Development of heat exchanger for heat recovery of process gases

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Abstract. Due to new requirements of the Russian laws on the environment and energy efficiency, studies on effective methods for recovering waste heat from flue gases are crucial. Most oil and gas, metallurgy and chemical manufacturers remove high-temperature process gases. Gas cooling preceding cleaning reduces a volume of cleaned gases. For example, the most efficient dust and gas cleaning systems usually operate at a gas temperature of up to 200 °C. An increase in gas temperature can cause irreversible deformations of metal structures of the gas cleaning equipment and its premature failure. In addition, bag filters used for gas cleaning have strict limitations on gas temperature. As a part of the present project, an optimal design of staggered heat exchange elements in the form of perforated copper ribs was developed. The design documentation was developed and an experimental heat exchanger was designed. To monitor and control heat exchanger parameters, sensors were installed on the experimental heat exchanger (EHE). The algorithms of the automated system were developed. Laboratory and pilot tests proved the efficiency of the equipment designed for cooling waste process gases. The heat exchanger can be installed in gas flues of various diameters. The number of cooling units depends on technical requirements and operating and installation conditions.

1. Introduction

The project aims to develop a system for cooling process gases in order to reduce their physical volume, recover thermal energy and reduce heat waste into the atmosphere. The review of existing engineering solutions on thermal energy utilization identified the rationale for using a shell-and-tube heat exchanger.

As a part of the research, ANSYS models were developed. Thermodynamic processes at the "gas-liquid" boundary were studied using engineering solutions for optimizing the design of the heat exchanger having a low static resistance. Based on the calculation model, a laboratory heat exchanger was developed and laboratory tests of heat exchange processes were carried out.

The laboratory heat exchanger became a prototype of the experimental heat exchanger (EHE). The priority task for EHE development was to create an optimal design of heat exchange elements and their spatial arrangement to ensure maximum heat transfer efficiency.

The design documentation was developed and the experimental heat exchanger was designed. To monitor and control heat exchange parameters, sensors were installed on the EHE, and algorithms of the automated system were developed.

Pilot tests of the experimental heat exchanger were carried out. The tests proved the efficiency of the EHE for recovering waste heat from flue gases.
The authors have applied for a patent on the heat exchanger and gas cooling technology. The possibility of commercialization of research results in the oil and gas, metallurgy and chemical industries is being explored.

2. Research plan
Stage 1 “Analysis of waste gas cooling and heat recovery”:
- the analysis of scientific and technical research and patent search were carried out;
- ANSYS models of the heat exchanger were developed. Thermodynamic processes at the “as-liquid” boundary were studied using engineering solutions for optimizing the design of the heat exchanger having a low static resistance;
- market research was carried out.
Stage 2 “Development of an experimental model of the heat exchanger”:
- development of optimal design parameters of the heat exchanger;
- development of an experimental model of the heat exchanger with a low aerodynamic resistance and identification of optimal gas cleaning parameters at different temperatures of gas media.
Stage 3 “Waste heat recovery technology implementation”:
- carrying out laboratory studies of heat transfer processes in gas multicomponent media, development of a diagram design of a site for pilot tests;
- carrying out pilot tests of the shell-and-tube heat exchanger;
- intellectual property patenting;
- technical and economic evaluation of research results commercialization possibilities in the oil and gas, metallurgy and chemical industries.

3. Description of the Experimental heat exchanger
At present, in industrial centers and large cities, oil and gas, metallurgy, chemical and other industries release a large amount of high-temperature flue gases into the atmosphere.

According to the Russian laws, manufacturing industries have to reduce negative impact on the environment and improve energy efficiency. Therefore, development of a method for recovering waste heat from flue gases is a crucial issue.

The review of existing engineering solutions identified the rationale for using waste heat of flue gases for water heating, etc. Besides, a decrease in gas temperature has a positive effect on gas cleaning performance and gas cleaning equipment life cycle. Cooling decreases a gas volume which reduces operating cost. The need for cooling is due to the fact that in warm seasons, the inlet gas temperature can be 190 °C, and polyester bag filters used for gas cleaning in recent years cannot operate at temperatures exceeding 140÷145 °C. The use of heat-resistant filters which can operate at temperatures above 200 °C causes a three-four-fold increase in operational cost.

Currently, there are various approaches to waste-gas cooling. The choice of gas cooling methods depends on process conditions, temperature conditions, cleaning methods and chemical composition of gases.

The simplest solution is application of air in the gas flues using adjustable dampers. However, it can increase the volume of energy consumed by heat air guns and cause the need for additional filter cloth which increases gas cleaning unit maintenance cost.

Another method for gas cooling is water spraying in the gas flow entering the gas cleaning unit. But this requires compressed air and purified water and, as a result, permanent monitoring and maintenance.

It is possible to cool gases as they are moving along the gas flue using a core cooler developed and patented by Solios. Pressure losses in the system are compensated for by reduced volume of released gases due to their cooling by about 10 °C.

Additional cooling can be achieved by using heat-removing ribs arranged spirally on the outer surfaces of the flue which allows for partial winding of the air current surrounding the flue and increasing the heat transfer to the environment. The ribs can increase the area of the heat-dissipating surface. However, they increase the dimensions of gas-flue networks.
According to some authors, one of the most efficient solutions for heat utilization is application of a heat exchanger. The method has some disadvantages as far as it requires constant maintenance due to regular clogging of pipe stills and the use of additional equipment (a water pipe, a heat transfer loop, measuring devices, etc.). The advantage of the method is waste heat recovering which improves energy efficiency due to water heating for production needs, heating or cooling, distilled water production, electric energy generation, etc.

Thus, the studies on the design of a recuperative heat exchanger cooling process gases, reducing their physical volume and ensuring the efficient use of waste heat from flue gases are crucial.

Heat exchangers are widely used in the oil refining, petrochemical, metallurgical, chemical, nuclear, refrigeration, gas and other industries, as well as in the energy industry and utilities system. The heat exchanger design depends on application conditions.

A virtual model was developed, and research tests of the laboratory shell-and-tube heat exchanger were carried out as a part of the project. The most optimal design in terms of weight, dimensions, strength and performance characteristics was identified.

Virtual simulation was performed using known cooled gas mass flux s and inlet temperature values. The efficiency was assessed by comparing a decrease in cooled gas temperature and hydraulic resistance of the structure with target parameters.

To increase heat exchange efficiency, gases were cooled using water through a copper/aluminum wall. The required heat exchange surface is smaller in comparison with a steel wall as copper or aluminum has a higher thermal conductivity.

In order to optimize the Experimental heat exchanger (EHE) design, calculation models were developed and ANSYS tests of heat exchange elements were carried out.

Based on the virtual simulation results and required heat exchanger parameters, heat exchange elements from rectangular flat tubes with staggered perforated copper ribs were selected.

Based on the virtual simulation results and laboratory tests, an experimental heat exchanger was developed. It was identified that the design shown in Figure 1 is the most optimal in terms of weight, dimensions, strength and performance characteristics.

The housing is designed as a “pipe” rectangular with dimensions 2230×2044×6144 mm. The inner section has 2030×1874 mm sizes. Inside the housing is inserted thirteen (13) of the cooling unit, consisting of the heat exchanger elements. The blocks are fixed to the frame by means of bolting pads at the top and bottom of the housing through the outer walls of processing windows, these windows capped by taps on pads (top, bottom, Figure 1b). Through the bottom tap it is made of cold water supply by the piping system, pressure and water flow rate in each heat exchanger unit is regulated by a ball valve Dy80, mounted on the water supply nozzles (Figure 1a).

To the body, at the ends of the housing mounted cone transitions by bolting connection that connect the heat exchanger with gas pipelines.

On the bottom cover, there are connections through which a heat transfer fluid passes through between-frame space. To increase the heat transfer, the finning of heat exchange tubes is applied which is arranged by soldered tape along the entire length of the tube.

The movement scheme of gas and water in the developed heat exchanger is shown in Figure 2.
The heat transfer surface of the apparatuses can range from a few hundred square centimeters to several thousand square meters. Thus, in our case, the part of the heat exchanger is composed of 169 tubes with a total exchange surface of about 200 m². Total heat exchange units are 13, consisting of 13 pipes each (Figure 3) with the heat exchange area of about 464 m².

The pipe heater of the heat exchangers is made of direct copper sheets (thickness: 1 mm). Three tubes are welded to each other and on both sides are supported by stiffening ribs (Figure 3). Finning is made of flexible copper sheet 0.5 mm thick; ribs are performed openings for increasing heat transfer and gas flow.

**Figure 1.** Overview of experimental heat exchanger.
Heat exchange tubes are mounted in the block (Figure 4), which is convenient to mount and perform maintenance during operation. The exchanger is a frame of 2 welded flanges of a closed cross section, interconnected by longitudinal beams of the angular cross section, the inner side of the steel sheet, reinforced by vertical stiffness ribs. The thickness of the wall of the housing is determined by the pressure of the working environment and the size of the housing, but taken at least 3 mm.

**Figure 2.** A scheme of a heat exchanger (section).
Based on the technical and engineering solutions, the design documentation was developed and the experimental heat exchanger was designed (Figure 5).

Pilot tests of the EHE were carried out under manufacturing conditions. The tests were carried out in the following sequence:

- supply of cooling water to the EHE pipeline;
- visual check for sealing;
- direction of the high-temperature gas flow from the bypass flue to the EHE flue using a manual gate;
- stabilization of the gas flow temperature and aerodynamics and heat exchange petameters regime of the gas and the coolant;
- recording of test results.

Aerodynamic gas parameters and cooling liquid temperature were measured at the EHE inlet and outlet where automated system sensors were located.

The test results confirmed performance characteristics of the experimental heat exchanger (Table 1).
Table 1. Performance characteristics of the experimental heat exchanger.

| Parameter                        | Unit   | Value   |
|----------------------------------|--------|---------|
| Volume of waste gases            | nm³/h  | 76000   |
| Inlet gas temperature            | °C     | up to 150 |
| Outlet gas temperature           | °C     | less than 100 |
| Gas flow speed                   | m/sec  | more than 10 |
| Aerodynamic resistance           | Pa     | less than 100 |

4. Conclusion
Pilot tests identified that the total heat-up of the heat exchanger was not less than one hour. The initial gas temperature was in the range of 120-150 °C. The gas flow speed was not less than 14 m/sec which reduced the mass of dust deposits on EHE elements. The CPCS controlling the coolant supply using a regulating damper of the flowmeter allows for proper control of the water flow. The flow rate of the heat carrier in the range of 10-20 m³/h made it possible to decrease the temperature of flue gases at the EHE inlet and outlet by 30-50 °C. At the same time, the coolant heating temperature does not exceed 15 °C of the initial value.

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