Fusion-Biomass Hybrid Concept and Its Implication in Fusion Development

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Abstract. Limited Q plasma combined with fuel production from biomass is proposed to be a possible option of fusion energy in the near future. High temperature blanket concept with LiPb and SiC, and conversion of cellulose and lignin to H2-CO mixture at the temperature around 900 oC at high efficiency over 90% were both experimentally tested by the authors. This product H2-CO gas mixture can further yield either more hydrogen by Shift reaction, or artificial oil such as diesel by Fischer-Tropsch Synthesis. By adding the original chemical energy of the waste biomass, total apparent energy conversion efficiency from fusion to the product as a form of gaseous fuel approaches 270%. This energy "multiplication" significantly relaxes the requirement of plasma Q factor, because net energy production by the plant is possible with Q<5 plasma, compared with the requirement to exceed Q>20 in the case of pure electricity generation from fusion. Unlike in the case of electricity generation, pulsed, and/or driven burning plasma may be used because the product is a fuel, that does not require steady state operation. This energy plant can be regarded as Fusion-Biomass hybrid, that is free from all the technical complication of the fission-fusion hybrid. Based on these features, the authors have designed a reduced scale tokamak of Q~5 with R~5m, fusion power around 500MW, as a plant that can eventually demonstrate positive net energy production as fuel. This paper will also report our recent development of high temperature blanket, such as 900 oC LiPb loop, SiC components, heat exchanger(IHX) and tritium recovery. This concept provides possible option of the early realization of fusion with opportunity of engineering maturity of reactor technology.

1. Introduction

This paper proposes a new fusion plant concept that suggests the possibility of faster and easier introduction of fusion energy in the earlier half of this century, with based on technical confidence, reduced size and difficulty and with larger and more attractive market possibility.

Requirements and expectations for the energy generating technology have drastically changed over the past decades, and significantly different from what was supported fusion development in its earlier age. The ever-increasing demand for energy source combined with recent violent change of oil price and global climate change problem require advanced energy technology to indicate solutions. Although limitless and "clean" energy would always be welcome, current global environmental problem and energy market requires faster answer to replace fossil fuel in the earlier half of this century to reduce carbon dioxide emission.

However fusion energy that will demonstrate burning plasma with ITER in late 2020th and will be introduced to the electricity market in the middle of this century can respond to neither expectations for the carbon dioxide reduction nor rapid increase of energy demand in the next 50 years. It is very likely that the clean electricity market will be occupied by nuclear, solar, wind, and other renewable technologies.

On the other hand, demand for fuels is much larger than that of electricity, and while fraction in total energy consumption would decrease due to the increase of electricity, 4 times larger needs than that of electricity is anticipated at the end of this century. Net increase of fuel demand will be roughly doubled, and unlike in the case of electricity, nuclear or renewables will not be the solution except for hydrogen production from water. Biomass-based fuel could be another solution, because it is regarded as carbon neutral, but conversion from biomass to fuel is inherently poor due to the required energy to convert it. The authors have suggested that fuel supply is important for non-electric fusion application, because expectations to replace fossil fuel is very strong, and before 2050, little substitute is known to be available.

2. Biomass Process

The authors have proposed that hydrogen production from biomass is possible with high temperature blanket being developed for fusion reactor. Recent experimental results confirmed that conversion of waste biomass (represented by cellulose and lignin) to H2-CO mixture at the temperature around 900 oC at high reaction efficiency over 90% is feasible;

$$C_6H_{10}O_5+H_2O \rightarrow 6H_2 + 6CO -814\ kJ \quad . \quad (1)$$

In the experiments, small pellets of cellulose are supplied to the reactor made of quarts tube filled with metal or glass grains at prescribed temperature in moist Ar stream. Product gas was analyzed by micro-gaschromatograph to detect hydrogen and C1-based gases such as CO,CO_2 and CH_4.

It was observed that cellulose pellets immediately reacted in the preheated reactor, and reaction completed within 60 second each for this pulsed experiments, with no residue left in the heated part of the reactor. Figure 1 shows the gas composition at the outlet of the reactor as the function of reaction temperature. Theoretical composition is shown as line, and the experimental composition is expressed as bars, and hydrogen is plotted as dots. Both theoretical equilibrium of C-H-O system and the experimental results with and without metal grains as catalysts are shown. Equilibrium calculation and experiments agreed fairly well, and with Ni metal, ca. 95% of the carbon in the cellulose was converted to gas mixture consists of CO, H_2 and CO_2.

Quantity of hydrogen was also measured, and a little smaller than that expected from the amount of CO, CO_2 and CH_4 that must generate corresponding amount of hydrogen by the reaction, suggests loss of hydrogen or error in analysis. At the lower temperature region where conversion of carbon of the cellulose does not look high, corresponding loss of carbon is suspected become tar that was sometimes observed at the downstream of the experiment.

Experiments with rignin, that is a major compound of woody biomass, were also performed and although the conversion ratio was not as good as the case of cellulose, the results were essentially similar, and indicates gasification over 80% was possible.

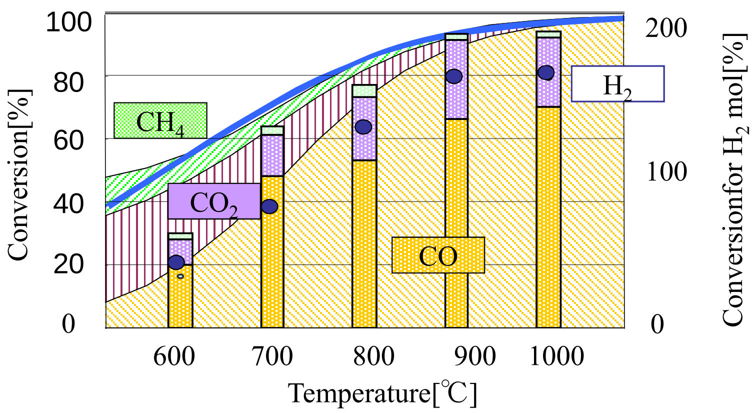

FIG. 1. Gasification of cellulose at high temperature.

Amount of absorbed heat by the reaction was measured by the integration of the temperature decrease in the reactor, calibrated with known endothermic reaction of the decomposition of strontium carbonate. The results showed good agreement, indicating the conversion of heat to the chemical energy occurred as expected with this reaction.

This product H_2-CO gas mixture can yield either twice more hydrogen by the shift reaction with existing technology,

$$CO + H_2O \Leftrightarrow H_2 + CO_2 + 32\ kJ \quad (2)$$

or, by the well-known Fischer-Tropsch Synthesis reaction, gaseous mixture , CO + H_2 make

$$2H_2 + CO \rightarrow -CH_2- + H_2O + 160KJ \quad (3)$$

reaction to be artificial oil, such as diesel, kelosene or jet fuel. In either case the use of the gaseous or liquid fuel product, i.e. hydrogen or oil cause little carbon dioxide emission, because the raw material of waste biomass is regarded as carbon neutral. Thus, these energy products (fuels) are another option of the use of fusion energy besides electricity.

Because of the nature of this endothermic chemical reaction (1), fusion energy can be converted to chemical energy without being limited by the thermal cycle efficiency that discards more than half of generated fusion energy as waste heat. By adding the original chemical energy of the waste biomass, total apparent energy conversion efficiency from fusion to the product chemical energy as a form of gaseous fuel by reaction (1) approaches 270%, and with oil synthesis (1) and (3) that involves heat rejection, apparent efficiency is approximately 200%.

It should be noted that the efficiency of other hydrogen production processes based on electrolysis is limited by the conversion using thermal cycle, and the thermo- chemical water decomposition such as I-S process also discards heat by exothermic reaction and none exceeds 50% efficiency. Energy efficiency of the reaction (1) was experimentally demonstrated to be ca. 80% that effectively changes fusion energy to chemical energy.

The figure 2 summarizes the material and energy balance of this biomass conversion process. Biomass as raw material of 1 kg can be converted to approximately 0.5 liter of liquid fuel to be handled current energy infrastructure. Because of the original chemical of the biomass that was evaluated from its combustion heat, was added and make the apparent energy efficiency for fusion triple in the case of hydrogen and double in fuel production.

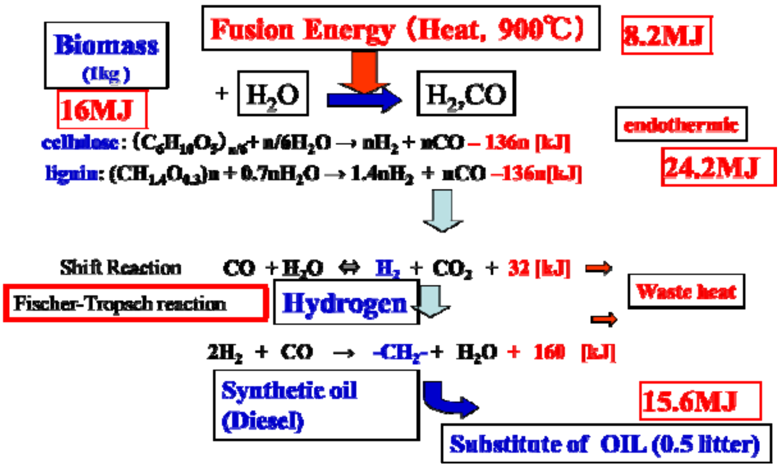

FIG. 2. Material and Energy Balance of biomass conversion.

It is noted that the waste heat from shift reaction and FT reaction is borne by 300-400 degree coolant and could be used for further electricity generation, that is ignored for simplicity in this paper.

3. Biomass-Fusion hybrid

One of the features of fusion energy is, unlike in the fission reactors that have fixed temperature of heat as primary energy product depending on the reactor concept, various temperature can be considered to be extracted from the same type of plasma device. In the case of fission, high temperature reactors, typically high temperature gas reactor HTGR or VHTR are being developed for the utilization of high temperature heat. Not only coolant, but the entire reactor concept is different from other application, and the design is dedicated for high temperature heat. To utilize the fusion energy, the location of fusion reaction in plasma and the device to extract its energy is geologically separated, and blanket concept has some independence from plasma confinement device. Development of blanket has been independently implemented from fusion plasma study.

Blanket is composed of vessels of several 10 cm thickness and filled with lithium containing materials, and heat transfer media circulate in it. Most of the current blanket designs consider the temperature from 300 degree C to 900 degree, but because original energy of neutrons are far higher, this temperature is mainly limited by the materials and technology to handle it. Energy utilization technology of fusion therefore depends on the heat transfer media and the blanket concept to generate it. Because water[1,2], liquid metal or high temperature helium[3] are considered as blanket coolant, energy utilization technology planned for water cooled reactors, liquid metal fast reactor and high temperature gas reactor can all be applied for fusion. Technology developed for the utilization of fission reactors are thus applicable for fusion with adequate modification.

Hydrogen production processes, such as electrolysis, including vapor electrolysis, IS process, and biomass conversion can all be regarded as possible applications for fusion[4,5], if adequate blanket that provides heat at required temperature is developed. Among these hydrogen production processes, waste biomass conversion proposed by the author attracts particular attention because of its superior potential efficiency [6] as described above. Because unlike in the case of fission, this particular feature of energy efficiency enables fusion reactor to be feasible in different way.

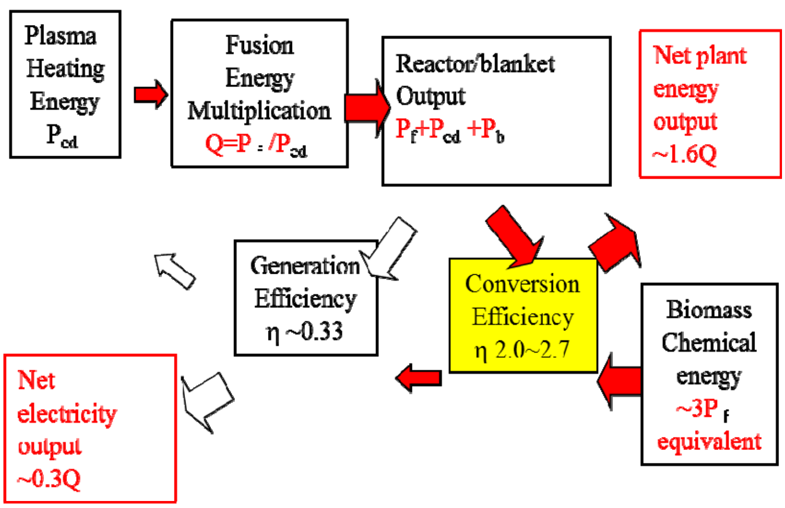

FIG. 3 Energy Balance for Biomass-Fusion hybrid.

In the development of fusion energy, famous Lawson criteria is regarded as the measure of the feasibility of fusion as viable energy source. Because of large amount of energy needed to generate and heat burning plasma, external energy supply, that is electricity, should be far smaller than its product fusion energy, that has been originally regarded as conventional steam based generation of 33% efficiency.

This energy plant based on Fusion-Biomass hybrid, that takes advantage of both fusion and biomass energy as shown in the fig.3. Compared to the regular electricity generation that cannot overcome the thermal cycle limit of some 33%, this energy "multiplication" significantly relaxes the requirement of plasma energy multiplication factor Q, because original Lawson criteria depends on the conversion efficiency to be recycled to plasma. Although the hybrid obtains product energy as fuel, a part of that could be used for conventional generation with 33% efficiency to sustain plasma. Of course in the current or near future technology, this conversion can be far more efficient, because if hydrogen or H2-CO mixture is used for gas turbine generation or fuel cell, efficiency is expected to exceed 50%.

The modified Lawson criteria is shown in the fig.4. While pure fusion electricity DEMO plant is required to achieve Q>20 to yield net plant output corresponding to 6 times larger than the input energy at the generation efficiency 33%, net energy production of 8 times is possible with Q<5 plasma when combined with biomass fuel production, this effect relaxes required Q for energy plant. Biomass conversion is also possible for high temperature fission reactor, but only fusion can take this advantage of hybrid effect to generate net output.

This "hybrid" effect is well-known for fission fusion hybrid that utilizes fission reaction to multiply output energy of fusion neutron. In the case of fission-fusion hybrid, some variations are identified, such as energy multiplication in the fissile blanket, or fissile fuel production that will be utilized outside of the plant. In the case of biomass-fusion hybrid, net positive energy output is obtained from the plant as a form of commercial fuel product. It could be either liquid fuel that will be immediately applied for existing oil-based infrastructure, or if desired, hydrogen can be produced.

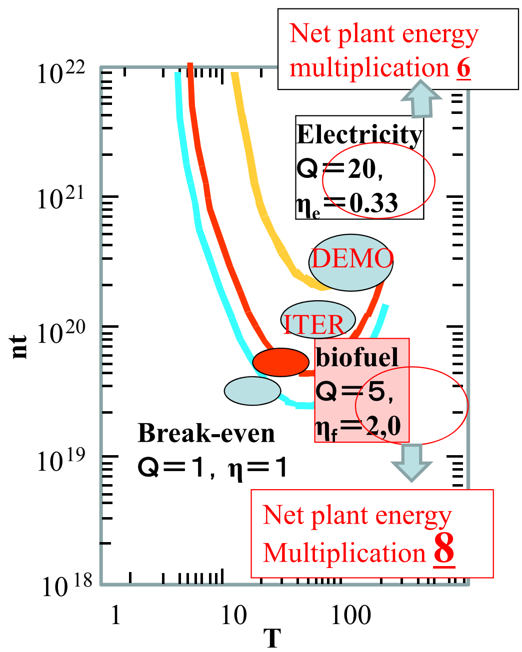

FIG. 4 Lawson criteria for biomass-fusion hybrid.

It should be noted that no other processes such as fuel reprocessing technology that is essential for fission hybrid would not be needed.

This hybrid concept reduces the technical difficulty of plasma significantly. Unlike in the case of electricity generation, pulsed, and/or driven burning plasma may be used because the chemical reaction does not require steady and stable operation. Assumed technical requirements for this plant concept are realistic ones that are already applied to ITER with currently available scaling, or with reasonable extension of the current technology. Because modest Q is sufficient for biomass-hybrid, tokamak device could be smaller than ITER, and will not require extremely large construction cost. Low pressure blanket system and throughout the power train is another major safety advantage of this plant concept.

4. High temperature blanket and plant

The authors have designed a reduced scale tokamak fusion machine of Q~5 with a major radius 5m for biomass fuel production. Figure 5 shows its power flow, with fusion output P_f to be 300MW, and the plant can provide positive net energy production as fuel, while additional 60MW of external electricity is needed.

Feasibility of the high temperature blanket, that seems to be challenging, is one of the key issue of this concept. High temperature LiPb liquid metal blanket combined with SiC/SiC cooling panel is designed and being developed and tested to make this option possible. The conceptual design of the blanket structure was made using neutronic and thermal hydraulic analyses. Cooling panel made of SiC composite that can actively cool and achieves controlled isolation between hot LiPb and ferritic steel is developed and tested. This technique can be used for the intermediate heat exchanger (IHX) in fig.5, needed for heat transfer from the primary high temperature LiPb coolant to the secondary media. Dual coolant LiPb/He loop above 900 degree C is operated to demonstrate small scale SiC components. Control of tritium transfer and recovery is also evaluated to be feasible based on the experiments.

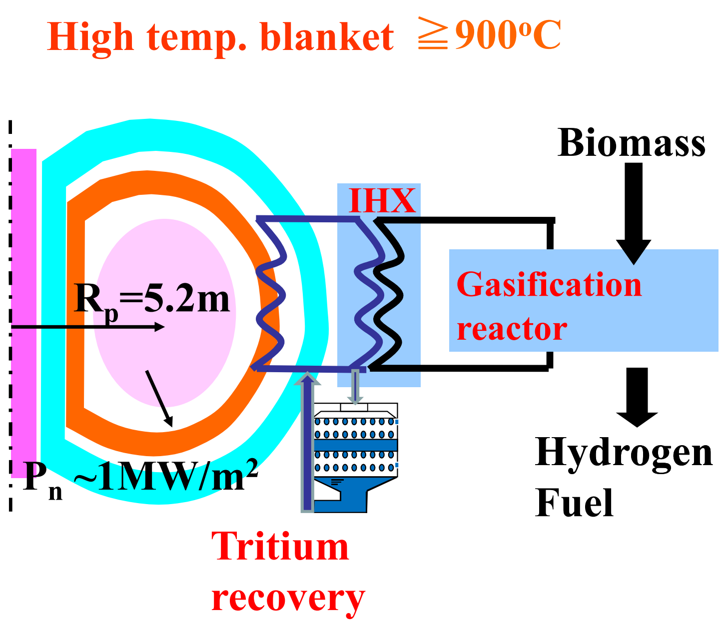

FIG. 5 Plant system for biomass-fusion hybrid.

5. Conclusion

This plant concept "Fusion-Biomass Hybrid" enables fusion to be realized in the nearer future. Such a small device will necessarily play a role as the facility for component development until the entire plant would be technically mature. That will also directly demonstrate the substitution of fossil energy by fusion, and will respond to the expectation for the possible solution for the climate change problem in earlier half of the century. It will suggest far larger future market possibility and reduction capability of carbon dioxide emission by substituting fossil by fusion. This fusion application could be more competitive when compared with renewable or existing nuclear fission that do not generate high temperature heat. Producing artificial oil will emphasize the fusion as a major near future energy alternative of fossil that can be commercially deployed taking advantage of the existing social infrastructure, and immediately decreases CO2 emission that is required by the current public.

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