Prospects for the use of steam-piston engines to increase the economic attractiveness of environmentally friendly processes for the processing of copper-molybdenum concentrates of promising deposits in Kazakhstan

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Abstract. The use of old metallurgical processes is accompanied by releasing process gas into the atmosphere because its subsequent processing is not possible. New technological processes using oxygen flash smelter make it possible to obtain a sufficient concentration of sulfur oxide in process gases for sulfuric acid commercial production. A necessary element of the new type of power plants is heat recovery boilers that generate steam that can be used to generate electricity, which will increase the economic efficiency of oxygen flash smelter plants. The article shows that it is practically impossible to use steam turbines to generate electricity from this steam, and the use of steam-piston engines is proposed.

1. Introduction
Deposits in Kazakhstan’s existing non-ferrous metallurgy centers are already depleted [1], but Kazakhstan has several discovered and explored deposits of non-ferrous metals. The largest reserves are concentrated in the copper-molybdenum deposits of Aktogay, Koksay, Bozshakul, Shatyrkul, and others [2]. Modern autogenous processes should be used for the development of these deposits. With the use of the old metallurgical processes, a process gas with a low concentration of sulfur dioxide was obtained, this gas was released into the atmosphere. Modern technological processes provide a sufficient concentration of sulfur dioxide in process gases for sulfuric acid commercial production. Heat recovery boilers are essential elements of such metallurgical units. At present, heat recovery boilers are practically not used for generating electricity due to their low steam capacity. The use of turbines at such low steam flow rates is impractical due to low efficiency; in addition, in most cases, waste heat boilers generate saturated steam, which cannot be used in conventional steam turbines since the impact of water droplets causes erosion of the turbine blades. In this article, it is proposed to use a steam-piston engine, the efficiency of which does not depend on their power and which can operate on saturated steam and even overheated water [3].

2. Results and discussion
Currently, the thermal energy of the steam generated by the heat recovery steam generator (HRSG) of high-temperature non-ferrous metallurgy plants is used practically only for space heating and hot water supply. In this regard, the consumption of heat energy is unstable during the day and over the
seasons and, as a rule, is small compared to the amount of steam generated. As a result, steam is generally not used useful. The steam generated by most HRSGs is not superheated and has a high moisture content, which makes it difficult to use this steam in steam turbines. However, even in the case of superheated steam, its low volumetric flow rate makes the use of steam turbines impractical due to the low efficiency of low-power turbines. This article will discuss using a steam-piston engine to generate electricity from steam generated by the HRSG. The concept of "steam-piston engines" was introduced into scientific circulation by one of the authors [4]. Such engines run not only on wet steam but also on overheated water. The efficiency of this type of engine, as with classic reciprocating steam engines, is practically independent of power, so they can be installed next to each HRSG, which can be located at a considerable distance from each other. With this arrangement, long pipelines for steam transportation are not required. Steam-piston engines, unlike classic reciprocating steam engines, have a fairly high rotational speed. As a result, they are smaller and can be connected directly to modern power generators with a 1500 rpm speed. Such engines can be manufactured by converting serial internal combustion engines, which significantly reduces their cost and provides a short payback period for such equipment.

This scientific work is devoted to one of the areas of energy conservation, namely the use of secondary energy resources of thermal energy of process gases formed in pyrometallurgical processes and steam from evaporative cooling systems of high-temperature non-ferrous metallurgy installations. This direction becomes even more relevant in connection with the transition of non-ferrous metallurgy around the world to the most promising autogenous processes [5], which, due to the use of the heat of chemical reactions of metal-containing raw materials with oxygen, reduce the cost of fossil fuel, and sometimes even its complete replacement. The development and application of various autogenous smelting methods made it possible to intensify metallurgical production, significantly reduce fuel and energy costs, increase the complexity of the use of raw materials, and greatly reduce the level of environmental pollution [6]. Autogenous smelting methods require the use of oxygen flash smelter plants. The result is a high-temperature process gas with a high sulfur oxide content, which makes it economically viable for sulfuric acid production.

The gas obtained in such processes must be cooled in front of the filters; therefore, the HRSG generates thermal energy and is an integral part of the equipment for such processes. Also, the HRSG acts as a coarse filter.

On the other hand, the use of oxygen in the blast leads to increased energy consumption. For the production of 1000 m3 of blast air, 49.5 kW * h is required, and for the production of 1000 m3 of oxygen, 462 kW*h is required [5]. In this situation, the conversion of heat energy received from the HRSG into electrical energy becomes relevant. Moreover, when cooling gases with high sulfur content, HRSGs must have a vapor pressure of 4 MPa or more to have a heating surface temperature higher than the dew point of sulfuric acid. Currently, HRSG steam is not used because the average HRSG steam output for one metallurgical unit, based on the actual operating time, is only 7-8 tons/hour [7]. Steam condensation turbines are not produced for such low steam consumption. To estimate the hypothetical turbine power for such a steam consumption, we use the specific steam consumption of the lowest-power Russian condensing steam turbine K-6-35. Its power is 6 kW, steam consumption is 28.5 tons/h [8]. Thus, the specific steam consumption of this turbine is 28500/6000 = 4.75 kg / kW*h. In this case, the capacity of such a hypothetical turbine will be 8000/4.75 = 1684 kW, which is almost 4 times less than the capacity of the existing turbine. The K-6-35 turbine operates on the following steam parameters: 3.43 MPa and 435°C [8]. A turbine that can hypothetically use HRSG steam should have almost 4 times less power and, as a result, a very low internal relative efficiency. Indeed, the internal relative efficiency of the turbine stage compartment shown in the graph in Figure.1 borrowed from [8] falls sharply with decreasing volumetric steam flow rate.
Figure 1. Internal relative efficiency of turbine stage depending on volumetric steam flow rate

Volumetric steam flow rate $V$ according to [8] is calculated as follows:

$$V = M \cdot (V_1 \cdot V_{2a})^{1/2}$$  \hspace{1cm} (1)

In equation (1), $M$ is the steam flow through the turbine compartment, kg/h, $V_1$ is the specific volume of steam before the first stage of the compartment, m$^3$/kg, $V_{2a}$ is the specific volume of steam at the outlet of the compartment during isentropic expansion, m$^3$/kg. The specific volume of steam in front of the first compartment of the K-6-35 turbine will be determined at a steam temperature of 435°C and a pressure of 3.43 MPa. According to [9], with such steam parameters, the specific volume is $V_1 = 0.09247$ m$^3$/kg. With these parameters of steam, the entropy is 6.9738 kJ/K [9]. We will consider the isentropic process of maximum expansion of steam to a minimum pressure at which it still remains superheated. According to [9], at an entropy of 6.9626 kJ/K, the pressure is 0.34 MPa, the temperature is 140 °C, and the specific volume $V_{2a} = 0.5420$ m$^3$/kg. Thus, the volumetric steam flow through the K-6-35 turbine will be:

$$M \cdot (V_1 \cdot V_{2a})^{1/2} = 28500 \cdot (0.09247 \cdot 0.5420)^{1/2} = 6380.3 \text{ m}^3/\text{h}$$

According to Figure 1, at such a volumetric flow rate, the internal relative efficiency of the turbine is 0.7, and at a volumetric flow rate of 4000 m$^3$/h it is already 0.6, and with a further decrease in the volumetric flow rate, this efficiency falls almost vertically. This means that a hypothetical turbine will have this efficiency close to zero. That is why condensing turbines of such low power as the hypothetical one are not produced. Indeed, at a steam flow rate from HRSG of 8000 kg/h and with the same steam parameters as for the K-6-35 turbine, we have a volumetric flow rate:

$$M \cdot (V_1 \cdot V_{2a})^{1/2} = 8000 \cdot (0.09247 \cdot 0.5420)^{1/2} = 1791 \text{ m}^3/\text{h},$$

which is 2.32 less than the volumetric steam flow rate at which, according to Figure 1, the internal relative efficiency begins to drop vertically with decreasing volumetric flow.

With a sufficient number of metallurgical units at one enterprise, it is possible to organize the generation of electricity using steam turbines from HRSG steam if the steam is supplied to the combined collector, which will allow a steam flow rate sufficient for the use of a steam turbine. However, for this it will be necessary to lay long steam pipelines and there will inevitably be losses of thermal energy of steam. But most importantly, in most cases, HRSGs generate saturated steam, which...
cannot be used in conventional steam turbines, due to its condensation in the flow section of the turbine and erosion of the blades under the impact of water droplets flying at or near supersonic speed.

In this situation, a reciprocating steam engine may be considered. The authors do not propose to use classical reciprocating steam engines for generating electricity from HRSG steam, since they have many disadvantages. For example, such engines have large dimensions and metal consumption. Also, it is impossible to use the direct drive of modern high-speed electric generators without a multiplier because of the low speed. Also, such machines have a high content of lubricating oil in the exhaust steam, which does not allow the use of its condensate to power the HRSG without a complex cleaning system.

On the other hand, classic reciprocating steam engines have several advantages over steam turbines. In particular, they can operate on saturated steam. The specific steam consumption of reciprocating steam engines is practically independent of power so that they can operate efficiently at relatively low steam consumption, typical for HRSG in non-ferrous metallurgy. In connection with the above, using the classic reciprocating steam engine principles, which retains these advantages, the authors proposed a steam-piston engine that does not have the above disadvantages for generating electricity from steam from HRSG in non-ferrous metallurgy. A high-speed reciprocating steam engine with a single expansion speed of 1000 rpm is called a steam-piston engine (SPE). They can be produced by converting internal combustion piston engines. The disadvantage of the steam-piston engine is its lower mechanical efficiency than the classic reciprocating steam engine. This is due to their higher rotational speed. The mechanical efficiency of the classic reciprocating steam engine is 0.9-0.92; the steam-piston engine's mechanical efficiency will be at the level of piston internal combustion engines, which are converted into a steam-piston engine, that is 0.75-0.92.

To estimate the effective specific steam consumption of the steam-piston engine, one can use the data of the classical reciprocating steam engines on the specific indicator steam consumption, assuming that the mechanical efficiency of the steam-piston engine is 0.835 and multiplying it by the specific indicator steam consumption and data on the specific effective steam consumption of the high-speed reciprocating steam engine. The data of various reciprocating steam engines and the specific effective consumptions of steam-piston engine steam obtained from them are shown in Table 1. It should be noted that when using a steam-piston engine, multiple expansion is provided by a serial connection of several steam-piston engines. The first is part of the high-pressure steam power plant, and the second is part of the medium pressure and, in the case of double expansion, low pressure. This allows the steam-piston engine to be used more flexibly. For example, during the heating season, a part of the low pressure can be stopped. The exhaust steam/water mixture can be directed to a hot water boiler for heating purposes. Moreover, the relatively high pressures of the steam-piston engine exhaust steam make it possible to use its thermal energy for hot water supply. In contrast, steam turbines have very low exhaust steam pressures. For example, the already mentioned K-6-35 turbine has an exhaust steam pressure of 3.92 kPa and requires a cooling water temperature of 20°C [8].

Table 1 shows the steam-piston engines operating on the condensation principle as it provides maximum power generation from steam. It is possible to operate the steam-piston engine in cogeneration mode when the exhaust pressure exceeds atmospheric pressure, and the exhaust steam is used to generate heat energy. Such reciprocating steam engines currently exist; data on them are given in [3].

Supposed steam-piston engines, as can be seen from Table 1, can have almost any power, while the specific effective steam consumption does not depend on it. This means that the steam-piston engine system can drive various equipment of a metallurgical enterprise instead of an electric drive (pumps, smoke exhausters, compressors, etc.). This approach improves energy efficiency due to the lack of double-conversion of energy, which exists when using electric generators (mechanical energy into electrical, then electrical into mechanical). The efficiency of each such conversion is less than 1. In addition, when using a steam-piston engine instead of electric motors, emergency stops of equipment during short power outages are excluded. In [13], it is indicated that high energy saturation in the
production of non-ferrous metallurgy and the specificity of continuous metallurgical processes do not allow interruptions in the power supply.

**Table 1.** Data of the classic reciprocating steam engine and the estimated data on the specific effective steam consumption of the steam-piston engine with the same parameters of the inlet steam, exhaust steam pressure and expansion ratio

| Indicated power of reciprocating steam engine (kW) | Steam pressure (MPa) | Temperature (°C) | Expansion ratio | Pressure of exhaust steam (kPa) | SESFR |h | Literary source |
|-----------------------------------------------|----------------------|------------------|-----------------|-------------------------------|-------|-------|-----------------|
| 73,5a                                         | 2.6                  | 460              | 1               | Probably 40                   | 8,8   |       | [10]            |
| 500                                           | 1.6                  | 275              | 3               | 20                            | 9,1   |       | [11]            |
| 800                                           | 1.6                  | 300              | 3               | —                             | 7.9-8.14 |      |                 |
| 1100                                          | 1.5                  | 300              | 2               | 10                            | 7.9   |       |                 |
| 800                                           | 1.5                  | 300              | 2               | 5                             | 7.7   |       |                 |
| 183a                                          | 3.45                 | 392              | 2               | 26                            | 5,12  |       | [12]            |

a Power is effective, not indicative.
b Specific effective steam flow rate of steam-piston engine, with its mechanical efficiency 0.835

In [14] it is noted that the complete elimination of short-term power supply disturbances in modern power supply systems is impossible. At the same time, it should be added that independent generation of electricity without connecting to the power grid does not meet the requirements for the quality of electricity in terms of frequency when consumers are connected directly to an electric generator driven by any heat engine. There were no such engines that would ensure the accuracy of maintaining the rotational speed, which would make it possible to have current frequency deviations at the level of central power grids. A feature of the steam-piston engine is the ability to accurately maintain the frequency due to the phenomenon of self-stabilization [15,16,17].

However, when using Table 1 to determine the parameters of a steam-piston engine operating on saturated steam, it must be borne in mind that there is no really saturated steam, but there is either slightly overheated or steam of a certain dryness less than one. If it is low, then both the classic reciprocating steam engine and the steam-piston engine cannot work on such a steam-water mixture. There may be options when the HRSG produces such a working fluid. For example, at one of the enterprises of the copper industry in Russia, HRSG operates under a pressure of 4 MPa 190 ° C. Considering that at this temperature the pressure of saturated water vapor is 1.28 MPa, such an HRSG produces not steam, but superheated water, which at the outlet from it turns into a steam-water mixture. Under the scientific guidance of one of the authors, a single-cylinder steam-piston engine was created capable to run on a steam-water mixture.

3. Conclusion

The expediency of using a steam piston engine for generating electricity from steam generated by HRSG from high-temperature non-ferrous metallurgy plants and their evaporative cooling systems is shown.

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