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Management strategy of new energy-saving technology in the field of ground transport based on the principle of thermochemical regeneration of waste heat energy

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Abstract. The article describes the strategy of energy saving management in the field of operation of ground transport, developed on a fundamentally new basis for the effective transformation of the energy potential of waste heat energy. In the course of the work, the energy technological scheme is investigated and proposed based on the organization of thermochemical conversion of the initial hydrocarbon fuel using waste heat into a new type of synthesized fuel with higher rates of heat of combustion. The mechanism of this effect has not yet found its detailed consideration in the modern theory and practice of power engineering. It is based on the law of energy conservation, which in thermochemistry is interpreted as the law of Hess and its consequences.

1. Introduction

The energy carried away with the exhaust gases of the power plant of the vehicle determines the share of chemical energy of the fuel that is not realized in the engine duty cycle of the power plant. If we take into account that in some cases the heat loss with exhaust gases amounts to 50% of the chemical energy of the consumed fuel, then this aspect of the problem of fuel and energy savings deserves close attention.

It seems advisable to use some of this heat to minimize the thermal losses of the duty cycle of the power plant. One of the promising areas associated with the use of secondary heat of waste gases is the use of recycling tools. Heat-exchange regenerators and recuperators are used in the existing technological schemes for utilization of the energy potential of waste gases from stationary and aviation power plants. There are methods to regenerate heat, used in large stationary installations, based on the use of waste heat boilers or other means [1, 2]. All these technological methods of waste heat utilization and high mass-dimensional indicators of technical means used for its implementation, limit the possibilities of their practical application on ground vehicles.

This determines the feasibility of developing, on a fundamentally new technological basis, more acceptable for the transport system of heat utilization. Work towards finding acceptable utilization tools for power plants of ground vehicles, a priori, should be developed along the path of creating efficient and most compact systems. In general, for the effective conversion of the energy potential of the waste heat of the power plants into useful work, it is desirable to create conditions under which the greatest part of this heat could be reused in the duty cycle of the power plants, extremely minimizing thereby thermal losses of a cycle and, as a result, causing economy of the consumed fuel.



2. The principle of thermochemical recovery of waste heat

Taking into account this target orientation, an energy technology scheme based on the ability of some hydrocarbons to convert into a new type of energy carrier with a higher energy potential relative to the initial product has been investigated and proposed. Such a scheme has the most important advantages over other recycling schemes. During the thermochemical conversion of the initial hydrocarbon product, a mixture of gases is obtained: carbon monoxide and hydrogen. This is the so-called "synthesis gas", with higher calorific value index. The mechanism of this effect has not yet found its detailed reflection in the modern theory and practice of power plant engineering. Therefore, we consider this question in more detail.

From the point of view of energy expediency, it is desirable to organize the conversion at a relatively low temperature level, using a compact conversion structure with a catalytically active medium for this, which will allow to use exhaust gases as a heating coolant, that is, to organize the conversion process directly on board vehicles without additional heat sources. When using a converted gaseous product as a fuel with high calorific value, energy and effective performance and its fuel efficiency are increased. In addition, the presence in the fuel mixture of hydrogen, which is the activating reagent of the combustion process, can contribute to the improvement of the environmental qualities of the power plant [4].

Such power recycling scheme allows you to use of a number of commercial hydrocarbons, including alternative, able to implement efficient reactions of thermal catalytic conversion with the release of an energy-intensive target product. Thermal catalytic conversion is characterized not only by a high degree of utilization of waste heat, but also by improved kinetic and toxic combustion parameters of the produced fuel - synthesis gas. In modern energy-saving transport technologies, such efficient and compact systems have not yet found their practical application.

Since the proposed version of the energy technology scheme for utilization of the secondary energy resources of the power plant implies the need to organize the process of endothermic conversion (thermochemical conversion) of the initial energy carrier, it was named as *thermochemical regeneration of waste heat* (TRWH).

The concept of this type of waste heat utilization of the power plant has been developed on the basis of the fundamental principles of thermochemistry and can be implemented under the operating conditions of any type of power plant of the vehicle. It is based on the law of energy conservation, which in thermochemistry is interpreted as the Hess law and its consequences.

According to this law, the efficiency of thermochemical waste heat recovery directly depends on the chemical nature of the initial energy carrier, which determines the energy index of the endothermic effect of the reaction system of its conversion. It is clear that this indicator is equivalent to the amount of heat taken from an external source (heating coolant) and expended for the conversion process, and going to increase the energy potential of the target product of conversion reactions (synthesis gas).

We illustrate this with the example of the conversion of alternative alcohol fuels, in particular, methyl alcohol, which has been used for a relatively long time as a partial substitute or the main type of fuel for transport [5]. The heat of combustion of methanol $H_{u(m)} = 19670 \text{ kJ/kg}$.

The heat of combustion of the gaseous products of its thermochemical conversion (synthesis gas) is $H_u^k = 23870 \text{ kJ/kg}$. Thus, during the combustion of 1 kg of these synthesized products obtained from the same mass of liquid methanol, additional thermal energy is released, accumulated during the endothermic conversion of alcohol fuel, equal to $H_u^k - H_{u(m)} = 4200 \text{ kJ/kg}$. Therefore, in real conditions of the operating cycle, 21.4% of the available energy of the exhaust gases utilized for organizing the endothermic conversion cycle of 1 kg of methanol can be returned to the operating cycle and converted into additional work.

3. Efficiency of thermochemical regeneration of waste heat

The use of pre-chemical fuel conversion systems can improve the efficiency of its use, but under certain restrictions. The degree of regeneration depends on the temperature of the conversion process and increases with its decrease. Modern catalysts allow to realize the process of hydrocarbon conversion at certain operating temperatures (usually not below 280- 300°C [6]), thereby determining the minimum

possible temperature- limit of the exhaust gases, at which the organization of this process is feasible. If the temperature level of the exhaust gases is lower than the conversion operating temperature, an effective thermochemical regeneration of waste heat process is practically not feasible. Implementation of the TRWH effect at lower temperatures may be feasible in the future, if appropriate low-temperature catalysts are developed in the field of chemical technologies that can initiate conversion reactions of hydrocarbon compounds in such conditions.

The energy technological system for utilization of the secondary energy resources of the power plant, being a kind of “thermochemical adsorber”, takes away part of the waste thermal energy and returns it to the power plant for re-participation in the operating cycle (additional work). Therefore, in general, the thermodynamic cycle of this power plant can be considered as *regenerative*.

In the thermodynamic cycle of a traditional power plant (without a regeneration system), the heat Q_1 brought to the working fluid, resulting from the combustion of the fuel, is not fully used. Part of this heat Q_2 is removed from the working fluid and transferred to the “cold body”, causing that part of the chemical energy of the fuel that was not implemented for conversion into work. It is known [1] that the thermal efficiency of a cycle for such power plant is defined as:

$$\eta_t = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

In the working cycle with TRWH, part of the heat Q_2 is used to organize the process of endothermic transformation of the initial fuel to increase its energy characteristics: $Q_p = w \cdot Q_2$ (w - degree of regeneration), while the other part $(Q_2 - w \cdot Q_2)$ will be transferred to the “cold body”, thereby causing the level of irreversible heat loss in the cycle.

Then the indicator of the efficiency cycle with TRWH will be defined as

$$\eta_{tTXPOT} = \frac{Q_1 - (Q_2 - w \cdot Q_2)}{Q_1} = 1 - \frac{Q_2 \cdot (1 - w)}{Q_1}$$

It is easy to see that the value of the efficiency index of the cycle with TRWH will be higher than the thermal efficiency of the operating cycle of the power plant without regeneration, and increases with the growth of the degree of regeneration w .

The principal possibility of the effective implementation of TRWH in the operating cycle of the power plant, like any heat engine, will be determined by a number of conditions:

- the initial hydrocarbon product used for the conversion must be able, under the influence of the heat of exhaust gases (if there is an appropriate catalytic medium), to enter into conversion reactions with a pronounced endothermic effect;
- the available energy capabilities of the effluent gas flow from the power plant should correspond to the energy costs for compensation of the endothermic effect of the conversion reaction of the initial hydrocarbon product;
- the composition of the conversion products must reach the state of thermodynamic equilibrium, which is realized when the temperature state of the exhaust gases of the power plant corresponds to the level necessary for the efficient flow of the conversion process.

It should be noted another interesting in the scientific and practical sense aspect of the use of TRWH. With the appropriate organization of the thermochemical conversion of fuel, there is a unique opportunity to regenerate the entire energy potential of the off-gas flow. In addition to the thermal component of this potential discussed above, there is also a chemical component, which is caused by the content in the exhaust gases of incomplete combustion products whose chemical energy due to the imperfection of the combustion process has not been realized in the operating cycle of the power plant. It is possible to regenerate this component of the energy of gases by first passing them through the catalytic medium in order to oxidize the products of incomplete combustion of fuel (CO , CH , etc.). The heat released during the exothermic oxidation of these products contributes to an additional increase in the effect of TRWH.

The priority (RF patent No. 2249807) idea of complex regeneration of chemical and thermal energy of exhaust gases of power plant, is reflected in the development of a highly efficient sample of a methanol conversion reactor [7], combined with a catalytic chamber for oxidation of products of incomplete

combustion of fuel. The functionality of such a combined apparatus allowed, along with an increase in the degree of regeneration of heat energy from the exhaust gases, to reduce the content of *CO* and *CH*, that is, to improve the environmental quality of the power plant.

According to the results of a series of mathematical studies, the practical implementation of TRWH has been thoroughly studied and carried out in real conditions of the operating cycles of transport power plants. Compact thermocatalytic reactors have been developed, which according to their characteristics are coordinated with the operating conditions of the power plants for ground vehicles. Experimental testing of the effectiveness of TRWH was carried out for power plants (heat engines) operating on alcohol fuel in two thermal power cycles: the cycle with mixed supply of heat (diesel) and the Otto cycle (spark ignition engine) [8,9,10].

For the engine with the first variant of the organization of the working cycle, an increase in the energy efficiency of fuel due to the use of TRWH in the range of 4.5 ... 8.5% was registered [9,10]. The greatest value of the effect corresponded to the modes of high power. Along with the reduction in fuel consumption, due to the fact that the composition of the mixed fuel (synthesis gas) includes the hydrogen-containing component, the improvement of the environmental qualities of the engine was recorded: the content of soot in the exhaust gases decreased by almost 2 times, nitrogen oxides to 16%.

For an engine operating on the Carnot thermal power cycle, the energy-saving effect for individual modes reached up to 15% [8] with a significant improvement in its environmental qualities.

The established manifestation of the energy-saving and ecological effects of the onboard system TRWH makes it relevant for its application for the power plants of ground vehicles.

4. Conclusion

In the course of research on finding solutions to the problem of fuel and energy savings in transport, the following results have been obtained that are of scientific and applied importance.

4.1. Practical significance

Multi-million vehicle complexes of megacities emit billions of joules of thermal energy into the environment, which is irretrievably lost. The use of the proposed energy technology system TRWH will allow utilizing a significant part of this energy to convert it into useful work. This will lead to tangible savings in fuel resources in the field of energy consumption of transport. Due to the technological simplicity of the onboard organization of the conversion process, it can be implemented under the operating conditions of any type of ground vehicles power plants with minimal production and financial costs.

By its influence on the performance of the operating cycle, the TRWH energy technology system has the property of multifunctionality. Along with increased energy savings, it provides the possibility of using environmentally friendly alternative types of fuel. Thus, it allows solving important social problems of energy supply, conservation of traditional fuels and environmental safety in transport.

4.2. Scientific significance

In the course of theoretical research, a number of scientific statements have been formulated, which to date have not yet found their detailed reflection in modern heat power engineering.

1) A statement has been formulated on the possibility of complex thermochemical energy regeneration of the exhaust gases, including the thermal and chemical components of the energy of the gas flow. A similar scheme of the proposed version of the energy technology utilization of secondary energy resources of the power plant in modern research practice has not been studied in detail until now.

2) The principle of functioning of the proposed energy technological system TRWH is based on the principle reflecting only in general form the essence of the classical regenerative cycle of a heat engine. However, its "thermochemical scenario" includes an additional structural stage of the transformation of the chemical energy of the initial fuel, which causes its individual epistemological difference from the classical understanding of the regenerative cycle. In the field of modern research

and technology of power engineering this type of regenerative cycle has not yet found its real reflection.

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