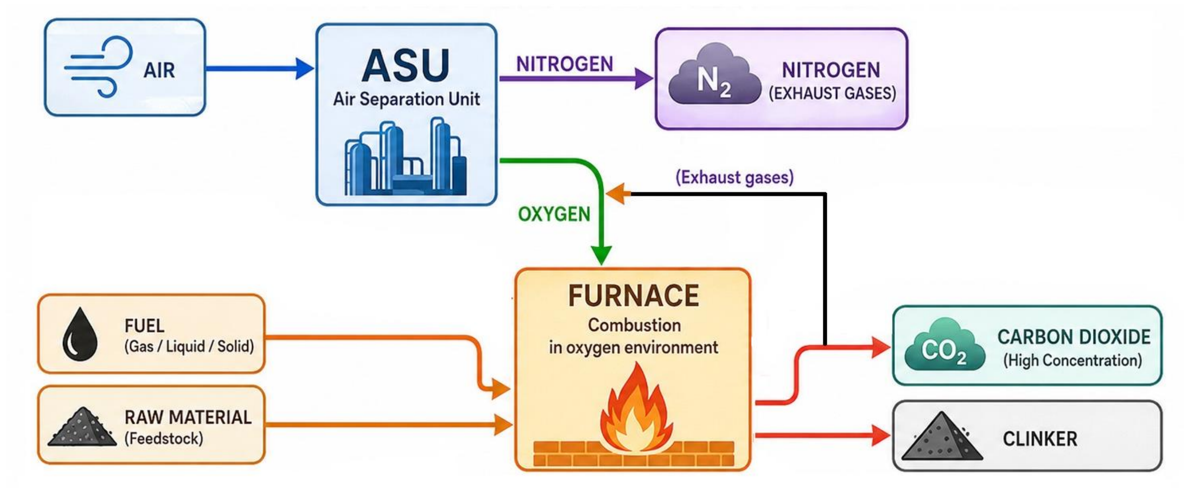


Fig. 1. Scheme of fuel combustion in an oxygen environment (ASU) [8].

The integration of Heat Exchanger Networks (HEN) plays a critical role in ensuring the economic feasibility of oxyfuel technologies in cement plants. SINTEF studies show that when designing heat exchange networks for oxyfuel cement plants, the Rankine steam cycle is preferable over organic Rankine cycles, allowing up to 10.5 MW of power to be utilized ideally and about 8.7 MW in an economically feasible configuration [7]. The features of heat exchange, mass transfer, and chemical transformations under conditions of combustion in an oxygen environment have yet to be studied and understood. This method is under active development; it seems that it has great prospects for the cement industry [5, 15, 16]. In 2025, Heidelberg Materials launched the Brevik project in Norway, the world's first industrial–scale cement plant with carbon capture [5]. In total, about 40 commercial CCUS projects in the cement industry are under development worldwide [5]. To implement this process, a developed capacitor design is required, which is proposed in this article. Thus, in the context of growing requirements for the environmental safety of industrial enterprises and the need to fulfill international obligations to reduce greenhouse gas emissions, the development of efficient heat exchange equipment for CO_2 capture systems is an urgent scientific and technical task.

The purpose of this study is to develop a highly efficient shell-and-tube condenser design for operation in a combined-cycle gas mixture containing a large amount of non-condensing gas and small particles. At the same time, CO_2 capture is considered as a key technology for decarbonizing industries, including cement production, using the example of the «ShymkentCement» Cement plant (Shymkent, Kazakhstan).

2. METHODS AND MATERIALS

The research object is the «ShymkentCement» plant, located in Shymkent, which was founded in 1958. The production capacity of the enterprise is 1.3 million tons of cement per year. In 2016, the plant became part of the international HeidelbergCement group. In 2017, the plant completed the construction of a new dry production process line, with a total investment of about 80 million US dollars. The new dry production line replaced four wet production lines, which improved efficiency and significantly reduced emissions into the atmosphere. According to environmental monitoring data, the volume of harmful emissions from the plant is: in 2022 – 31.6 thousand tons, in 2023 – 34.1 thousand tons, in 2024 - 35.7 thousand tons. The planned capacity of the enterprise is 1.3 million tons of cement per year or 1 million tons of clinker per year. The approved emission standards for 2025-2030 are 4,939,366 tons/year. To quantify the potential for reducing CO_2 emissions with the introduction of oxygen combustion, the calculation was performed using the formula recommended by IPCC:

$$E_{CO2}=M_{cl}\cdot EF_{cl} \quad (1)$$

where E_{CO2} is CO_2 emissions from cement production, tons; M_{cl} is the mass of clinker produced, tons; EF_{cl} is the emission coefficient for clinker, tons of CO_2/ton of clinker.

During the production of clinker, 0.83 t of CO_2 is formed per 1 ton of cement with a clinker factor of 80%, of which 0.45 t is accounted for by decarbonization of limestone and 0.28 t by fuel combustion. The specific direct greenhouse gas emissions from cement clinker production are 0.696–0.955 t CO_2-eq. per ton of clinker-. For the Shymkent Cement plant with a capacity of 1 million tons of clinker per year, the total amount of CO_2 emissions (with an average coefficient of 0.83 t CO_2/t clinker) is: $E_{CO2}=1000000 \cdot 0.83=830000$ t CO_2/year.

Intensification of heat exchange during condensation is an important task in the field of heat engineering and heat exchange processes. At the moment, there are several directions and technologies in the world aimed at improving heat transfer during condensation, which include the following: Nanostructured surfaces, microchannels, active control methods, the use of new materials, process optimization and combined systems. However, in this case, a factor such as energy intensity begins to play a role. The least energy-intensive methods of intensifying heat and mass transfer during condensation of vapors from combined-cycle mixtures include several relevant technologies and methods that are actively being researched and applied in the world: the use of nozzles and structured surfaces, microchannel heat exchangers, passive methods, combined systems, the use of new materials, optimization of process conditions and intermediate heat exchangers. The intensity of heat transfer in the condenser is influenced by the following factors:

1.The rate of liquid removal from the heat transfer surface. During steam condensation, condensate settles on the heat transfer surface in a solid film, which flows down the pipes, making it difficult for further steam condensation.

2. The speed of steam movement. At a high speed of steam movement, the movement of the liquid film accelerates, which is washed off faster from the heat transfer surface, increasing the heat transfer coefficient.

3. An admixture of air and non-condensing gases, reducing the heat transfer coefficient and increasing the condensation pressure.

4. Deposits on the walls of pipes: on the refrigerant side – oil carried away by steam from the compressor; on the water side – water stone (solid sediment of salts dissolved in water), rust; in air-cooled condensers – a layer of dust, paint. All these deposits have significant thermal resistance, reducing the heat transfer coefficient.

5. The speed of water movement. The higher the water velocity w (m/s), the greater the heat transfer coefficient from the pipe wall to the water, and therefore the heat transfer coefficient.

The listed methods and technologies are aimed at reducing energy consumption and increasing the overall efficiency of condensation processes, which makes them relevant in modern conditions. However, in difficult conditions, during the condensation of vapors from combined-cycle gas mixtures containing a significant amount of non-condensing gases and solid impurities, several additional problems appear: These include the following: reduced condensation efficiency, heat exchange problems, corrosion and contamination of equipment, phase change, increased cleaning costs and process control problems. Thus, in order to implement heat and mass transfer processes in such conditions, it is necessary to develop effective designs of devices capable of ensuring stable operation in these difficult conditions.

The intensity of the process or the specific thermal capacity of a heat exchanger is the amount of heat transferred per unit of time through a unit of heat exchange surface under a given thermal regime. The intensity of the heat exchange process is characterized by the heat transfer coefficient. The intensity and efficiency are also influenced by the shape of the heat exchange surface; the equivalent diameter and layout of the channels that ensure optimal speeds of the media; the average temperature pressure, the presence of turbulence elements in the channels, fins, etc. In addition to constructive methods of intensifying the heat exchange process, there are regime methods associated with changing the hydrodynamic parameters and the flow regime of the liquid at the heat exchange surface. Regime methods include: applying vibrations to the heat exchange surface, creating flow pulsations, injecting gas into the flow or suction of the working medium through a porous wall, applying electric or magnetic fields to the flow, preventing contamination of the heat exchange surface by strong turbulence of the flow, etc.

The method of calculating the film condensation of steam from a combined-cycle gas mixture on a horizontal pipe is based on the joint solution of the equations of heat transfer of the condensate film and steam mass transfer through the boundary layer of the gas. The thermal resistance of the condensate film and the diffusion resistance of the gas layer are taken into account [17, 18]. The main method is to use the heat transfer coefficient, adjusted for the presence of non-condensing gas. The main calculation steps are to determine the properties of the medium, calculate the heat transfer of pure steam, take into account the influence of non-condensing gas, calculate mass transfer and iterative calculation. 1. Determination of the properties of the medium: The calculation of the physical parameters of the liquid and mixture (density, viscosity, thermal conductivity, diffusion coefficient) is carried out at the average temperature of the film and mixture. 2. Calculation of heat transfer of pure steam (apl) The Nusselt formula is applied for a horizontal pipe (1):

$$\alpha_{\text{пл}} = 0.725\left[\frac{\lambda_l^3\rho_l^2 gr}{\mu_l d\Delta t}\right]^{0.25} \quad (2)$$

where r is the latent heat of vaporization, d is the diameter of the pipe, $\Delta t = ts\text{-}tw$ is the temperature difference 3. Taking into account the influence of non-condensing gas: In the presence of gas, heat transfer decreases. The ratio of the heat flow in the presence of gas to the heat flow of pure steam is used, often calculated using dimensionless complexes that take into account the concentration of steam.

4.Calculation of mass transfer ($\boldsymbol{\beta p}$): To determine the mass transfer coefficient, use the criterion equations (2):

$$Nu_D = \frac{\beta_p d}{D} = CRe^n Ga^m Pr_D^p \quad (3)$$

where D is the diffusion coefficient.

Iterative calculation: Since the surface temperature of the film depends on the heat flux, the calculation is carried out using successive approximations to determine the true heat flux density q and the temperature on the condensate surface. Features for a bundle of pipes. When calculating the pipe bundle of horizontal pipes, the effect of condensate draining from the upper pipes to the lower ones is taken into account, which increases the thickness of the film and reduces the average heat transfer coefficient.

3. RESULTS AND DISCUSSION

When creating new, more efficient capacitors, the designer should strive to: reduce the specific cost of materials, labor, and energy spent during operation compared to the same indicators of existing capacitors. The most important factor that the designer should focus on is the specific thermal performance of the heat exchanger, that is, the characteristic of the amount of heat transferred per unit of time through a unit of heat exchange surface under a given thermal regime should be as high as possible to ensure the best condensation performance.

In order to solve this problem, we have created a capacitor design for operation in difficult conditions [2, 19, 20]. This design refers to devices designed to condense vapors generated during the operation of ore-thermal furnaces, in particular, in the production of phosphorus, manganese, alumina, titanium [21-23], and rotary kilns in the production of cement clinker [24-26] and other industries [27-29]. Scrubber-type apparatuses are known, containing several columns connected in series by flues, in which furnace gases are moved and direct contact with the coolant is carried out using the counterflow method [30]. However, in these systems, water absorbs various impurities from gases, which chemically interact with it to form compounds that are difficult to separate from the condensed matter. This reduces the yield of the condensed product and its quality. Consequently, there is a need to use devices that exclude direct, i.e. direct interaction of the cooling medium, in particular, water and furnace gases. Thus, it is necessary to use devices in which direct contact of furnace gases with cooling water is excluded and allows you to choose it as a more promising one. As an example, capacitors containing a housing with a horizontally arranged bundle of pipes equipped with transverse ribs and pipes for supplying and discharging a vapor-gas mixture from the inter-tube space were considered [19, 30]. In particular, in the work of Afanasyev I in [31], 4 factors affecting the quality of heat exchangers (TA) are formulated:

1. Dependence on the external configuration of the edge and its location. Most often, the rib is fixed externally, but in some cases, the inner fins of the pipes are used.

2. The external structure of the supporting pipe. In finned TA, it is common to use pipes of round, elliptical and rectangular cross-sections.

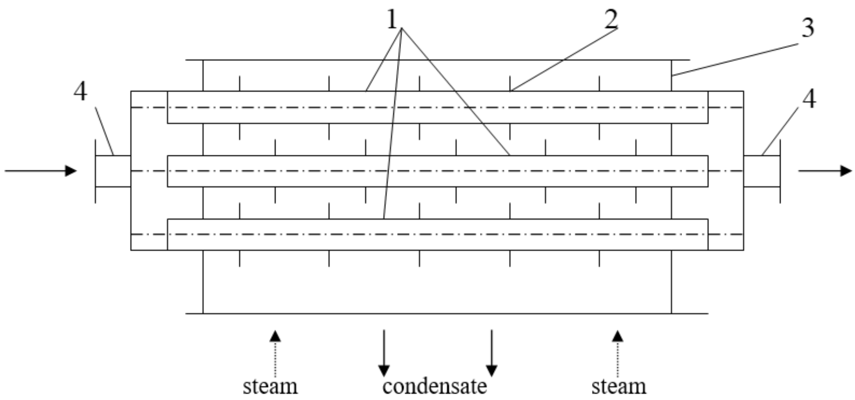
3. The method of connecting the structural components of a finned pipe to each other.

4. Operating conditions. The use of finned TA is widespread, and in this regard, the influence of the range of external temperature, pressure, the presence of an aggressive environment, air pollution, etc. is significant. However, these finned apparatuses cannot be successfully used for vapor condensation, for example, phosphorus or other combustion products of ore-thermal furnaces due to the relatively low values of heat transfer coefficients from the gas phase. A simple increase in the geometric surface of such heat exchange devices leads to an increase in the metal consumption of the condenser or to an increase in hydraulic resistance, which is unacceptable due to the safety conditions of the process. Therefore, the purpose of the development was to intensify the condensation process. This goal was achieved by the fact that in a condenser containing a housing with a horizontally arranged bundle of cooling pipes equipped with transverse ribs and pipes for supplying and discharging the combined-cycle gas mixture, they are made in the form of separate strips bent in alternating order, in opposite directions relative to the plane of the side rib, at different angles increasing from the vertical axis of the pipe in the direction of to its horizontal axis.

The condenser shown in Fig. 2 and 3 has a horizontally arranged bundle of cooling pipes 1, a housing 3, inlet and outlet pipes for cooling water 4, fins 2 on the cooling pipes, as well as inlet and outlet pipes for the steam-gas mixture. It is possible to install several cooling units in the condenser.

The presence of fins makes it possible to significantly increase the heat exchange surface, and its implementation in the form of distribution strips 3 makes it possible to increase the intensity of the heat exchange process. Thanks to these strips, the effect of tearing the film is achieved, which in the form of trickles and droplets irrigates the flow of the combined-cycle gas mixture and provides additional cooling. If two such cooling units are used, then after the first of them the mixture can be cooled to the dew point temperature, and in the second unit the main condensation will be carried out. The smooth bending of the fin strips allows for uniform irrigation of the condensate stream. This helps to create a gentle cooling mode that prevents fog formation in the volume of the device. Thus, the proposed design, while reducing material consumption, makes it possible to increase the degree of condensation.

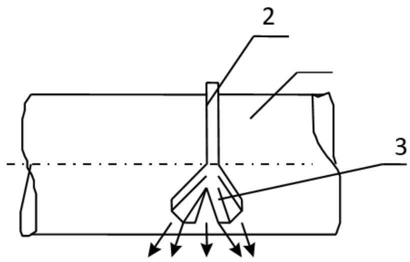
The distribution strips can be formed by cutting the lower edges of the ribs, followed by bending. In this case, the incision is carried out mainly along such lines so that the areas of the ribs above each of them are the same (or correspond to the cross-sectional area of the condenser irrigated by this strip) to ensure uniform distribution of condensate over the cooled surface in the volume of the condenser.



1 – heat exchange pipes; 2 – fins; 3 – housing; 4 – pipes

Fig. 2. Is a condensation apparatus with a horizontal bundle of pipes.

In the described design, turbulence of the vapor-gas mixture corresponds to a decrease in thermal resistance from the gas, which increases the coefficients of heat and mass transfer and increases the cooling rate. The described effects are particularly noticeable in the case of highly viscous condensate. Indeed, with increasing viscosity, the amplitude decreases and at the same time the frequency of the waves decreases, and their length increases. Reducing the frequency of the waves leads to a decrease in the cross-mixing coefficient, which also contributes to an increase in the effective mixing coefficient.



1 – pipe; 2 – rib; 3 – distribution strips

Fig. 3. A fragment of the fins of a horizontal heat exchange pipe.

The experiments performed have shown the efficiency of heat transfer when installing cut-off fin strips at an angle from 5° to 25° (Table 1).

Table 1. Results of experimental studies.

№	Angle of inclination of the fin strips, deg.	Heat transfer coefficient (α), W/m^{2}K	Heat transfer (Nu)	Degree of condensation (η), %	Note
1	5	260	6,3	95,1	
2	10	254	6,1	92,4	
3	15	251	5,7	90,1	
4	20	245	5,2	88,2	
5	25	240	5,1	85,3	
6	30	236	4,5	83,2	Low heat transfer coefficient
7	35	232	4,1	81,4	
8	40	227	3,6	79,8	
9	45	223	3,2	77,4	

The capacitor works as follows. The combined-cycle gas mixture enters through the nozzle 2, interacts in the first underlying section (tier) of the condenser with drops of cooled condensate flowing down from above and passes between the cooling pipes 5, fins 6 and strips 7 of their fins, and due to this turbulates and cools. The resulting liquid condensate condenses on the surface of the tubes 5, fins 6, and flows down them into strips 7, from which it flows into the steam-gas mixture stream in the form of trickles or droplets evenly distributed over the cross-section of the condenser. The uncondensed gases are discharged through pipe 3, and the liquid condensate flows down into the water bath. The cooling medium enters the finned pipes 5 of the apparatus through the nozzle 4 at a temperature above the melting point of the condensed component, receives the heat of the cooling vapor-gas mixture and the heat of condensation of liquid condensate and is discharged from the outlet pipe 4. Turbulence of the mixture contributes to a decrease in thermal resistance from the gas side, which increases the heat transfer coefficient and its cooling rate. An increase in the geometric surface of the heat exchange due to the contact of gas with the flowing condensate, unlike the known designs of condensers with a finned surface, intensifies heat transfer. Further, entering the second section of the condenser, the vapor-gas mixture gives off condensation heat on the heat exchange surfaces of the substance, the vapors of which condense. Part of the condensate evaporates, enriching the combined-cycle gas mixture. In this case, a sufficient amount of liquid is formed (taking into account the condensation of the evaporated part of the substance in the first section) for uniform irrigation of the first section. The presence of strips on the lower edges of the fins ensures an even distribution of the flowing condensate in the incoming steam-gas mixture stream, i.e. creates an additional cooling surface. This creates milder condensation temperature conditions that exclude the possibility of stable formations (aerosols), i.e. the degree of condensation increases and at the same time, the metal consumption of the condenser decreases.

Horizontal tubular condensers are of particular interest for the condensation of liquid vapors with high viscosity. The thermal resistance of the condensate in them is less than in vertical condensers, since the bulk of the liquid flows down the lower forming tube, while in the upper part of the section the thickness of the liquid film is very small. The calculation of the thermal resistance of the condensate in this case is much more difficult, since the thickness of the flowing liquid layer is uneven around the perimeter of the pipe. The calculation is particularly difficult for condensate of variable viscosity. This problem becomes essential in the design of condensers for sulfur-gas mixtures due to the fact that the viscosity of liquid elemental sulfur varies greatly with temperature. Such a change in viscosity cannot be ignored, and given that liquid sulfur has a relatively low thermal conductivity, the thermal resistance of the condensate layer accounts for a significant proportion of the total resistance of the process. Thus, determining the thickness of the condensate film is a necessary element in the calculation of capacitors. At the same time, various designs of heat exchange pipes and methods of their calculation were studied and used [32-34].

Based on Table 1, optimal in terms of the maximum degree of condensation (95.1%) and heat transfer coefficient (260 $W/(m^2{\cdot}K)$) is the angle of inclination of the distribution strips of 5°. An increase in the angle to 25° leads to a decrease in the degree of condensation to 85.3%, and at angles above 30°, the process efficiency drops to unacceptable values (below 83%). To quantify the effect of the introduction of the developed capacitor into the technological scheme during the reconstruction of the Shymkent Cement plant, the main technical and economic indicators were calculated. The thermal capacity of the proposed capacitor is determined by the formula:

$$Q = K \cdot F \cdot \Delta t\text{ср} \tag{4}$$

где, K is the heat transfer coefficient, $W/(m^2{\cdot}K)$; F – is the heat exchange surface, m^2; Δtср – is the average logarithmic temperature pressure, К.

When using finned pipes with distribution strips, the effective heat exchange surface increases 3-5 times compared to smooth-tube analogues. The heat transfer coefficient at optimal finning parameters (angle 5°) is 260 $W/(m^2{\cdot}K)$, which exceeds the performance of standard capacitors by 15-20%. Specific thermal performance of the device:

$$q = FQ = K \cdot \Delta t\text{ср} \tag{5}$$

At an average temperature pressure of 30-40 °C, the specific thermal capacity of the proposed condenser is 7.8–10.4 kW/m^2.

The reduction in metal consumption of the condenser compared to smooth-tube analogues is estimated at 12-15% due to more efficient use of the heat exchange surface and the possibility of reducing the overall dimensions of the device.

The relative and derived efficiency indicators of the developed capacitor are shown in Table 2.

Table 2. Relative and derivative values of the capacitor.

Angle, deg.	α/α_{max} (rel. heat transfer)	η/η_{max} (rel. degree of condensation)	Loss of η relative to the maximum, %	Increase of α by 1° (average), %
5	1.000	1.000	0.0	–
10	0.977	0.972	2.8	-0.46
15	0.965	0.947	5.3	-0.24
20	0.942	0.927	7.3	-0.46
25	0.923	0.897	10.3	-0.38
30	0.908	0.875	12.5	-0.30
35	0.892	0.856	14.4	-0.32
40	0.873	0.839	16.1	-0.38
45	0.858	0.814	18.6	-0.40

The presented table 2 allows us to trace the sensitivity of the main criteria (heat transfer coefficient α and degree of condensation nn) to changes in the angle of inclination of the fins distribution strips. All values are normalized to the maximum reached at an angle of 5° (α_{max}= 260 W/(m^2·K), η_{max}= 95,1 %). The table shows that the relative heat transfer (α/α_{max}) decreases monotonously from 1,000 to 0.858 with an increase in the angle from 5° to 45°, which indicates a gradual deterioration in heat transfer due to increasing aerodynamic drag and less effective film tearing and is described by the following equation α/α_{max}=-0.023x+1.0178 with an approximation coefficient (R^2) = 0.996. At the same time, the relative degree of condensation **(**η/η_{max}**)** drops even more noticeably, from 1,000 to 0.814. This indicates that even a small increase in the angle (for example, from 5° to 10°) results in an efficiency loss of ~2.8%, and at 45° the loss reaches 18.6% and is described by the equation: η/ηmax=-0.0177x+1.0148 with R^2=0.997. The column «Loss of η relative to the maximum clearly demonstrates that the angle range of 5-15° is "operational" with acceptable losses (up to 5.3%), while angles over 25° lead to significant (more than 10%) reductions in the degree of condensation and describes by the equation: η=2.295x-1.775 with R^2 = 0.996. And an increase of α by 1° (negative) is calculated as the average change between neighboring points; it shows that the sharpest drop in heat transfer occurs in the 5-10° and 20-25° ranges, which is probably due to a change in the structure of the strip flow.

The calculated values of the specific thermal performance q (with a fixed surface F = 100m^2 are given in Table 3.

Table 3. Calculated values of specific heat output q (with a fixed surface F =100m^2 and an average temperature pressure Δtcp=35 °C).

Angle, deg.	α, W/(m²·K)	Specific heat output q = α·Δt, кW/m²	Total capacity Q = q·F, кW
5	260	9.10	910
10	254	8.89	889
15	251	8.79	879
20	245	8.58	858
25	240	8.40	840
30	236	8.26	826
35	232	8.12	812
40	227	7.95	795
45	223	7.81	781

Table 3 shows the values of specific heat output q (кW/m²) Table 3 shows the values of specific heat output *Q* (кW) or an apparatus with a heat exchange surface of F = 100 m2 and an average logarithmic temperature pressure of Δtcp=35 °C (a typical value for condensers of combined-cycle mixtures of cement kilns). Table 3 shows that at an angle of 5°, the specific power is 9.10 кW/m², which is 14-16% higher than at an angle of 45° (7.81 kW/m2). For an industrial condenser with a surface area of, for example, 500-1000 m^2 (typically for lines with a capacity of 1 million tons of clinker per year), the difference in total power can reach 600-1200 kW, which significantly affects the size and material consumption of the device. The data obtained allows you to scale the design: knowing the required thermal load, you can determine the required surface at the selected angle, and then calculate the mass of the metal and the cost.

The proposed design of a horizontal shell-and-tube condenser was tested in laboratory studies, which resulted in the development of the following upgraded technological scheme for burning fuel in an oxygen environment during firing of a raw material mixture to produce clinker (Fig. 4).

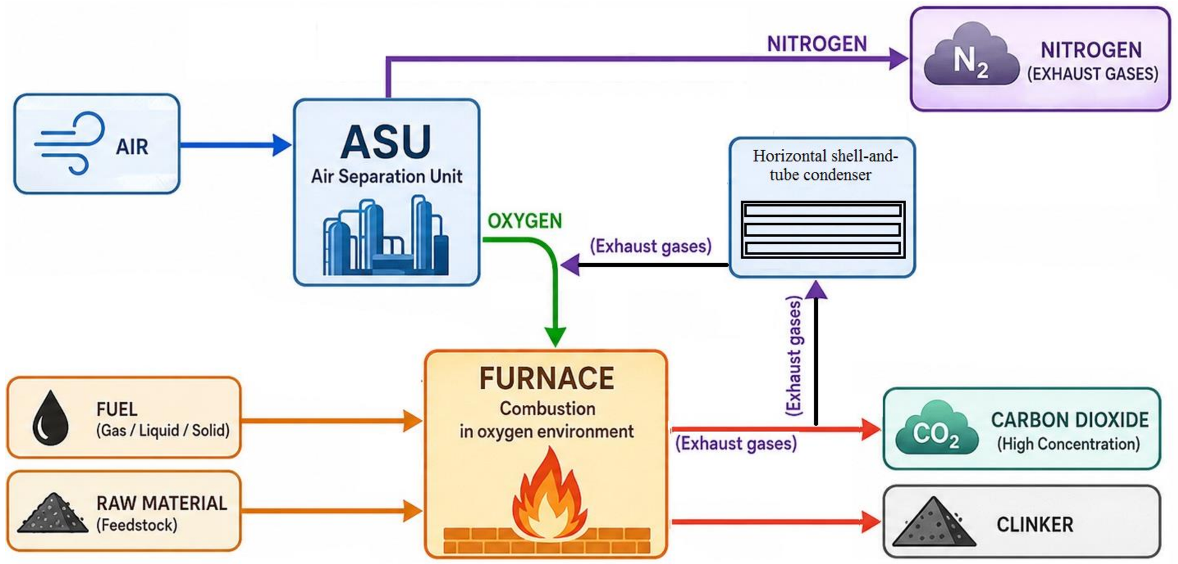


Fig. 4. Upgraded fuel combustion scheme in an oxygen environment.

According to the results of the preliminary tests of this capacitor design, samples of fine dust particles were captured, the elemental composition of which is shown in Fig. 5.

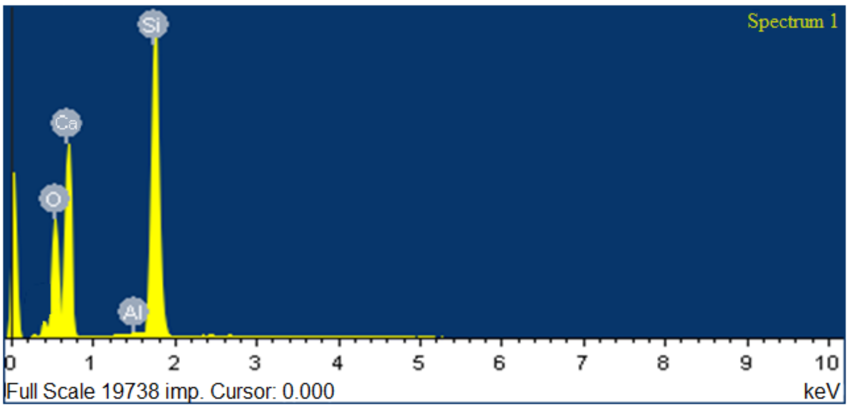
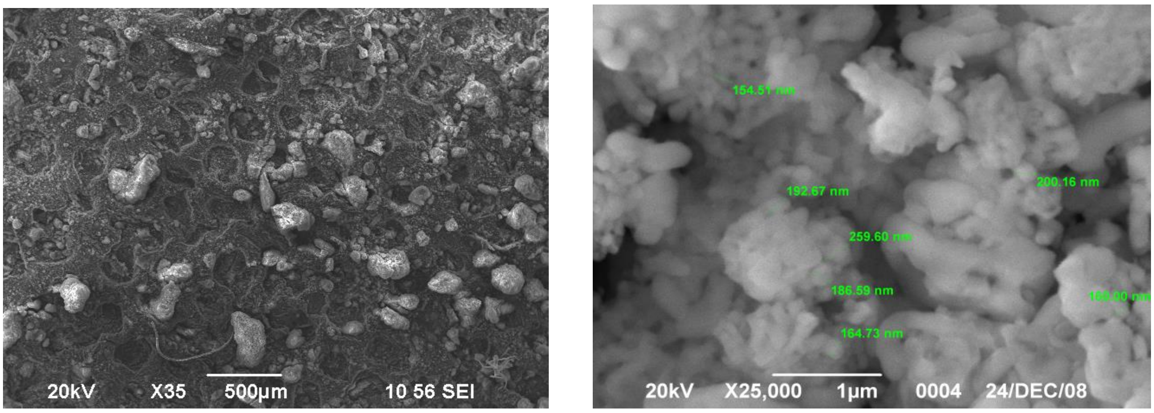


Fig. 5. Elemental composition of trapped waste dust.

Fig. 5 shows that the elemental composition of dust is represented by silicon, aluminum, calcium, and oxygen of about 100%. The size composition of the dust particles is shown in Fig. 6.



A) B)

Fig. 6. Micrographs of the general view (A) and the dimensional composition (B) of the captured waste dust.

Fig. 6 shows that the dust trapped with gases is represented by fine particles ranging in size from 160.0 to 200.16 nm, which are grouped into conglomerates. Thus, the condenser helps to clean the exhaust gases from dust in addition to its condensation properties.

The technical and economic indicators for the ShymkentCement plant during the transition to oxygen combustion using the proposed condenser design are shown in Table 4.

Table 4. Technical and economic indicators for the Shymkent Cement plant during the transition to oxygen combustion using the proposed condenser design.

Indicator	Basic version (without trapping)	Oxygen burning version + new condenser	Change
CO_2 emissions, thousand tons/year	830	41.5–83.0 (when capturing 90-95%)	↓ 90–95 %
Exhaust gas volume, million m^3/year	2.5	1.14	↓ 54.6 %
Concentration of CO_2 in gas, % vol.	~14–15	~94.8	↑ 6.3 times
Coal consumption, thousand tons/year	250	175	↓ 30 %
Metal capacity of the condenser (rel.)	1.00	0.85–0.88 (due to the fins)	↓ 12–15 %
Heat transfer coefficient K, $W/(m^2·K)$ (for smooth pipes – ~180)	~180	260 (for 5°)	↑ 44 %

Table 4 contains the integral results of the introduction of oxygen combustion with a new condenser on the scale of real production (1 million tons of clinker/year). A comparison of the basic version (without capture) and the proposed one makes it possible to quantify the resulting technical and economic effect, in particular:

– CO_2 emissions are reduced by 90-95 % (from 830.000 tons to 41.5–83.000 tons per year), which complies with strict climate regulations and makes it possible to participate in carbon markets;

– The volume of exhaust gases is reduced by more than half (by 54.6%), which reduces the load on gas cleaning equipment and fans, reducing energy consumption for traction;

– The concentration of Co_2 increases from ~14-15% to ~94.8%, which makes the capture technology economically feasible (no additional purification from nitrogen is required);

– Coal consumption drops by 30 % (savings of 60-75 thousand tons/year), which at current energy prices gives a direct financial effect of 6-12 million US dollars per year (depending on the cost of coal);

– The metal consumption of the capacitor is reduced by 12-15% due to the compactness of the finned surface, which reduces the cost of manufacturing and installation;

– The heat transfer coefficient increases by 44% (from 180 to 260 $W/(m^2·K)$), which allows you to either reduce the area of the device while maintaining power, or increase the productivity of the line.

In general, the introduction of the developed condenser in combination with oxygen combustion technology is economically and environmentally feasible for the cement industry. It allows us to simultaneously solve the problems of decarbonization, increase energy efficiency and reduce production costs. The presented tabular data and dependencies serve as a reliable engineering basis for decision–making at all stages - from feasibility studies to working documentation and subsequent operation of cement plants.

4. CONCLUSIONS

As a result of the performed analysis and experimental studies aimed at solving the urgent problem of increasing the efficiency of vapor condensation from combined-cycle gas mixtures at high temperatures, dustiness and the presence of non-condensing gases, the following conclusions can be drawn:

- That the introduction of oxygen combustion of fuel followed by condensation of water vapor is one of the most promising methods for reducing CO_2 emissions in the cement industry. However, the implementation of this method requires the creation of condensers capable of operating in difficult conditions with a high content of non-condensing gases (up to 20%) and solid impurities;

- Traditional scrubber type condensers lead to direct contact of cooling water with gases and the formation of difficult-to-separate compounds, and standard finned devices do not provide sufficient heat exchange due to the formation of a continuous film of viscous condensate and high thermal resistance of the gas phase;

- The developed condenser design with a horizontal bundle of finned pipes and bent distribution strips (at angles from 5° to 25°) allows:

- create the effect of tearing and dispersing the condensate film;

- turbulize the combined-cycle gas flow, reducing diffusion resistance;

- ensure uniform irrigation of the section of the device, preventing stable fog formation;

- Optimal in terms of the maximum degree of condensation (95.1%) and heat transfer coefficient (260 $W/m^2·K$) is the angle of inclination of the distribution strips of 5°. An increase in the angle to 25° leads to a decrease in the degree of condensation to 85.3%, and at angles above 30°, the process efficiency drops to unacceptable values (below 83%);

-According to the simulation data, linking the oxygen-enriched combustion process with cement production technology reduces the flow of exhaust gases by 54.62%. In the conditions of the Shymkent Cement plant with a capacity of 1 million tons of clinker per year, the volume of exhaust gases is reduced from 2.5 million m^3/year to 1.14 million m^3/year;

- The mass fraction of CO_2 in the stream increases to 94.83%, which greatly simplifies the subsequent capture and disposal of carbon dioxide. During industrial tests of the partial oxygen combustion system, the concentration of CO_2 in the exhaust gases was reached at the level of 82.7%;

-The use of oxygen combustion reduces coal consumption by 30%. In the conditions of the ShymkentCement plant, which consumes approximately 200-250 thousand tons of coal per year, savings will amount to 60-75 thousand tons of coal annually;

- The exergetic efficiency of the entire furnace system is increased by 17.56 % compared to traditional production technologies;

- Carbon dioxide emissions can be reduced by 90-95%. For the ShymkentCement plant, this means a reduction in annual emissions from 830000 tons of CO_2 to 41 500-83 000 tons of CO_2 per year;

- The proposed design makes it possible to reduce the metal consumption of the condenser compared to smooth-tube analogues and increase specific thermal performance without increasing hydraulic resistance. The calculation method, which takes into account the variable viscosity of condensate and the influence of non-condensing gases, ensures the correct design and construction of such devices.

The results obtained are of great practical importance for the modernization of heat exchange equipment during the construction of plants in the metallurgical [35-37], cement [38-40] and other industries [41-43].

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