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Review Article

On the problem of efficient production of hydrogen reducing gases for metallurgy utilizing nuclear energy☆

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ABSTRACT

One of the promising ways to reduce the energy consumption of metal production is the use of direct reduction technologies. The use of high capacity heat from high temperature gas-cooled nuclear reactors (HTGR) for the production of reducing gases from methane feedstock is a rational solution to the problems of fossil resources saving, reducing of power intensity of synthesis process and drastic lowering of foul gases release.

The application of radial flow scheme in the nuclear reactor core and in the methane converter allows to create the installations with minimal dimensions and lower hydraulic losses in comparison with currently existing units. It was conducted the investigation of gas flow and heat exchange with the elements of pebble bed in the case of radial flow, which allowed to receive the design equations for such an apparatus. The results of calculation of main thermohydraulic features of a prospective methane converter with radial flow of gaseous reaction mixture using these equations are given.

Introduction

Nowadays we can observe active development of atomic energy as an electricity source. But the share of electricity in total energy resources consumption is about 20%. The rest 80% of oil, natural gas, coal and other energy resources is expended for housing and transport needs and energy supply of various industrial technological processes. Burning of organic fuel in energotechnological processes inevitably leads to the generation of anthropogenic greenhouse gases. Developing of large-scale nuclear hydrogen energy can supplant expensive hydrocarbonic fuel from the energy sector and save oil and natural gas for the branches of industry where it is more difficult to replace them [1–5]. It also allows to reduce drastically the foul gases release.

We can regard a high temperature gas-cooled nuclear reactor (HTGR) as an energy source for the industrial

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processes because it allows to receive high-grade heat of 800–1000 °C. Pebble bed HTGR has additional benefit because this type of nuclear reactor does not need to stop its operation for refueling. The heat production in HTGR is realized by cooling of the reactor core consisting of spherical fuel elements with helium moving in the space between the fuel elements. The main disadvantage of HTGR consists in the following. It is demanded to spent large amount of energy to pump the coolant through several meters of pebble bed. Therefore, the auxiliaries of such plants are unattractively large. The application of radial gas flow allows to receive a compact apparatus with lower hydraulic losses in comparison with traditional axial flow [6].

Iron and steel industry has the second position after power engineering in the rank of consumers of fuel resources. One of the promising ways to reduce the energy consumption of metal production is the use of technologies of direct reduction of metals, especially iron, from the ore. Direct reduced iron (DRI) is produced from oxides by destructing chemical bounds without melting. The result of direct iron reducing is the highly metalized material with a complex of features (composition, structure, size etc.) which depends on the applied technology. The main DRI consumer is electrometallurgy, but it can also be processed in open-hearth and converter furnaces instead of scrap metal. Blast-furnace process is entirely excluded in this type of production [7].

That is why raw material that is achieved in the direct iron reducing process allows to reduce the negative impact of metallurgy on the environment, including the reduction of the carbon dioxide emission into atmosphere. The methods of metal production without blast-furnaces and in the first place the direct reduction method are widespread all over the world. It is connected first of all with increasing need for pure metal.

There are two factors that limit the development of direct reduction methods. The first one is the need of rich ore to maximize productivity. The second is the need of natural gas or other reducing gases and a sufficient quantity of energy resources to run the process effectively.

DRI-technology with hydrogen-containing gases

One of the most effective ways of the direct reducing of iron from the ore is the application of hydrogen-containing gases. The technologies of iron direct reducing from oxides (the so-called DRI and HBI technologies) are used actively worldwide. These methods consume up to 400 m^3 of natural gas per 1 ton of metallic pellets produced [7].

Today we can observe the trend of iron production profitability reduction for the conditions of the rise in prices of the organic fuel.

In the DRI process the enriched iron ore is reduced by the certain gas mixture under the high temperature conditions. Iron ore is usually processed in the form of pellets that contain about 70% of iron by weight. The reduction process can be run in shaft furnaces or rotating pipe furnaces in the atmosphere of reducing gases such as carbon monoxide and hydrogen [7].

Let's examine the process of DRI production on the example of Midrex process. Midrexcompany is the recognized leader of the DRI facilities market which works in this sphere since 1969.

Enriched iron ore in the form of pellets or lumps is charged into Midrex shaft furnace. The typical raw material for the process has the following content:

- Fe – 67%
- $SiO_2+Al_2O_3$ – 3%
- S – 0.008%
- TiO_2 – 0.15%
- P – 0.03%.

The overall reduction reactions are

$$Fe_XO_Y + CO = Fe + CO_2 \tag{1}$$

$$Fe_XO_Y + H_2 = Fe + H_2O \tag{2}$$

The product of the Midrex process contains 90 … 94% Fe.

The process of iron reducing from oxides runs by sequential transition from higher to lower oxides. It can be schematically described as

$$Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe;\ \text{temperature higher than } 570\,^\circ C$$

or

$$Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow Fe;\ \text{temperature lower than } 570\,^\circ C$$

Hydrogen has lower reducing ability than carbon monoxide if the reaction temperature is lower than 810 °C, but in the temperature range higher than 810 °C it becomes much more stronger deoxidizer [3].

The rate of the oxides reducing process increases significantly if pure hydrogen is used as a reducer. Due to technical and economic difficulties of hydrogen production the sphere of its application is limited and it is used for the production of metallic powders and the creation of nitric and hydrogenous atmosphere for the processes of thermochemical treatment of metals.

The large-scale production of metal pellets is connected with the reducing processes based on synthetic gas (mixture of CO and H_2). Synthetic gas can be produced in a steam methane converter or Midrex reformer from natural gas. It also can be obtained from coal or coking gas. The reducing gas composition affects the quantity of the iron produced. The greatest iron output was achieved when H_2 to CO ratio in the reducing gas fed into the shaft furnace for the reducing process was equal to 1.

The reaction of steam methane conversion

$$CH_4 + H_2O = CO + 3H_2 - 206\ \text{kJ/mol}, \tag{3}$$

$$CO + H_2O = CO_2 + H_2 + 41\ \text{kJ/mol} \tag{4}$$

in view of high endothermicity is run in pipe furnaces with large amount of upright pipes filled with dispersed catalyst and heated by gas burners from the outer side. To heat the steam and methane mixture and to supply the heat of endothermic reaction, large amount of gas is consumed, up to 50% of total amount.

The production of hydrogen by electrolysis for the purposes of metallurgy is limited by high energy consumption of the electrolysis process. Electrolysis energy consumption is 5 times higher than the inherent energy capacity of the received