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Contribution of nuclear energy on new energy systems post Fukushima

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ABSTRACT

Nuclear energy contribution on new energy systems post Fukushima was discussed in this study. A new energy transformation concept based on carbon recycling, called the Active Carbon Recycling Energy System, ACRES, was proposed for a zero carbon dioxide emission process. ACRES is driven with consumption of primary energy that does not emit carbon dioxide such as nuclear and renewable energies. A smart ironmaking system based on ACRES, iACRES, was also proposed. Carbon monoxide was thermodynamically the first candidate for recycling carbon media in iACRES because it had higher energy densities than hydrogen and was highly compatible with conventional iron-making process. From a feasibly study of iACRES driven by high-temperature gas reactor had the most availability for conventional ironmaking processes in the stand point of energy output rate in comparison with solar energy system. It was expected that nuclear energy could contribution on conventional industrial processes by using ACRES as a new energy system post Fukushima.

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1. Introduction

Energy system designs are required to be changed following with social structure. The Great East Japan earthquake and nuclear accident at Fukushima Daiichi Plant of Tokyo Electric Power Company in 11 March, 2011, showed the risk of Japanese energy system. Most of nuclear power plants in Japan were closed, especially all plants were shut-down after operation stops of last plants in Ooi plant in Kansai Electric Power Company in September, 2013. Japanese primary energy resources were shifted from nuclear power to natural gas after the disaster even there were some efforts for utilization of renewable energies. Then, the electricity price and carbon dioxide emission per unit in Japan were increased after 2011.

Energy supply security is important matter for industrial and economical developments of a society. Steep change and instability of the market prices of primary energy sources is causing economic confusion in any ages. Carbon is the most important energy media for manufacturing industry and social life of human being. Carbon supply security is an essential condition for a sustainable society. In Japan, the supply of fossil fuels of primary energy almost depends on import. Energy balance and flow in Japan was shown in Fig. 1 (Minister of Economy 2006). Fig. 1(a) shows the representative present energy flow in Japan based on data in 2004 at which Japanese energy consumption flow was almost stable during decade. Enthalpies of import fuel and nuclear power were 84% (18.9×10^{18} J) and 10% (2.5×10^{18} J), respectively, of the total primary energy corresponding with 723 GW in Japan. However, liquefied natural gas (LNG) was imported alternatively for nuclear power after 2011. Then, the historic deficit of the trade balance has been caused by LNG import cost change from 3.5 Trillion JPY in 2010 to 6.0 Tri. JPY in 2012 (Trade statistics of Ministry of Finance of Japan in, 2012). Not only technical availability, but also economical one for the restart of nuclear power plant should be required in future. Fig. 1(b) shows a future energy flow proposed in this study. Nuclear power use for electricity as before 2011 is needed firstly for economic recovery for Japan. Japan had obligation internationally to follow the IPCC plan after the Kyoto protocol, and is required drastic reduction of carbon dioxide (CO_2) emission. However, CO_2 reduction connects with restriction of usage of carbon resources and causes depression of activity of manufacturing and service industries. In energy usage in Japan, electricity and process heat is shared around 36% and 51% in primary energy base, respectively. Nuclear power usage to process heat becomes more important for the CO_2 emission mitigation without economic activity in future. Then, co-establishment of carbon supply security and reduction of

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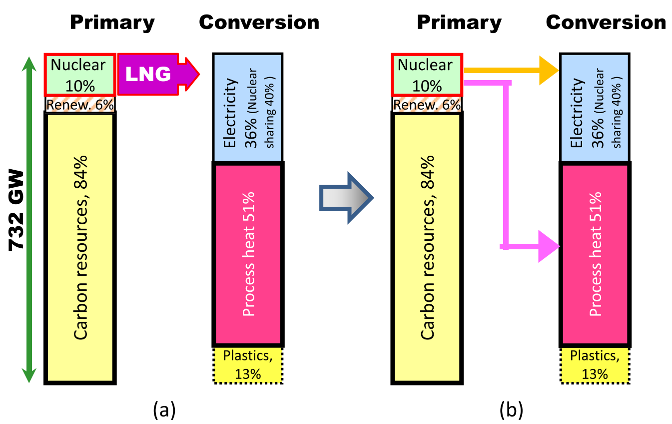

Fig. 1. Energy balance and flow in Japan (a) present, (b) this study proposed future.

CO_2 emission is an important subject for a development of a modern society.

A new energy system in which carbon is reused cyclically was discussed. A carbon recycle system has already existed in nature as a natural carbon neutral system. A concept of an Active Carbon Recycling Energy System, ACRES, was proposed against natural carbon recycling energy system (Kato, 2010). CO_2 is regenerated artificially in hydrocarbons consuming a primary energy source with no-CO_2 emission, and re-used cyclically in ACRES. ACRES recycles carbon, and transform energy without CO_2 emission. ACRES can be applicable for iron-making process. The feasibility of smart ironmaking system based on ACRES, iACRES, was discussed thermodynamically in this paper.

2. Principle of ACRES

A concept of the proposed ACRES is shown in Fig. 2. Carbon dioxide (CO_2) with/without water is the ground state of carbon. CO_2 is converted into carbon materials by non-fossil primary energy using some chemical technologies (Kusama and et al., 1996). Produced carbon material is useful for co-production process. The carbon materials provide thermal and electricity energies during oxidation into CO_2. The carbon materials are capable to be used as raw material for industrial materials. The carbon materials are ease to be stored and transferred under lower compression pressure in comparison with H_2. The carbon materials have quite high affinity with common manufacturing industries. If the carbon recycle system can be established thermally and kinetically, it is expected that the system is diffused easily into conventional industries. Natural carbon recycle energy system has already been existed by plant lives in nature, and an ideal recycle system. However, potential amount of bio-mass is not enough for a modern society. Especially it is less than 10% of all demand of energy in Japan. The natural recycle system is not enough for energy demand in Japan (Kameyama and Kato, 2005). Then, an artificial active carbon recycle system was proposed as ACRES in this study.

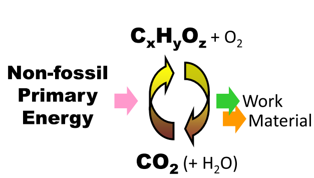

Fig. 2. Concept of ACRES.

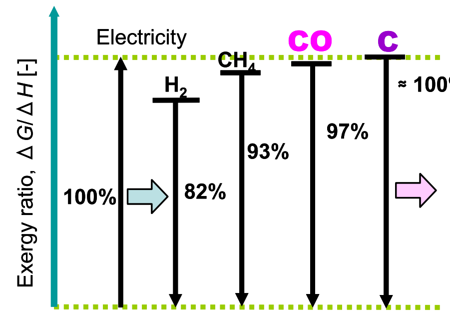

Fig. 3. Exergy ratio ($\Delta G/\Delta H$) for carbon materials and hydrogen (HHV).

The structure of ACRES consists of three elemental processes of carbon material usage, CO_2 recovery and separation, and carbon material regeneration. In the usage process, the carbon material can be used for both heat source and material. CO_2 generated from carbon material consumption is recovered by physical and chemical sorptions. Sorbed CO_2 in a sorption material is separated thermally by a heat input. This process produces high-concentrated CO_2. Recovered CO_2 is regenerated into carbon material in the regeneration process. The regeneration process is endothermic and need energy input. In ACRES, total energy input at recovery and separation (E_S), and regeneration (E_R) should be larger than the energy output at the usage process (E_U).

$$E_S + E_R > E_U \tag{1}$$

ACRES is energy consumption process, then, a discussion of the energy balance of the system is required for the feasibility evaluation of the system.

The selection of the recycling carbon material in ACRES is the first key point. The recycling material must be a high-quality energy media and compatible with conventional energy consumption processes. The exergy of the material is the main criteria for energy density, and is defined as the ratio between the Gibbs free energy (ΔG [kJ/mol]) and reaction enthalpy (ΔH [kJ/mol]). Fig. 3 shows the ratios ($\Delta G/\Delta H$) of some carbon materials (high heating value (HHV) base). Electricity has a ratio of 100%, and the ratios for the selected carbon materials are higher than that of hydrogen at 82%. Carbon monoxide (CO) and simple carbon have ratios that are close to that of electricity. If a flow-type reactor is used for an ACRES process, a gas medium is suitable. It was concluded that CO was the best gaseous candidate for the recycling carbon material because CO has a higher energy quality and density than hydrogen, and has a high affinity for conventional energy consumption systems such as ironmaking and chemical processes.

Simple carbon (C) is also a good material for ACRES, because C has a higher energy quality and density in comparison with other carbon materials and is easily stored and transferred in the solid phase. It is proved thermodynamically that CO and C have higher energy density than H_2, and other hydrocarbons. CO is in gas phase, easily transformable and popular energy material for iron-making process. Then, ACRES using CO is expected as a practical process. CO usage, recovery and separation processes are able to be covered by conventional industrial technologies. Development of efficient CO regeneration process is important for the establishment of ACRES.

3. ACRES for ironmaking process

ACRES concept has possibility to be used in conventional industrial processes. Ironmaking process is one of candidates for application because the process is representative process driven by

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