Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: N V Valtsev *et al* 2017 *J. Phys.: Conf. Ser.* **891** 012195

The development of a high temperature air heating unit based on the external combustion for integrated gasification combined cycle

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Abstract. The use of heat exchangers in which the working fluid before it enters the gas turbine is warmed up due to the combustion of fuel or other external energy source still is of interest due to the method advantages: the cleanliness of the working fluid; the ability of using cheap low-grade fuels, solar or nuclear energy; the possibility of usage of the closed gas turbine cycle with gases as a working medium, that having favorable thermodynamic properties in comparison with air (helium, CO_2, etc.). However, the desired gas turbine inlet temperature – up to 1,700°C currently not possible to provide even with the use of ceramic heat exchangers. Therefore, this technology is now being considered for solid-fuel micro gas turbines operating at temperatures 900-1100°C, or for reducing the need for fuel gas of integrated gasification combined cycle (IGCC) by the means of preheating of cyclic air as well as it is considered for solar gas turbines and gas turbines on the basis of high temperature gas cooled reactors. The authors have developed a metal recuperative air heater based on external combustion of coal for 500 MW IGCC power plant, the development of IGCC is determined by the Energy strategy of Russia for the period up to 2030. In the article the thermal characteristics of the heating of pressurized air, the possible options for the configuration of the heater, heat-resistant materials suitable for its production and the results of the feasibility calculations are considered. In conclusion the design that allows to significantly reduce the specific capital and operating costs for the heater compared to the classic one is proposed.

1. Introduction

The mostly well-known solid-fuel gas turbine technologies are based on integrated gasification, but they have a significant drawback - the need for deep purification of the syngas before it is fed into the combustion chamber of the gas turbine (GT) that significantly increases the cost of the plant, reduces its efficiency and reliability. The presence of large gasification island not only reduces the reliability of the IGCC operation, but also leads to a significant decrease in the ratio of gas to steam turbine power in comparison with the natural gas combined cycle, and, consequently, the overall plant efficiency, due to the appearance of significant heat flux with steam directly into the lower steam-turbine cycle.

The main advantage of implementation of high-temperature heat exchangers with external combustion in IGCC is the opportunity to use cheap low-grade fuels for heating on proven technologies of complete combustion maintaining the purity of the working fluid (usually compressed air). In this paper we consider the possibility of creating a high-temperature air heater for IGCC, where air with a pressure of about 2 MPa should be heated by coal combustion [1].

2. Selection of the key parameters of the air heater

Before starting the design of a high-temperature air heater, we need to determine its key parameters, such as: parameters of working fluid; type of fuel used; type of air heater as heat exchanger (recuperative - regenerative, etc.). Undoubtedly, these parameters are in many ways interrelated and the final choice is to a certain extent a compromise and partly relies on author’s subjective preferences.

As the unit operates on an open cycle - air is the only possible working fluid, its parameters are determined by the gas turbine: the inlet temperature is 1400°C, the pressure ratio is 18. Such a temperature cannot be obtained in the air heater due to material limitations, so it is only used for a partial heating. The heating is completed in GT’s combustion chamber by the combustion of syngas.

The fuel used in external combustion plants should be as cheap as possible. Therefore, low-grade solid fuels or poor gases, obtained as a by-product in metallurgy, chemical industry, etc, could be used. In the middle of the 20th century several dozens of such coal-fired plants were built all over the world, including one in the USSR. Also there is an operating experience of external combustion units fueled by petcoke, coke gas and natural gas [2]. Low-grade fuels have one more advantage because its low flame temperature eases the operating conditions of the heating surfaces. In this paper coal fired air heater is considered.

As for the air heater type, there are two main ways of high-temperature air heating: regenerative and recuperative ones. Regenerators are widely used in various technological processes, mainly in metallurgy and materials production. The main advantage of this technology is the possibility of heating air to high temperatures up to 1200-1400°C using a ceramic checker (which is much simpler than making a ceramic recuperator). However, the practical application of regenerators for high-temperature heating of compressed air by coal combustion in the IGCC is not very realistic due to a number of problems related to:

- possible coal combustion products (solid particles, sulfur compounds, alkali metals, etc.) insertion into the heated air and, consequently, into the GT, which is unacceptable;
- blockage of the regenerator checker with slag and ash;
- the complexity of heating air under pressure (cyclic ~2 MPa and up to 4 MPa for the gasifier);
- providing significant capacity for IGCC operation, which as it seems will require a large number of parallel units.

Nevertheless, regenerators are proposed especially for small plants with micro-GTs, primarily on biomass [3].

Recuperative air heaters have an undoubted advantage over regenerative ones, providing a reliable separation of a clean working fluid and products of solid fuel combustion. For high-temperature air heating at small plants modular devices with a large number of channels or traditional shell-and-tube heat exchangers could be used, and with respect to a large ones air heaters are designed like pulverized coal fired boilers or less frequently fluidized beds.

3. Material challenges

High temperatures and often severe operating conditions place high demands on the materials used, so their choice becomes one of the key issues, determining entire power plant configuration, operating parameters and costs.

Heating of the air to high temperatures can be ensured only in ceramic heat exchangers, which have a number of advantages over metallic ones, the main are: high operating temperatures; high resistance to corrosion and wear. However, they also have significant technological shortcomings that prevent their mass use: high cost of ceramic pipes and the difficulty of obtaining long pipes with uniform structure and properties; the complexity of the sealing of individual elements; brittleness.

IOP Conf. Series: Journal of Physics: Conf. Series **891** (2017) 012195 doi:10.1088/1742-6596/891/1/012195

The silicon carbide is the most suitable for high-temperature heat exchangers of external combustion units. However, the main types of ceramics proved to be unstable to corrosion from the liquid slag [4], therefore it is possible to heat the air while working on solid fuel only to ~1100°C, if the inherent problems are solved. Nevertheless, the use of ceramic materials can be considered as a modernization reserve for the future development.

Metal constructions, in comparison with ceramic ones, have lower temperature and corrosion resistance, but are much more resistant to dynamic loads and allow obtaining better gas-tightness, ensuring high operational reliability of the heat exchanger. For the high-temperature it is necessary to use nickel alloys. Such alloys considered for advanced ultra-supercritical power plants (A-USC) [5] and very high temperature reactors (VHTR) [6] are given in the table 1.

Table 1. Nickel alloys for high temperature heat exchangers.

Alloy	Application
IN617 (CCA617), Haynes 230, IN740	Pipes and headers, superheat and reheat tubing of A-USC (700-760°C, 35 MPa, 10^5 h)
IN617, Haynes 230, 800H, Hastelloy X, CrNi55MoWZr (Russian)	Intermediate heat exchangers of VHTR (up to 950°C, up to 5-7 MPa, $2{\bullet}10^5$ h)

Oxide dispersion strengthened (ODS) alloys, such as MA956 and PM2000, which could be used up to 1100-1150°C are also promising, but the problem of reliable joining of separate elements is not completely solved, in addition, their cost remains very high [7], therefore they are not considered in this paper, but have in mind for the future.

The existing domestic high-temperature alloys are designed primarily for the manufacture of various parts of gas turbines, which have a much shorter lifetime, in comparison with boiler equipment. Due to the lack of the data on the strength of alloys at high temperature with the test base of 10^5 h in the literature, we will rely on the calculated values of the stress-rupture strength, extrapolated on the basis of well known relationship between the time to rupture at a constant temperature and stress. The required minimal stress-rupture strength at an air pressure of 2 MPa is estimated as 9 MPa.

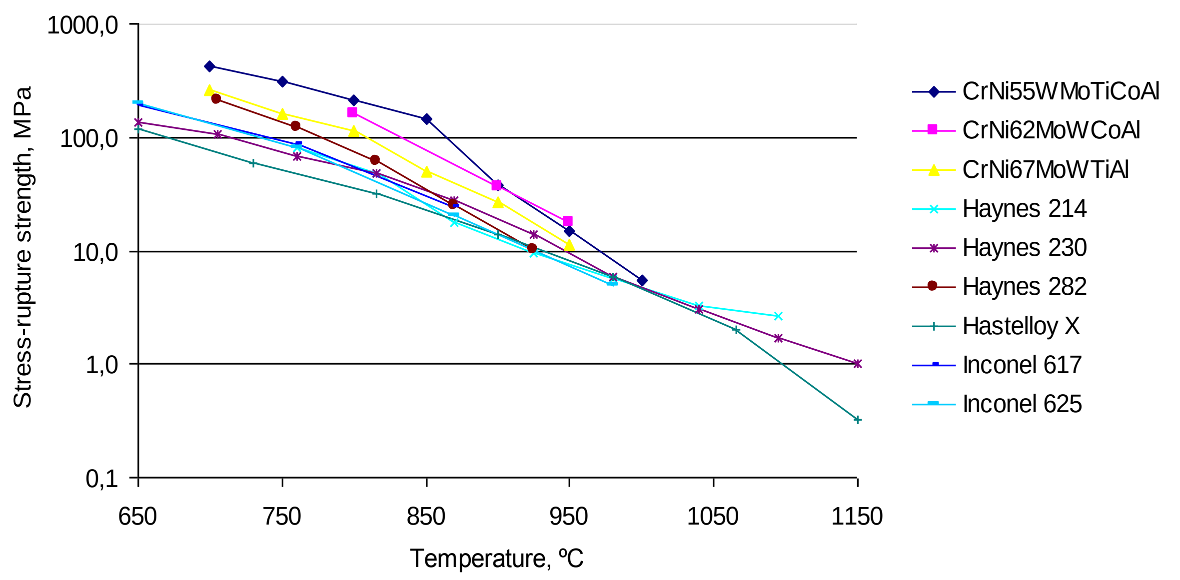

Figure 1. Stress-rupture strength for various nickel alloys

The strength of more than 30 high-temperature alloys was calculated and a comparison of the properties of domestic and foreign alloys has shown that domestic alloys are slightly superior to foreign ones. Thus, the use of high-temperature nickel alloys, such as CrNi55WMoTiCoAl and CrNi62MoWCoAl, allows heating of compressed air up to 900-950°C. The results for several alloys are shown at figure 1.

Despite the availability of a large number of available high-temperature alloys additional material studies are needed to confirm mechanical properties based on 10^5 operating hours and to determine the corrosion resistance in coal combustion products. In addition, a serious factor limiting their use is their high cost. According to [8], the cost of an IN617 or IN740 alloy varies in the range of 55-110$ per kg.

To reduce the corrosion and wear of the heating surfaces of an air heater, it is advisable to provide their protection with coatings, that will not only increase the reliability of operation of the unit, but it can also reduce the pipes wall thickness, by reducing the increase to the calculated wall thickness, and hence reducing the overall costs. At present, laboratory studies are carried out to test different protective coatings for nickel alloys.

4. Air heater designing

As the air pressure rises, the heat transfer coefficients at constant velocity increase significantly, mainly because the dynamic viscosity increases slightly with increasing pressure, while the density increases linearly, which leads to a significant decrease in the kinematic viscosity and consequently to an increase in the Reynolds number, and hence the average convection heat transfer coefficient. It means that the optimum speed intervals will not coincide with those used in the industry (3-8 m/s for convection sections, 20-40 m/s for radiation ones), in addition, the high cost of the materials used also requires distinct design solutions.

To reduce gas temperature and ease output sections of air heater operating conditions the new design of the air-heating unit was proposed. The combustion of solid fuel is carried out in the adiabatic pre-furnace with the subsequent mixing of the combustion products with the recirculation gases to cool them to the temperature about 1000°C (for complete elimination of slagging). So, the air heater has only convective sections, behind which a regenerative air heater for combustion air is installed. More detailed description is in [9].

The main contribution to the cost of the air heater is made by high temperature heating surfaces produced from nickel alloys, which price is an order of magnitude higher than of stainless steel used for input air heater sections. Relative steels and alloys costs are given for example in [5, 7]. So, the optimization of the most heat-stressed part of the air heater is of critically importance. The calculation of total costs per year, that consists of capital costs of heating surfaces and costs associated with air pressure losses, was carried out. The results for the last surface where air is heated from 800 to 900°C are shown at figure 2. The calculation was made for three inner diameters of heating surface tubes: 10, 20, 50 mm and for two prices of nickel alloy tubing: favorable – 3.5 mln rubles per ton (figure 2 (a)) and unfavorable – 7 mln rubles per ton (figure 2 (b)). It is assumed that plant works 8000 h per year, the electricity price for auxiliaries is 1.5 rubles per kW and unit lifetime is 10^5 h.

It is seen that smaller diameter can significantly reduce costs of heating surface – by 3 times while diameter is decreasing from 50 to 10 mm. Also there is optimal air velocity and it increases with growth of capital costs through larger diameter or higher metal price. It is happening due to it becomes reasonable to have higher pressure losses instead of larger number of parallel tubes from expensive alloy. For cheaper construction materials the optimal velocity will be lower. But in a relatively wide range around optimal value velocity has not strong impact on total costs, so it gives some window to designer for changing air heater geometry.

Therefore due to the total costs minimization we need to have a heating surface that consists of a large number of parallel short tubes of small diameter because with a decrease in diameter, the tube length required by heat exchange conditions is also reduced. As a result the design of convective high temperature air heater similar to conventional tubular air heater of steam boiler is proposed with the difference that air will pass inside tubes and flue gases between them.

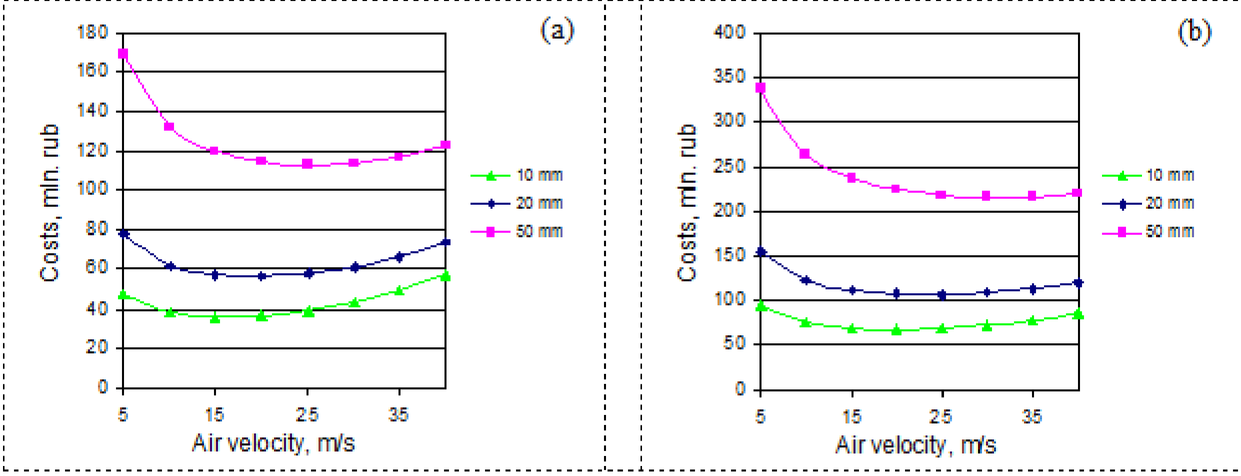

Figure 2. Total costs per year of high temperature section of air heater

5. Conclusion

In the paper main issues of coal-fired high temperature air heater development were considered. It was found that with the use of domestic nickel alloys compressed air could be heated up to 900-950°C in the unit based on external coal combustion. It was shown that small tube diameter (about 10 mm) and compressed air velocity in range of 15-20 m/s are preferred for expensive high temperature air heater sections. Therefore, the new design of convective high temperature air heater similar to tubular air heater of steam boiler is proposed.

Acknowledgments

This work was carried out at the Ural Federal University and financially supported by the Russian Science Foundation (project number 14-19-00524).

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