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Citation	Proceedings of the JGSEE and Kyoto University Joint International Conference on Sustainable Energy and Environment (SEE). Hua-Hin, Thailand, December 1-3, 2004, 63-66
Issue Date	2004
Doc URL	https://hdl.handle.net/2115/50116
Type	conference paper
File Information	SEE2004_63-66.pdf

Thermoelectric Power Generation Using Hot Fluid Flow of Sodium

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Abstract: A prototype system for thermoelectric power generation was studied as a potential heat recovery system from spent nuclear fuel at fast breeder reactor (FBR), which is cooled by liquid sodium. Experimentally, six modules consisting of 180 pairs using Fe_2VAl cast alloy were mounted on the outer surface of a stainless tube which was internally heated by flowing liquid sodium. The element surface was directly cooled by forced air flow. The output power was evaluated to be about 4.2 W/m assuming that the entire pipe surface was covered by the elements.

Keywords: Thermoelectrics, Power Generation, Sodium, Spent Nuclear Fuel, Heat Transfer, Air Flow.

1. THERMOELECTRIC POWER

Temperature difference (ΔT) at the thermoelectric element between the hot and cold junctions generates the movement of electric carrier such as electron. The electromotive force is proportional to the product of ΔT and Seebeck coefficient, α. This principle is well known as the thermocouple. When a few thousands of thermocouples are connected in series, we can obtain a few volt as direct current. One of the characteristics of thermoelectricity is the high reliability because of lack of moving parts.

The conversion efficiency of thermoelectric power generation was in a low level of only a few %, but it has been recently improved to a level of 10% due to materials innovations [1]. Comparing with a high efficiency of electro-mechanical conversion such as the turbines in the electric power plants, it seems still difficult that the thermoelectric technique replaces the conventional turbine based on hot water vapor. However it would be necessary to prepare the fundamentals of system designs for a better thermoelectric material which will come soon.

The serial connections of the thermoelements are required in a large scale because a single pair of thermo element generates only a very small voltage. The electric energy generated by a pair is lost as an Ohmic heat, when it passes through the other pairs. Since we can not set an infinitely large thermal bath, the thermal energy is carried by the thermal fluids to a thermoelectric power generator, where the high temperature parts are cooled down and the low temperature parts are warmed up by the heat exchange through the thermoelectric modules, as shown in Fig.1. Resultantly the temperature difference applied to the large-scale thermoelectric assembly becomes smaller along the fluid flow, and the generated power becomes smaller.

The authors have been developed the system designs to minimize these lost energy in thermoelectric power generation from the three aspects; material research, assembly technology, and systemization in a large scale plant, aiming at the future application to practical recovery of thermal energy, especially, from the nuclear power plants. This study reports these fundamental concepts and an experimental trial.

2. LIQUID SODIUM AS HEAT CARRIER

Liquid sodium is practically used as the thermal fluid to extract heat effectively from the nuclear power plant. A prototype fast breeder reactor (FBR), "Monju", is installed at Tsuruga, 120km northeast from Kyoto, Japan. In Monju, the liquid sodium is required to control the nuclear reaction, and the heat is extracted from this reactor also by liquid sodium,

and transferred to water vapor through the double sodium loops. It is finally converted to the electricity at the turbine, as shown in Fig. 2 [2].

This coolant selection enables 500K - 800K system temperatures of the heat transport system. The sodium circulation piping is also applied at the spent fuel storage facility [2] Spent nuclear fuels have 660KW decay heat, at maximum, after withdrawal from the reactor core, and they have to be stored for about 400 days until the decay heat decreases in this facility. The generated heat is released to the open air through sodium-air heat exchangers, as shown in Fig.3. This spent fuel storage facility is one of the targets where the thermoelectric power generation is tested.
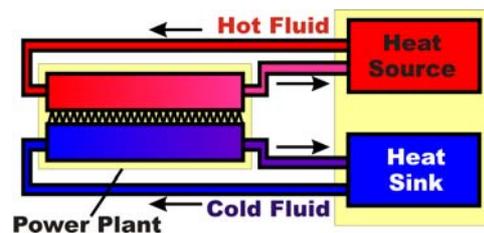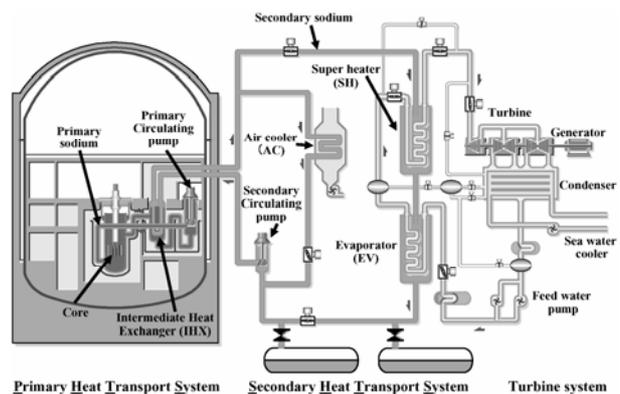

Fig. 1   Extraction of heat by fluids.

Fig. 2   Heat transport system of a prototype FBR, Monju.

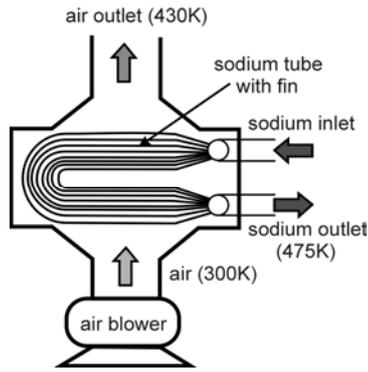Corresponding author: suzuki@energy.kyoto-u.ac.jp

Fig. 3   Heat exchanger for the cooling of spent nuclear fuel.

In this study, a series of thermoelectric power generation is tested at the prototyping Fe_2VAl modules with liquid sodium circulation, aiming at providing fundamental understanding for further consideration of module fabrications and system application.

3. USAGE OF Fe_2VAl ALLOY

Most of commercially available thermoelectric materials such as Bi_2Te_3 are not applicable for heat utilization because of high temperature [1]. The ferric alloys are superior for plant-wide application, because they are free from resource restriction, toxicity and environmental problems [3]. Some previous reports show that Fe_2VAl thermoelectric material has a good Seebeck coefficient close to the conventional semiconducting thermoelectric materials [4]. The Seebeck coefficient of Fe_2VAl varies widely between +100 and –150 μV/K sensitively depending on the composition as shown in Fig.4. The characteristics of Fe_2VAl alloys are also reported by the other researchers [5-8], but open problems still remain in modularizations and system applications.
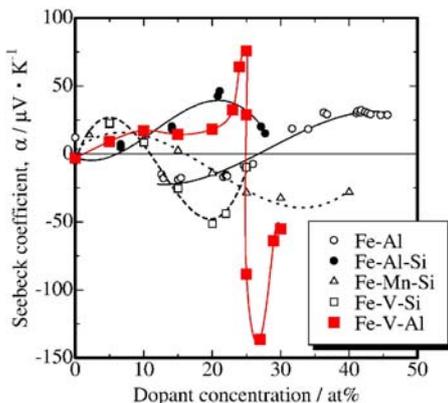

Fig. 4   Seebeck coefficients of iron-based alloys [4].

4. PROTOTYPE MODULE

About 40kg ingots of Fe_2VAl alloys were made by factory castings. Compositional deviations in an ingot were acceptable for practical use without any heat treatment [2]. This suggests mass production possibility with laboratory manufacturing quality. A good castability and poor machinability of this alloy will be reported separately.

The prototype thermoelectric modules were designed with a simple shape to avoid fabrication problems on welding. Copper wires were selected as the P-elements to release the

thermal stress. Fig. 5 shows an experimental module installed on a sodium-heated pipe surface. One module consisted of serially soldered 30 couples and two copper bar electrodes at the both terminals.
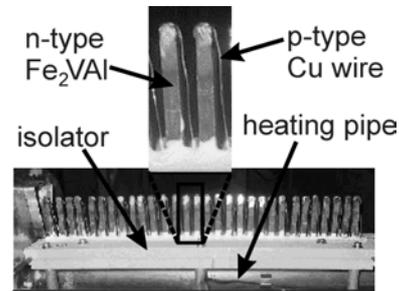

Fig. 5 Fe_2VAl module installed on a sodium heated pipe.

Figures 6 and 7 show the entire structure of the experimental apparatus. Liquid sodium as the heat source of the prototype modules was supplied at flow rate of about 8 l/min into the pipe (O.D. 34mm). 6 modules were serially installed on the pipe surface in the sodium flow direction, as shown in Fig.6. These modules were covered by an air channel, so that the other ends of the couples were cooled by counting forced air flow, in order to maintain temperature difference. The air flow rate and temperature were controlled by a blower, a flow control valve and a heater at the air channel inlet. The air channel covered 1/12 periphery of the pipe surface. The remaining pipe periphery and the outside of the air channel were thermally insulated. The module electrodes were connected by bold copper wires to externally installed variable resister, in order to measure open-circuit electromotive force (EMF) and electrical outputs.

The inlet flow rate of sodium was measured by an internally electromagnetic flow meter installed at the mother sodium loop. Inlet and outlet temperatures of the air channel were monitored by the installed thermocouples. The air flow rate was measured by a mass flow meter at the blower outlet. K-type thermocouples were installed inside the modules in order to measure the hot end temperature of the thermoelectric device. The temperature of cold junction could not be measured by thermocouples due to the strong air flow. All the measured data were stored in a computer through a data logger on line.

5. RESULTS AND DISCUSSIONS

EMF and output power with variable external resisters were measured for more than ten cases for combinations of inlet sodium temperature, sodium flow rate, air channel inlet flow rate and air inlet temperature. The steady-state data were taken after temperatures and flow rates stabilized.

Temperature and output power of electricity were expected to correspond to an axial temperature profile of a counter-flow heat exchanger, because the thermoelectric modules were serially installed between mutually counting sodium and air flows. However, no meaningful distribution was observed. This was because the heat resistances between the thermoelectric devices and the pipe surfaces unwillingly varied, although a boron nitride paste was coated on these surfaces. Values of electric resistance and temperature of all the modules were dispersed, even in the most successfully measured modules C and D, as shown in Fig. 8. A good electrical isolation and a good heat conductivity between the thermoelectric devices and the metallic pipe is a key issue to be solved.
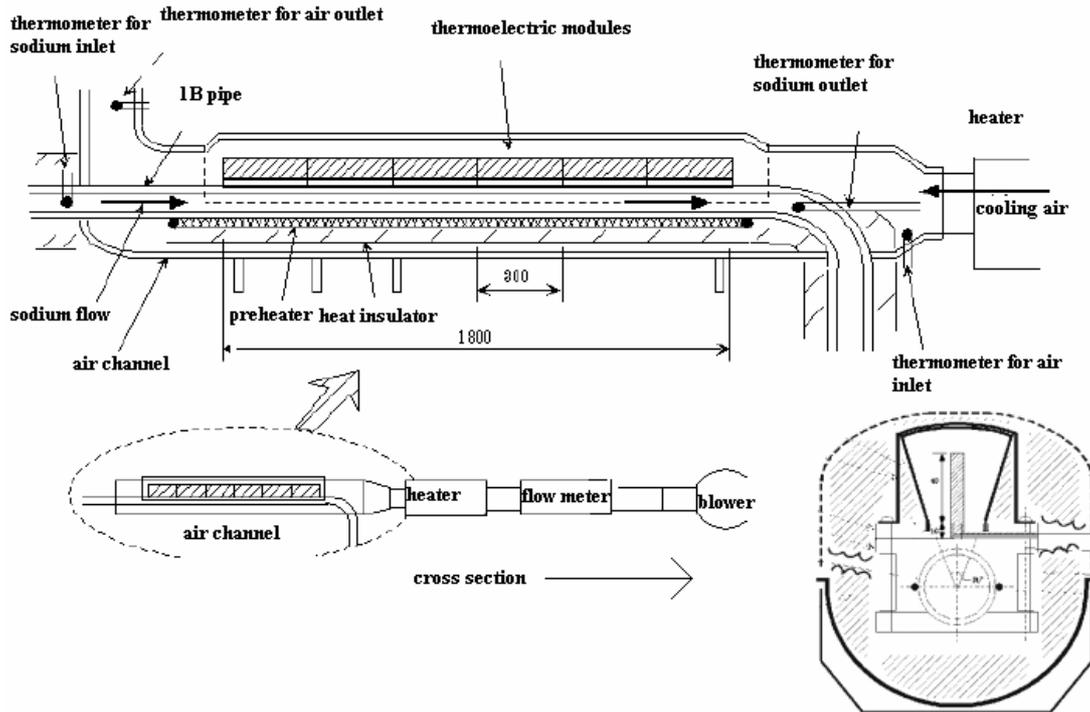
Fig. 6   Experimental apparatus for the thermoelectric power generation test, where the Fe$_2$VAl alloy, the liquid sodium and the cold air are used as the thermoelectric material, hot and cold heat sources, respectively.

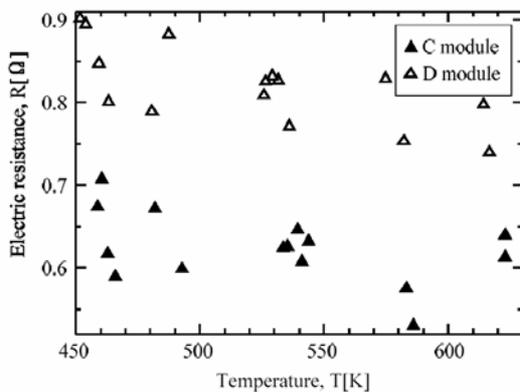**Fig. 7**   6 modules installed on the pipe.

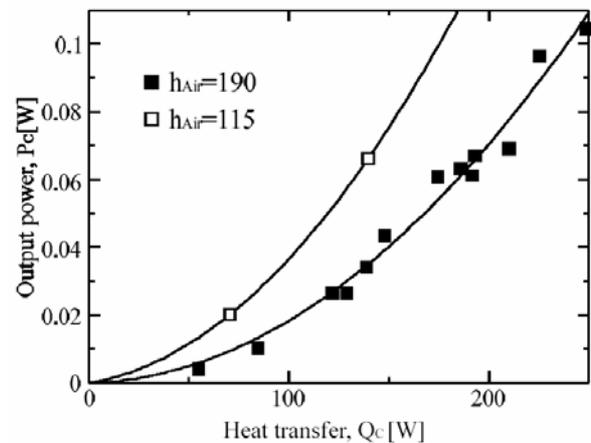**Fig. 8**   Temperature dependency of electric resistance.

Fig. 9   Relationship between transferred heat and output power from the thermoelectric module.

Relationships between electricity output and transferred heat is in accordance with theoretical prediction, as shown in Fig. 9. The pin-type thermoelectric module demonstrated significant enhancement of effective heat transfer coefficient, h, from pipe surface to air. Electricity generation was confirmed, for example, when sodium and air inlet temperatures were 673K and 313K, respectively, with observing EMF=2.6V and successfully putting an light bulb on.

Maximum electricity outputs from the thermoelectric modules were then derived. The current and voltage at the module terminal were measured by connecting with the external load resistance. The output power of electricity was evaluated as their product. Fig. 10 shows an example for this measurement, when sodium and air inlet temperatures are 673K and 313K, respectively. The maximum output was

calculated as the peak value of the function fitted from the measured values. Assuming circumference installation of the thermoelectric modules along the pipe surface, EMF and the maximum electricity output of 1.8 m length sodium heated pipe are expected as 37.8V and 7.52W, respectively. The efficiency, η, could be deduced as 0.49%, which is defined as,

$$\eta = P/Q \qquad (1)$$

where P and Q denote electricity output and transferred heat from the pipe to the air, respectively. Q was calculated from the heat balance based on the measured temperatures and flow rates.

There are still significant rooms for performance improvement. A combination of P and N type materials both from Fe_2VAl is expected to achieve about 2.5 times better performance than the so far presented modules, where Cu was used as N-type material. Another direction of improvement is high density installation using the thinner elements. Because the Fe_2VAl material has very low electric resistance as shown in Fig. 10, the higher internal resistance matches with the external electrical resistances of practically expected equipments or devices (much higher than 1Ω). This improvement can provide more efficient electricity source with higher voltage. The alternative solutions are the long thermoelectric modules such as a few km long [9] or multiplation of tubes [10-14].
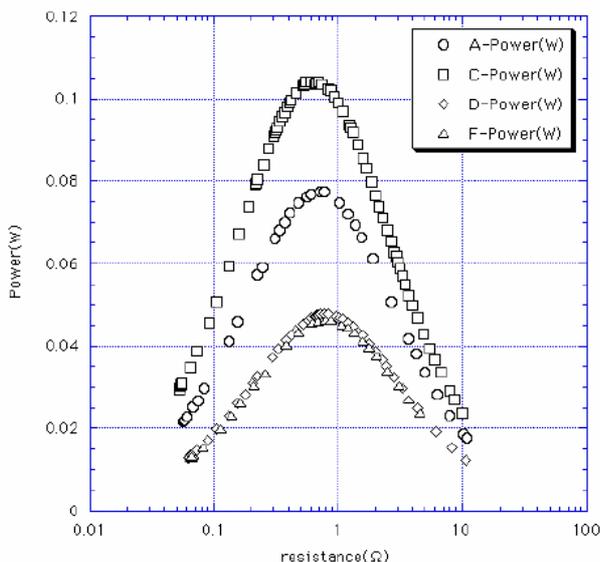

Fig. 10   Electricity output at the modules A, C, D and F when the external resistance was loaded.

6. SUMMARY

Electricity generation using our prototype Fe_2VAl thermoelectric modules has been demonstrated by installing on sodium heated pipe. Although facing problems including device design, device array density and heat transfer resistance between device and pipe surface, mass production of this ferric alloy thermoelectric devices with acceptable cost has been foreseen. The authors are going to improve module design in accordance with thermal characteristics of the target plant system, and to further study applicability of thermoelectric modules to large scale plant systems.

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