Steam condenser for plants with carbon dioxide recovery

O O Milman\textsuperscript{1,2}

\textsuperscript{1}Kaluga State University named after K.E. Tsiolkovski, Russia, 248023 Kaluga, 26 Stepana Razina Street
\textsuperscript{2}CJSC Scientific Production Company “Turbocon” (CJSC SPC “Turbocon”), Russia, 248010 Kaluga, 43 Komsomolskaya Roscha

E-mail: turbocon@kaluga.ru

Abstract. Power plants with CO2 utilization have been designed by Allam, Mateant, Turbocon, etc. One of the main problems of this plant is a condenser for steam-gas mixture with high concentration of non-condensable gas. The process of development of steam condenser for steam-gas mixture is described. Its design is based on the idea of maintaining a constant steam-gas mixture velocity along the steam condensation channel. The shape of the channel with constant SGM velocity is described. To research the heat-mass transfer of gas-team mixture the test plant with tubes crosscut by thermocouples is realized. In the process of testing, gas-steam mixture velocity, pressure and air concentration changed from 0% to 18%. The experimental results have been summarized in a dimensionless equation. The pressure drop and increase of air concentration contribute to the decrease of saturation temperature. The optimal velocity is reached when the surface area of the channel in the condenser is minimal. The optimal velocity is about 30 – 50 m/s. The research results are implemented in the experimental model of high-efficiency condenser. The heat transfer coefficient in this model is equal to about 4500 – 2700 W/(m\textsuperscript{2}K) if air concentration at the inlet is 0–8 %. The designs of high-efficiency condenser for gas-steam turbine plant of 25 MW capacity and the condenser with vertical tubes have been presented.

The parameters and composition of the steam-gas mixture in the condensers with carbon dioxide utilization cycles are determined. The process of developing a steam condenser from a steam-gas mixture (SGM) is described. The design is based on the idea of maintaining a constant velocity of the steam-gas mixture along the entire channel. The shape of the channel with a constant SGM velocity is described. To study heat and mass exchange from SGM, a test plant with heat exchange tubes crosscut with thermocouples is developed. In the process of research, the velocity of the steam-gas mixture, the pressure and the air concentration vary from 0% to 18%. The experimental data are generalized with a dimensionless equation. Since pressure losses and an increase in air concentration lead to a decrease in the steam saturation temperature, there is an optimal SGM velocity when the condenser surface is minimal. The value of this velocity is in the range of 30-50 m/s. The research results are implemented in a prototype of a high efficiency condenser. Its heat exchange coefficient lies in the range of 4500-2700 W/m\textsuperscript{2}K with an air concentration at the inlet of 0-8%. A design of a condenser for a 25 MW gas-steam turbine and a condenser with vertical tubes is presented.

The environmental requirements of the new era stimulate the creation of power plants with a minimum impact on the environment and global climatic parameters. Such plants include everything
related to hydrogen energy, as well as the Mitiant, Allam and Turbocon cycles. These cycles differ significantly from each other, but they have a fundamental commonality: they are focused on the combustion of fossil fuel, the oxidizer is oxygen, and CO$_2$ is utilized at the outlet.

![Diagram](image)

**Figure 1.** Schemes of electrical plants with the carbon dioxide utilization (a) Allam (b) Turbocon.

In all these plants, it is necessary to separate CO$_2$ from water steam in a condenser-separator (CS), and remove the condensation heat into the environment. With an efficiency of 45 ÷ 55%, heat removal is realized in the condenser-separator, the dimensions, weight and cost of which significantly affect the technical and economic characteristics of the plant as a whole. For example, in the Allam cycle, the heat of condensation of water steam, generated during natural gas combustion, makes up 30% of the total heat removed. In this case, the volume concentration of CO$_2$ at the inlet to the condenser-separator will be more than 30%, and the mass concentration will be more than 50%. Thus, the task of creating an effective water steam condenser from a mixture with combustion products (SGM) becomes quite relevant.

The presence of non-condensable gases (NCG) is the main reason for a sharp decrease in the heat exchange coefficient from the SGM to the condensation surface, around which a diffusion layer with a high concentration of NCG is formed [1]. A real way to reduce the size of this layer is the dynamic effect of the high-velocity SGM flow. This is how the idea of a condenser with maintaining a constant steam velocity was during condensation arose [2]. The shape of the steam channel under the condition $w_s = $ const is shown in Figure 2a, and the constructive implementation in Figure 2b.

An increase in the SGM velocity increases the heat exchange coefficient with a simultaneous increase in pressure losses, which reduces the partial pressure and saturation temperature $t_s$. Steam condensation as it moves in the channel also decreases $t_s$.

Obviously, there is an optimal SGM velocity when, for a given heat removal, the condenser surface area is minimal. Figure 3 illustrates this dependence for various steam velocity $w_s$ and, what is important, for various cooling water velocity inside the tubes [3]. Indeed, the heat exchange surface is determined by the intensity of heat transfer $\alpha$ from both sides of the dividing wall, and at a low value of the heat exchange coefficient of water $\alpha_w$ from the water side, an increase in the velocity of the steam-gas flow will not give a noticeable effect.
Figure 2. Channel shape for steam condensate from SGM.

Figure 3. Calculation of the optimal steam velocity at the water velocity 2 m/s (1–4) and 4 m/s (5): value pc: 1 – 5 kPa; 2 – 10 kPa; 3 – 15 kPa; 4 – 20 kPa; 5 – 10 kPa.

Calculations of the optimal SGM velocity for technically pure steam (mass concentration of air at the inlet of no more than 0.01%) have been performed. The calculation results shown in Figure 3 illustrate this situation: with an increase in water velocity from 2 to 4 m/s, the optimal value of \( w_{\text{opt}} \) increases from ~35 to 50 m/s. It is important to note that \( w_{\text{opt}} \) is practically independent of the steam pressure.

For the case of technically pure steam, a prototype condenser with vertical tubes with a diameter of 16 × 1.5 mm made of CuNiAl alloy has been developed to provide a cooling water velocity of up to 4 m/s (and or brass tubes - of up to 2 m/s). The configuration of the steam channel with a constant steam velocity in the model with a vertical arrangement is shown in Figure 4.

With the water velocity of 3.4 m/s, a heat exchange coefficient of 5.5 kW/m²K is obtained, which is unattainable for classical steam condensers.

In the case of condensing technically pure steam, the presence of non-condensable gases makes affect at the end of the condensation process, in the last rows of the narrowing steam channel. In the case of a
power plant operating according to the Allam or Turbocon cycle, the concentration of NCG is significant at the very beginning of the condensation process at the inlet to the condenser-separator. To calculate heat and mass exchange in such a channel, it is necessary to obtain experimental data on the influence of the SGM velocity and NCG concentration on the intensity of the condensation process. For this purpose, a test plant has been created; its working section is shown in Figure 5 [4].

Figure 4. Steam condenser with vertical tubes. (a) the layout of the vertical tube bundle; (b) test results with a variable cooling water speed; and (c) with variable air construction.

Figure 5. Working section of the test plant: (a) – construction arrangement; (b) – installation of thermocouples.
A steam-gas mixture of a given concentration is formed in the chamber at the entrance to the working section, the SGM flow passes through a leveling grid and a section of 5 tube bundles for hydraulic stabilization and condenses on five copper tubes of 26×2 mm with thermocouples (4 pcs. in each tube). In the process of testing there are changes in the velocity of SGM, pressure and air concentration in the mixture.

The result of the experiment is shown in figure 6.

Figure 6. The effect of the air proportion in the steam on $\alpha/\alpha_{Na}$ during steam condensation from moving steam gas mixture: 1 – $\rho_w^2 = 64$–66 Pa; 2 – $\rho_w^2 = 61$ Pa; 3 – $\rho_w^2 = 40$ Pa; 4 – $\rho_w^2 = 22.5$ Pa; 5 – $\rho_w^2 = 9.5$ Pa; 6 – $\rho_w^2 = 0$, 7 – calculation $\alpha$ L.D.Berman at $v=0$; pressure $p=25$–35 kPa.

The experimental results are summarized by the equation

$$\frac{\alpha}{\alpha_{Na}} = 28.3\Pi^{0.08}N_u^{0.58}(1 + 245\Pi)^{0.33}e^{-11.1\Pi^{0.08} - 0.84},$$

where $\Pi = \frac{\rho_s w^2}{\rho_c gd}$ is the modified Froude number; $\rho_s$, $\rho_c$ are the densities of steam and condensate, $w$ is the mixture speed, and $d$ is the diameter of the heat exchange tubes.

This equation is the basis for creating a computer program to calculate the SGM condenser.

The research results are implemented in an experimental model of a high-efficiency condenser [5], the photographs of which are presented in figure 7.
Figure 7. Schematic layout of tube bundle groups in a high-efficiency condenser model (a) and a photo of the condenser at the test plant (b).

The condenser test results are shown in figure 8 for various parts along the SGM run with a change in volumetric air concentration at the inlet from 0 to 8%; the average value of K heat transfer coefficient lies in the range from 4500 W/(m$^2$K) ($\nu = 0$) to 2700 W/(m$^2$K) ($\nu = 8$%)

Figure 8. Dependence of the heat exchange coefficient A of tube bundles on the air concentration at the inlet at $q_{\text{nom}}=41$ kW/(m$^2$K), 1÷6 – group numbers along the steam run, 7–dependence of the average A on the air concentration at the inlet.

The design of the condenser for gas-steam turbine units with a capacity of 100 MW is shown in figure 9.
Conclusions

It is advisable to design a high efficiency steam-gas mixture condenser with carbon dioxide utilization on the basis of a typical heat exchange module of a triangular shape.

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