Review of ways to increase efficiency of energy generation at TPP at the account of additional energy carriers

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Abstract. The problem of increasing the efficiency of generation facilities through the use of additional energy carriers is considered. Presented are the modern achievements of ways to increase the efficiency of energy production at TPPs: 1) transition to super-critical parameters of steam and 2) multigeneration. Increasing the parameters of steam increases the energy efficiency of electricity production, and multigeneration allows to produce additional energy carriers (hydrogen, oxygen, compressed air, cold, etc.) due to the unclaimed capacity of the equipment used or the utilization of flows inside the generating facility. The additional energy carriers produced as a result of such processes can be centrally supplied to external consumers or used inside the production cycle, for example, to switch to super-critical steam parameters. The transition to over critical parameters is possible when using high-temperature over heaters or when using new boiler units.

1. Introduction
The development of domestic energy up to 2030 is approved in the energy strategy [1]. One of the problems is the high wear of the fuel and energy complex. According to various estimates, the share of this equipment in the country's energy complex can reach 60-80% of the entire country's complex [2-4]. The main peak of the power unit’s construction at existing thermal power plants (TPPs) occurred in the 80s of the 20th century. Because of this, more than half of the current energy capacities of the Russian Federation have been operating for 35-40 years without any significant modernization. [2-11]. According to Russian scientists, this problem was also caused by low financing of the country's energy complex and an internal and external geopolitical factors combination of [1, 3-4]. During this time, the global energy sector has made progress in the energy, environmental and economic sectors. Therefore, our energy generation facilities are inferior to world leaders in reliability, efficiency, automation level, environmental parameters and electrical efficiency coefficient low values (30-36%) [11-12]. Based on this need, the Russian power industry sets itself the task of modernizing existing equipment and developing new highly efficient power units based on over critical steam groups (overcritical, super-overcritical and ultra-overcritical steam parameters). The efficiency of such power units should be over 50% [2-5, 9, 11-12].
2. The research problem statement
In this paper, the task is to study modern ways to increase the generation facilities efficiency through the production and use of additional energy sources, such as hydrogen and oxygen.

3. The steam parameters increase to over critical parameters
The steam over critical parameters development is a very popular area in the world and Russian energy. The overcritical steam groups-over critical parameters, super-overcritical parameters, and ultra-overcritical parameters. The steam parameters classification at generation facilities is presented in Table 1 [11-12].

| The steam parameters          | Vapor pressure, MPa | Steam temperature, °C | CoE, %: |
|-------------------------------|---------------------|------------------------|---------|
| Critical                      | <25                 | 375                    | 39      |
| Overcritical                  | 25                  | 560                    | 42.5    |
| Super-over-critical           | 30                  | 620                    | 45      |
| Ultra-overcritical            | 35                  | 700                    | 50.5    |

This method of increasing work efficiency has been mastered at coal-fired thermal power plants. In the world power industry, power units based on steam super overcritical parameters have been mastered and are widely used in practice, and in Russia, there are no such power units [3]. 55 power units in the world on over critical steam groups are known, but only two of them are located in Russia, Kashirskaya TPP and OGK-2 Troitskaya TPP [11-12].

The environmental effects of the transition to over critical groups are well studied based on coal TPPs. So, the transition from the steam subcritical parameters, at which TPPs in Russia operate, to ultra-overcritical parameters will reduce carbon emissions, according to various estimates, by 12-50% [12, 14].

The ultra-overcritical power unit’s development is hampered due to technical limitations that are based on the materials used. The materials used in such power units must meet high heat-resistant, corrosive and plate requirements in the field of extremely high temperatures. Such alloys are many times more expensive, and most are trade secrets [11-12].

The steam turbines development also depends on the study of the structural materials [11]. Such materials are necessary for turbine rotors, steam turbines blades and casing equipment cast elements. The most modern steam turbines are not suitable for high steam parameters. The need for the various types of steam turbine equipment development is described in [3-6].

The transition to increased steam parameters can be carried out by introducing a high-temperature over heater into the technological process or by boiler units modernizing.

3.1. High-temperature over heater
High-temperature over heaters (HTOH) is a new key element in the nuclear power plants schemes (NPPs) and thermal power plants. They can act as an element for switching to high steam parameters, to cover irregularities in the load curve and to accumulate electricity in hydrogen systems. The hydrogen plants efficiency for electric energy storage and their comparison with other systems are considered in [15–16].

Installations using nuclear fuel [15-19] and fossil fuels [20-28] are divided depending on the generation object and fuel type.

For TPPs, fossil fuels use to increase steam parameters is relevant. Water vapor, which comes from the steam generation unit, enters the HTOH chamber where an oxidizing agent mixture (preferably oxygen) and fuel is burned. In the chamber, the temperature can reach 3500 °C. The resulting water
vapor can have a temperature up to 1700 °C. This steam is sent to a steam turbine. The steam turbine electric power grows, as the heat amount that is removed on the turbine grows. The station electric power can increase up to 2.5 times [11]. Surplus electrical power can be sent to additional plants, such as electrolyzes for hydrogen and oxygen production.

Hydrogen or natural gas can be used as fuel for the HTOH. Many domestic scientists in their studies conducted an experimental comparison of the hydrogen-oxygen mixture combustion and methane-oxygen mixture [20-22]. It is stated that the methane-oxygen mixture combustion can be not only not lower but even higher than the production and hydrogen-oxygen mixture combustion, taking into account the compressing gas fuel cost and removing non-condensable gases from the spent vapor-gas mixture condenser [20]. The hydrogen-oxygen mixture combustion is characterized by absolute ecological purity, since only water vapor is formed as a combustion result, which is directly mixed with the water vapor entering the unit, thereby increasing its amount.

It is also customary to use high-voltage transformer substations between the steam turbine stages. It is customary to use from one to three of HTOH for organizing hydrogen overheating between turbine stages [23, 29]. Each installed chamber for hydrogen overheating increases the station efficiency by 2-3% [11]. In [11], promising schemes were proposed with one chamber and two chambers for hydrogen overheating, the efficiency of which can reach 75.6%.

The use of HTOH positively affects the maneuverability of thermal power plants [11, 15-17]. A power unit needs less than 50 seconds to start, its adjustment range becomes more accurate and in case of an emergency, the unit can work for 2-3 hours, which will allow for all necessary repairs.

3.1. Boiler Unit

The transition to high steam parameters is possible when using new boiler units, which principle operation does not differ from the current steam boilers operation principle at thermal power plants. A fuel and oxidizer mixture, which is burned in the boiler furnace, is fed through the burners to the boiler unit. The resulting water vapor is fed to a steam turbine and then through the technological cycle.

The first over critical and super overcritical steam boilers were developed in the USSR [30]. The boilers development and their introduction ceased, but with the adoption of an energy strategy, it began to gain momentum again. The paper [11-12, 30] presents the technologcal effects of the introduction of high-temperature boilers in pulverized coal thermal power plants. There is a 2-fold reduction in emissions of NOₓ, a reduction in CO₂ emissions and an increase in the efficiency of power units to 55-60%. In Russia, in 2011, a 660 MW coal-fired power unit was installed at OGK-2 - the Troitsk State District Power Plant, in which the transition to over critical steam parameters is carried out using a steam boiler [31].

To switch to high steam parameters, current steam boilers need to be modernized. With the increasing temperature in the boiler path, the requirements for the material properties of the increase of the internal surface. This primarily concerns evaporative surfaces, over heater surfaces and the economizer. The high parameters boiler unit’s development directly depends on the new materials and alloys study for these areas. To reduce capital costs for the new boiler unit’s construction, it is proposed to reduce the high-temperature steam pipelines length. This is proposed to be achieved by changing the boiler layout. Changing the layout will reduce the high-temperature steam pipelines length by 2 times [11-12, 32].

The advantage of such a transition to high steam parameters is independence from the fuel type and wide assimilation of experience in the generation facilities use in domestic and world energy.

4. The switching to multi-generation mode

An increase in the thermal power plants energy efficiency is also possible along the multi-generation path [33]. Multi-generation is the combined simultaneous production of at least two energy carriers, as well as other useful products, from a single primary energy carrier at a generation facility. Trigeneration, the combined production of cold, electric and thermal energy is distinguished separately. Trigeneration is considered in [34–38]. Figure 1 shows a diagram of a multi-generation complex that combines the transition to increased steam parameters and multi-generation due to hydrogen and oxygen production.
At generation facilities, transferring process to multi-generation mode can be used to cover the load unevenness and the unclaimed secondary production products use. The thermal power plants uneven load is covered by such equipment operating modes organization when it operates with maximum efficiency regardless of the consumer needs. It is known that in the summer season, the need for thermal energy decreases, so it is more advisable to send excess heat to additional production, rather than to throw it into the atmosphere.

Figure 1. Scheme of a multigeneration complex with additional production of hydrogen and oxygen
1 – steam boiler; 2 – high-temperature boiler superheater; 3, 4 – pipelines of supply of hydrogen and oxygen; 5 – system for hydrogen production by natural gas conversion methods; 6 – oxygen plant; 7 – heat exchanger for hydrogen heating; 8 – heat exchanger for oxygen heating; 9, 10 – exhaust gases from the steam boiler; 11 – steam turbine; 12 – electric generator; 13 – condenser; 14 – heat recovery boiler; 15 – steam to the high-temperature boiler superheater; 16 – steam mixer; 17 – production extraction; 18, 19 – lower and top heating extraction; 20 – steam from the steam boiler; 21 – electrolysis plant; 22, 23 – synthesis gas supply and return pipeline; 24 – flue gas to carbon dioxide and oxygen plant; 25 – carbon dioxide and oxygen production; 26 – fuel to steam boiler; 27 – oxidizer to steam boiler; 28 – water to steam boiler; 29 – high parameters of steam turbine; 30 – axle turbine; 31 – electricity to consumer; 32 – electricity to electrolysis plant; 33 – water to electrolysis plant; 34 – electricity to oxygen plant; 35 – air to oxygen plant; 36 – oxygen to pipelines; 37 – oxygen to consumer; 38 – hydrogen in steam boiler; 39, 40 – exhaust gases to the atmosphere; 41 – steam from steam turbine; 42 – water from condenser; 43 – make-up water; 44 – water treatment plant; 45 – pump; 46, 47 – district heater; 48 – production steam to consume; 49 – steam to steam mixer; 50 – fuel to hydrogen production system by natural gas conversion methods; 51 – hydrogen to consume; 52 – hydrogen to pipeline; 53 – steam to hydrogen production system by natural gas conversion methods; 54, 55 – oxygen to hydrogen production system by natural gas conversion methods; 56 – carbon dioxide to hydrogen production system by natural gas conversion methods; 57 – secondary products to heat recovery boiler; 58 – steam to steam turbine; 59 – water to heat recovery boiler; 60, 61 – exhaust gases to the atmosphere.

Secondary energy carriers (SEC) are divided into thermal, combustible and power energy carriers [39]. Each of these energy carriers can be used for multi-generation needs. At TPPs, it is important to use thermal SEC to cover the load unevenness by including industrial (P) and heat recovery (T) not only for own needs but also for the additional production needs. This method is relevant for thermal power plants when high pressure and temperature steam can be sent to additional production, for example, of hydrogen, by the natural gas steam conversion method.
The National research university MPEI is actively developing schemes in which the principles of multi-generation [40-41] are applied.

In the multi-generation complex [40], in addition to electric and thermal energy, hydrogen and oxygen are produced. For this, an electrolyze and a system for the hydrogen production by conversion methods are installed.

Electricity is supplied to the electrolyze from a steam turbine. The produced oxygen and hydrogen can be sent to external consumers and can be sent to their needs in a steam boiler or HTOH. Thermal energy is also used from the steam turbine offsets, which can be sent both to an external consumer and to own needs for the production of hydrogen by conversion methods.

The advantages of multi-generation include increasing the existing equipment efficiency through the primary energy sources better use, the additional energy sources centralized production, which will allow them to be generated with great efficiency and environmental friendliness, reducing unit costs for the basic and additional energy sources production, as well as creating new income sources for generating facilities.

CONCLUSION
1. The overcritical, super overcritical and, in the future, ultra-overcritical steam parameters use will increase the existing generation facilities energy efficiency. This will positively affect the economic, technical and environmental situation in the domestic energy sector.

2. The multi-generation introduction will increase the modern generation facilities efficiency and will create the ability to produce on an industrial scale new energy sources for domestic consumption in the cycle and for external consumers, which will expand the Russian energy market, as well as create the basis for the technology development on new energy sources.

3. Increasing the generation facilities efficiency will help to solve the generation process environmental shortcomings and improve the energy production profitability.

4. The prerequisites possibility for the combining of over critical steam parameters and multi-generation are revealed. This combination can combine the advantages of both ways to increase efficiency.

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