Development of a small-size cogeneration system using thermoelectric power generation

— Recovery system of high-temperature waste heat by new thermoelectric oxides —

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As energy and environment issues become serious, there is an urgent need to improve efficiency of industrial energy use as well as to alter lifestyles. To realize thermoelectric conversion technology that allows power generation from waste heat, we newly discovered thermoelectric oxides that possess high safety and durability at high temperatures. We then developed a prototype of a small-size generation system that functions at temperature range of 773~1173K in collaboration with a private company

Keywords **:** Thermoelectric power generation, oxides, module

1 Background of research

The production of fossil fuel, our mainstay of energy, is expected to reach its peak in a few years, and humankind is faced with challenges to find early solutions for stable supply of energy and environmental problems. Therefore, many research institutes are actively tackling R&D of new heat and energy conservation technologies. One of the solutions to these serious issues is efficient use of waste heat that is unused and disposed of into the atmosphere. Japan consumes and imports several hundred million kiloliters of primary energy in crude oil equivalent every year. However, about 70 % are disposed into the atmosphere as heat energy (Figure 1)[1]. Using this unused waste heat and improving energy efficiency are extremely important issues along with the development of alternative energy to oil.

Even though the total quantity of waste heat is massive, there is actually little energy disposed by a single heat engine. Waste heat energy is dispersed widely and thinly.

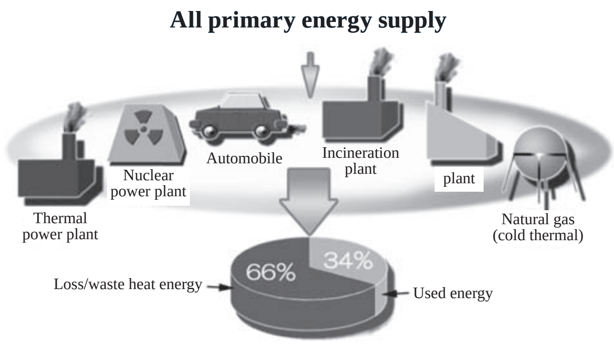

Fig. 1 Huge amount of waste heat.
In Japan, about 70 % of all primary energy supply is unused and disposed into the atmosphere as waste heat.

Thermoelectric power generation is drawing attention as the best candidate for technology that allows conversion of waste heat into electric power. This is because, since there is no scale effect in thermoelectric conversion, however small the heat energy, electric energy equal to the thermoelectric conversion efficiency spent on the heat energy can be obtained. For example, it is calculated that if 20 % of waste heat disposed from automobiles, plants, garbage incineration plants, and others could be converted to electricity, we can obtain 35 thousand GWh of power a year[2]. This figure is equivalent to power produced by a medium-size nuclear power plant. Also, thermoelectric generation system does not produce CO_2 or radioactive material, has no moving parts such as a turbine, and is a clean, maintenance-free, and long-lasting energy conversion system.

Thermoelectric power generation has been studied for quite a long time, and there were great expectations each time new materials were discovered followed by great disappointments. Therefore, users often regarded thermoelectrics with cold eyes: “Oh, thermoelectric again….” This was because even if a material had excellent properties, when putting it to civilian use, it often ran into major problems of safety, durability, cost, or of manufacturing technology. Also, in the United States, 10 years ago, civilian use of thermoelectric power did not arouse enthusiasm due to the attitude, “Gasoline is cheap so we don’t need thermoelectric power” , thus retarding its civilian use. However, expectation for thermoelectric power is rising again because of the shift in consciousness for energy and environment issues. It is rising from the demand from users rather than researchers of thermoelectric materials. One of the triggers of such movements was the discovery of excellent thermoelectric oxides by Japanese researchers including the Authors.

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2 Strategy for realization of thermoelectric power generation

As the energy issue is becoming serious, the expectation for effective use of waste heat is increasing. Waste heat includes a wide range of temperatures from cool waste heat of about 80 K to high temperatures of over 873 K, as well as various forms of heat in gas, fluid, and solid phases. The most convenient form of thermoelectric power generation that employs temperature difference is to use high-temperature waste heat. In general, high-temperature waste heat at a certain energy level can be recovered by heat converter using boilers. Therefore, in thermoelectric generation research, the main focus was on the development of material that functioned below 700 K. However, since the exergy[Term 1] decreases with decreasing temperature of waste heat, the thermoelectric generation system to recover heat will become large in scale. Diversification of energy conversion with such systems as medium- to-small-scale cogeneration system and boiler using biomass being in progress, effective use of waste heat was difficult from efficiency and cost aspects since practical amount of waste heat could not be obtained using the existing heat recovery system. In other words, in using waste heat for small systems, high temperature waste heat was preferred. However, this might decrease the efficiency of the thermal system to which the thermoelectric generation would be installed. The Authors, therefore, considered recovering energy through thermoelectric conversion at higher temperatures than required by the thermal system, and then operating the thermal system afterwards. Thinking from a different angle, we proposed a topping heat recovery system in which waste heat from thermoelectric generation was used in the "main house" thermal system (Figure 2). This system would improve energy efficiency of the entire system by optimizing energy use in thermoelectric generation and thermal system. In the development of the topping system, the Authors looked at water heaters using natural gas.

In home-use gas water heater, the combustion temperature of natural gas reaches 1473 K, while the hot water obtained is only about 323 K at the most. It is very wasteful when looking just at temperatures. Therefore, the Authors conducted joint research with Osaka Gas Co., Ltd. to create a cogeneration system where topping heat recovery and water heating can be done simultaneously through thermoelectric conversion in gas water heater. Moreover, we attempted generation of superheated steam as well as hot water in this cogeneration system.

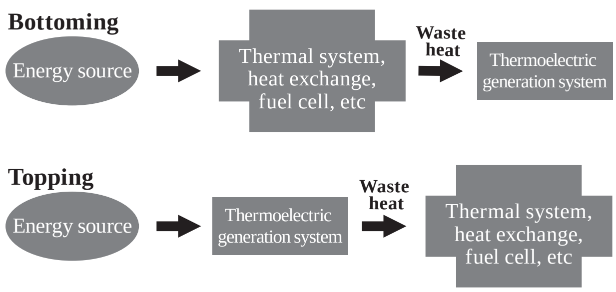

Fig. 2 Concept of bottoming and topping waste heat recovery.

3 Necessity of thermoelectric power generation in gas appliances

Gas appliances used in homes including water heater, cooking stove, and fan heater require electricity for ignition or control of the device. Users are faced with inconveniences such as requirement of a power outlet in addition to a gas valve, inability to heat the house or make hot water during power outage, and having to pay for electricity . If the gas appliance can generate its own power so self-sustained operation is possible without power supply from an outlet, the usability will increase dramatically. Also, household use of superheated steam is becoming common such as for cooking and sauna. With the development of small steam generator, electrical appliances are ahead, but considering energy efficiency and instantaneity of heating, steam can be generated in high volume and a short time if gas combustion is used. However, due to issues of heat deterioration in heat exchangers and incomplete combustion from a decrease of flame temperature (production of CO), small steam generators using natural gas combustion have not been widely used. In other words, the key to development of small steam generator using natural gas is the development of technologies that protect the surface of the heat converter and prevent the decrease of flame temperature. To solve the above problems, it is effective to coat with material with excellent heat durability such as oxides, just to a level that does not compromise heat exchange property. If thermoelectric conversion function can be added to this coating layer, both steam and electricity can be generated simultaneously by gas combustion, and a new cogeneration system that is extremely useful to the user can be developed.

4 Technological issues for gas-hermoelectric cogeneration system

Figure 3 shows the technological issues for constructing small cogeneration system using natural gas. We started our investigation from "downstream." To produce superheated steam and hot water by gas combustion, it is necessary to heat cool water by heat conversion. Therefore, we decided that the thermoelectric module should be in pipe form, and the temperature difference would be created by heating the exterior of the pipe and by running water inside the pipe to conduct simultaneous thermoelectric generation and heat exchange. In the main-stop type water heater for home used in this study, the heat converter was located 15~20 cm above the burner, and the space between was empty. To generate superheated steam, it was necessary to bring the pipe-type module close to the burner. The thermoelectric module was installed in the space between the heat converter and the burner. Technologies necessary to manufacture the pipe-type module included technologies for: manufacturing thermoelectric element; joining of p- and n-type elements at low resistance and high strength; junction of element and pipe with high heat transfer, sturdiness, and electric insulation property; heat collection to transfer gas combustion heat into the module; and low cost manufacturing. To synthesize these technologies, “upstream” technologies were necessary for materials that not only possess high thermoelectric performance but also have high durability in natural gas combustion and high temperatures both chemically and mechanically, as well as materials to stably join electrode to element in high temperatures. Moreover, the material must not contain toxic and/or rare elements due to safety and cost concerns. Basic researches such as physics to design such material and chemistry for nanotechnology were also necessary. In this paper, basic research undertaken by the Authors to develop a small gas cogeneration system using thermoelectric power generation, intermediate integration technology that combines the technologies, and the power generation performance of pipe-type module installed in a water heater will be explained.

5 Basic research: birth of new material

In 1998, the Authors started a search for safe, inexpensive thermoelectric oxides that were stable in high temperatures and air. The design concept of the material was a low-dimensional material or a layer structure that was drawing attention at that time[3]. One of the Authors, Funahashi, has been working on superconducting oxides with layer structure, and has synthesized Co layered oxide derived from that research. However, this was removed from the list of development material since no significant property was found. Fortunately, upon assessing the thermoelectric property, it was discovered it had good p-type property in high temperatures and air. The composition of this oxide is $Ca_3Co_4O_9$ (Co-349), and Figure 4 (a) shows the diagram of its crystal structure[4]. This oxide has a layer structure where CoO_2 layer composed of octahedron with 6 Os arranged around Co and Ca_2CoO_3 layer with rock salt (NaCl) structure are stacked alternatively. The dimensionless thermoelectric figure-of-merit (*ZT*) [Equation(1)] at 973 K for oxide monocrystal was about 1.1.

$$ZT = S^2T/\rho\kappa \quad \dots (1)$$

Here, *Z* is called thermoelectric figure-of-merit, and when it is multiplied by absolute temperature *T*, it is called dimensionless thermoelectric figure-of-merit. *S*, ρ and κ represent Seebeck coefficient, electrical resistivity, and thermal conductivity, respectively. Greater the *ZT*, better it is as thermoelectric material.

ZT for Co-349 is normally at the same level as the highest figures for compound semiconductors in bulk, but these values are measured in vacuum, and only Co-349 shows high thermoelectric performance in high temperatures and air (Figure 4(b)).

To construct an efficient thermoelectric generation system, development of n-type thermoelectric material was necessary. However, since it was extremely difficult to find excellent material as in the above case, the Authors developed high-efficiency search technology for thermoelectric materials using sol-gel synthesis to increase chances of discovery. Using this technology, $LaNiO_3$ (Ni-113), an n-type material stable in high temperatures and air, was discovered, although its ZT was about 0.01 in 973 K and its performance was still insufficient[5]. We also succeeded in manufacturing thermoelectric generation module that brought out the performance of these oxides to a maximum, but the conversion efficiency was still about 1.5~2 %.

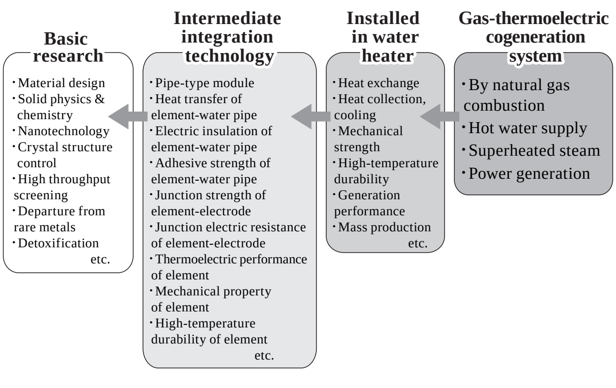

Fig. 3 Technologies needed for gas/thermoelectric cogeneration system.
We constructed “upstream” technology to respond to demand from “downstream”.

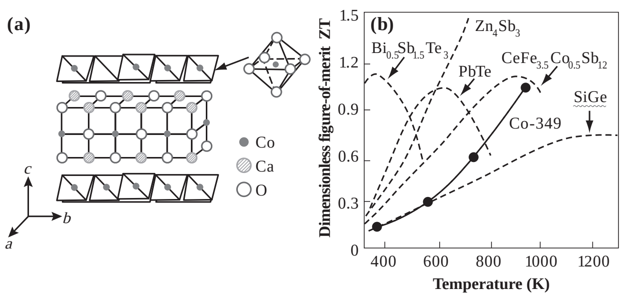

Fig. 4 Crystal structure of $Ca_3Co_4O_9$ (Co-349) (a) and temperature dependence of dimensionless figure-of-merit ZT (b).
Co-349 has a structure where electrically conductive CoO_2 layer and insulating Ca_2CoO_3 layer are stacked alternatively. The *ZT* of monocrystal of this oxide was 1.1 at 973 K. This is equivalent to conversion efficiency of over 10 %. The performances of metal materials with high *ZT* are also shown in the graph. Excluding Co-349, *ZT* of all other materials were measured in vacuum.

However, we believe that we will be able to construct a heat recovery system by utilizing high-temperature durability, which is the greatest advantage of oxide materials, and we are continuously working on the thermoelectric generation system for efficient use of high-temperature energy.

6 Intermediate integration technology

6.1 Joining technology

To obtain good thermoelectric module, it is necessary to form junctions with excellent heat durability, high mechanical strength, and low electric contact resistance between thermoelectric and electrode (generally metal) materials. However, for joining metal (Ag in this research) and oxides, problems of high contact resistance and detachment occur due to differences in Fermi energy and thermal expansion (Figure 5). More work is needed on joining materials to solve these problems.

6.1.1 Manufacture of element

The element was created by joining a pair of sintered Co-349 and Ni-113 onto alumina substrate of which the surface was metalized with Ag, and the electric contact resistance and the heat resistance were assessed[6]. The joining material was Ag paste containing powder of Co-349 or Ni-113 at 0~10 wt.%. Normally, it would seem better to use the same powder for both p- and n-type elements, but since application of Ag paste using screen printing required a "2-color printing" technology, in this research, we created an element using one of the composite Ag paste with either p- or n-type powder. The oxide composite Ag paste was applied on the surface of a sintered oxide compact, and placed on a metalized surface of alumina substrate. The Ag paste was solidified by heat treatment at 1123 K while applying uniaxial pressure 65kg/cm^2 vertical to the junction surface, to create a thermoelectric element composed of a pair of p- and n-type sintered compacts. The compositions of sintered compact were $Ca_{2.7}Bi_{0.3}Co_4O_9$ and $La_{0.9}Bi_{0.1}NiO_3$, where part of Ca and La of Co-349 and Ni-113 were replaced with Bi. The sintered compact was made by hot pressing the powders. The reasons for replacing Ca and La with Bi were: for p-type, S, ρ and κ [Equation(1)] were improved[7]; and for n-type, ρ only could be reduced while maintaining S constant[8].

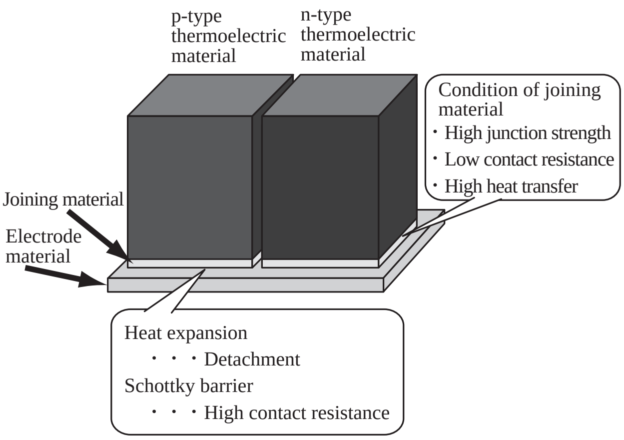

Fig. 5 Issues in joining technology.
Joining technology is mandatory for creating module with high durability and power generation performance. Particularly, developments of joining material and method to realize strong junction strength and low contact resistance are important for practical application.

6.1.2 Property assessment

Compositing Co-349 powder into Ag paste was found to be effective for reducing internal resistance (R_I) of the element[6]. Lowest R_I was obtained when Co-349 powder content was 6 wt.%. This reduction was caused by a decreased contact resistance between Ag paste and sintered oxide compact. Although the mechanism is not clear yet, it is thought to be due to a reduction of the effect of Schottky barrier and an improvement of contact by increasing wettability between the Ag paste and the surface of the sintered oxide compact.

The smoothness of the joining surface of sintered compact was important to strongly and closely connect the oxide material and the Ag electrode. The surface of sintered oxide was buffed before applying the Ag paste, and was joined to the alumina substrate using Ag paste composited with Co-349 powder at 6 wt.% and at the same condition as above. The smoothed surface of sintered oxide was effective in forming good junction.

Next we shall describe the durability of thermoelectric element against the heating and cooling cycle. The thermoelectric element was placed in an electric furnace, temperature raised to 1073 K over 3 h in air, kept in that state for 1 h, removed directly out of the furnace at high temperature, and cooled rapidly to room temperature. This procedure was repeated 5 times, and R_I before and after the heating/cooling cycles were measured and variations were calculated. In elements connected only with Ag paste, R_I increased significantly after the cycle at 600 K or less. On the other hand, in elements using oxide composite paste, R_I increase due to heating/cooling cycles became extremely small[6]. It was found that compositing of oxides into Ag paste was effective in improving durability against heating/cooling cycles. As a result of observation under scanning electron microscope (SEM), large cavities were found in the Ag paste in the element made with Ag paste only. On the other hand, in the thermoelectric element using Ag paste composited with 6 wt.% Co-349 powder, it was found that alumina substrate and sintered oxide were joined closely, although some fine holes were observed. The improvement of fine structure was the reason for controlling the R_I increase in heating/cooling cycles. The reasons for production of cavities are thought to be: contraction due to sintering of Ag, difference in heat expansion bet dispersal ween Ag and oxides, and exfoliation due to poor wettability.

6.2 Electric insulation technology

Thermoelectric module to be installed in gas cogeneration system must convert water used for cooling into superheated steam at the same time as generating power. To accomplish this, both high heat transfer and electric insulation must be maintained between the water pipe (stainless steel) and the thermoelectric element. Water pipe and thermoelectric element were insulated by insulating paste and ZrO_2 coating formed by thermal spraying on the surface of the water pipe. Here, the problem was breach in insulation due to of Ag from Ag paste that joined the element and electrode. The dispersed Ag pierced the ZrO_2 layer and reached the water pipe. This dispersal was prevented by adding other elements to the Ag paste. Since technology for preventing Ag dispersal by adding Pd particles was already used in industry, we investigated the effect of compositing Pd paste into Ag paste composited with Co-349 powder.

6.2.1 Sample manufacturing and assessment method

The assessment method for breach of electric insulation due to dispersal of Ag to insulating paste is shown in Figure 6(a). Ag paste composited with 0~10 wt.% Pd paste was applied and solidified on an alumina plate. Insulating paste and silver sheet were layered on top, and the paste was solidified. After heat treatment of a layered sample at 1023 K for 30 h, conductivity was assessed with a tester. Five samples with varied Pd contents were assessed, and the insulation property was calculated.

6.2.2 Electric insulation property

Figure 6(b) shows the insulation property at different conditions. Insulation increased with increased amount of Pd paste, and in case of 10 wt.%, all samples maintained electric insulation property even after heat treatment at 1023 K for 30 h. Upon observation of fine structure under SEM, it was found that Pd composite prevented Ag from dispersing into the insulation paste.

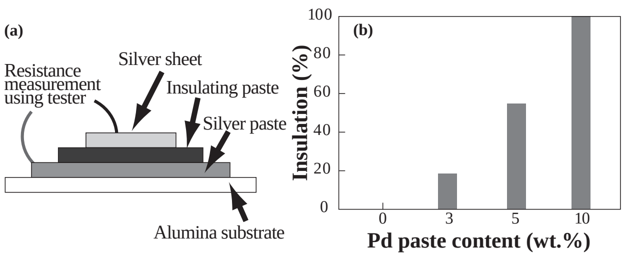

Fig. 6 Assessment method for electric insulation of multilayer structure (a) and dependency on Pd paste content for insulation of multilayer sample after heat treatment at 1023 K for 30 h (b).
Five samples were created with varying contents of Pd paste composites. The insulation property between Ag paste and Ag sheet mediated by insulating paste after heat treatment was assessed.

6.3 Structure and manufacture of pipe-type module

The structure of pipe-type thermoelectric module manufactured in this research is shown in Figure 7. The pipe-type module has a structure where 2 rows of elements composed of 27 pairs of elements sandwich the stainless steel water pipe. $Ca_{2.7}Bi_{0.3}Co_4O_9$ was used as sintered compact for p-type element, and $CaMn_{0.98}Mo_{0.02}O_3$ for n-type element. In this research, we installed this module in a small water heater. The combustion room of the water heater was small, and the module had to be kept compact, so the number of thermoelectric elements was limited. However, numerous elements were necessary to obtain high voltage by thermoelectric generation. To solve this dilemma, we manufactured the module using $CaMn_{0.98}Mo_{0.02}O_3$ which had higher S values than $La_{0.9}Bi_{0.1}NiO_3$. ZrO_2 coat of 60~70 μm was formed on the surface of the water pipe by thermal spraying to provide insulation between water pipe and thermoelectric element. Commercial insulating paste was applied over this to bond the element rows and the water pipe. The thickness of insulating paste after solidification was 150~300 μm. To create the element row, the thermoelectric element was formed into arch shape by grinding the sintered oxide, and using Ag paste composited with 6 wt.% Co-349 powder, it was joined at 1123 K under pressure of 50 kg/cm^2 on the arch section. The element row was joined to the water pipe whose surface was insulated, to create a pipe-type module with a length of 30 cm (54 elements in pairs)[9].

7 Construction of small gas-thermoelectric cogeneration system[10]

Two of the above modules were bundled and installed in the main-stop type water heater (Figure 8). By gas combustion of water heater, exterior of the module was heated, and hot water (about 313 K) was supplied to the water pipe at flow

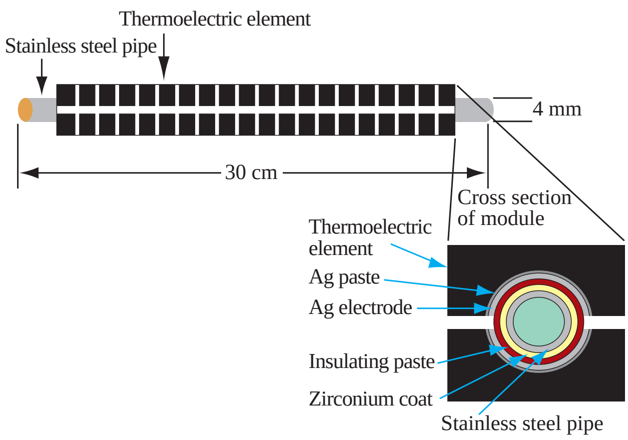

Fig. 7 Schematic diagram of Pipe-type module.
The total length of the pipe is 30 cm. The space between thermoelectric element and stainless steel water pipe is multilayer of Ag paste, Ag sheet, insulating paste, and ZrO_2. Although having thin structure is desirable to increase heat transfer, it is necessary to prevent breach of electric insulation by dispersal of Ag from the Ag paste.

volume of 16 cm^3/min from the water heater to produce temperature difference in thermoelectric element to generate power.

During gas combustion, temperature around the thermoelectric module reached approximately 1473 K. When the water heater was burned at full force, open voltage (V_o) and maximum output (P_{max}) reached 1.3~1.5 V and 0.28 W, respectively. After continuous generation for 1 h under heating condition where the V_o of the module reached 0.6 V or 1.0 V, combustion was stopped, allowed to cool to room temperature, and generation property was measured repeatedly. As a result, there was no deterioration of generation property by repeated heating and cooling for 1 h. Also, superheated steam of about 473 K was obtained from the end of the module water pipe. By installing pipe-type thermoelectric module that allowed direct heat conversion, an ordinary water heater became a multifunctional cogeneration system (Figure 9). Moreover, exhaust gas temperature was higher and CO partial pressure was reduced when gas combustion was done with pipe-type thermoelectric module installed in the water heater, compared to when water pipe without thermoelectric elements was installed. This was probably because by covering the water pipe with oxide thermoelectric element, incomplete combustion was prevented by halting the decrease in gas combustion temperature that occurred when water pipe with low surface temperature was installed.

In general, waste heat recovery is considered to be the use of exhaust gas after completion of heat engine cycle (bottoming). Although natural gas burns at about 1473 K, the temperature of hot water that comes out of the water heater is 323 K at the most. This means that the heat energy produced by combustion is not efficiently used. Therefore, heat use with high total efficiency becomes possible if unused high-temperature heat energy (potential waste heat) can be used for thermoelectric generation while the water is heated using waste energy from thermoelectric conversion (topping). Heat recovery by topping is possible due to oxide material that can be used in high temperatures, and this is a new method for using thermoelectric generation.

8 Future prospects

The development of oxide thermoelectric generation system for efficient use of high-temperature waste heat was explained. It was necessary to start from thermoelectric material to construct this system. We were fortunate in this aspect, and were able to find Co layered oxide with excellent conversion efficiency and durability. This substance not only enabled practical application of thermoelectric generation in high temperatures and air, but also was highly acclaimed in the academic society as a demonstrative example of high thermoelectric performance by nano-block integration with different functions. However, for construction of a generation system, various technologies and know-hows for joining, electric insulation, and heat transfer described in this paper must be integrated and mass production technology must be developed along with the development of new high-performance materials. Also, reduction in use or alternatives to rare metals must be sought for Co for p-type material, La of n-type, and Pd used in paste to widely diffuse thermoelectric generation in the future.

The market for thermoelectric generation is being developed at this moment. For practical application, we must create value for the users in thermoelectric generation using waste heat. To do so, it is necessary to give added function to the module in addition to thermoelectric conversion, or provide

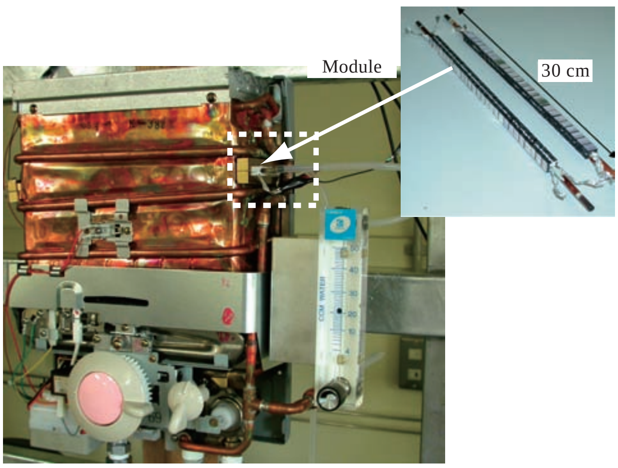

Fig. 8 Pipe-type module and main-stop water heater equipped with module.
By gas combustion in main-stop water heater equipped with pipe-type module, the water heater produced hot water and the module produced superheated steam and electricity simultaneously.

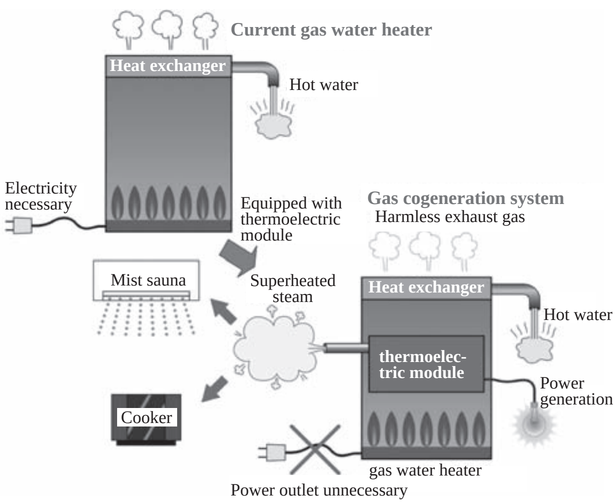

Fig. 9 Home water heater becomes cogeneration system.
By installing thermoelectric module and conducting topping heat recovery, it was possible to produce electricity and superheated steam in addition to hot water. Also, the CO content in exhaust gas was reduced.

added value to the system to which the thermoelectric module is installed. In oxide thermoelectric module, since the temperature on the low side can be set high, waste heat can be used efficiently by topping heat recovery. Using this concept, we expect improvement of total heat efficiency of heat conversion and energy conversion devices such as boilers and fuel cells. Also, high power density, an advantage of thermoelectric conversion, is excellent for application to mobile objects such as automobiles and power sources for cell phones. The Co-349/Ni-113 thermoelectric element can produce about 2 MW/m^3 power density.

By installing the thermoelectric system developed by technological integration described here to heat engine so waste heat can be used effectively, new value can be provided to users who were waiting for this, and great contribution can be made to solve the energy issues.

Some of the results described here were presented in other journals[10].

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Terminology

Term 1. Exergy: effective energy that can be converted to other energy.

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Discussion with reviewers

1 Greatest difficulty in this R&D

Question (Naoto Kobayashi)

I see that you were engaged in a series of significant R&D with a strategic vision toward the development of small-size gas cogeneration system, with a basic research including search and development of materials, an intermediate integration technology that combined with know-how, and a power generation by pipe-type module installed in a water heater. What was the most difficult point? And how did you overcome that?

Answer (Ryoji Funabashi)

The most difficult point technologically was material development. Discovery of a new substance cannot be planned beforehand, and one must be blessed with luck to succeed. We were able to discover Co layered oxide for p-type material, but we are still struggling for n-type material. I feel that the research for module realization, as described in the paper, went smoother than expected due to various collaborations and information gathering. Rather than technological matters, the real difficulty in realizing thermoelectric generation was to create value for thermoelectric conversion technology. We did not suddenly come up with small gas cogeneration system. We looked at the merit and demerits and listened to opinions of users in several fields, and finally arrived at the idea of topping, with specific application to a small gas cogeneration system.

2 Future research topics

Question (Naoto Kobayashi)

As described in the paper, I think a major contribution can be made to energy conservation if the waste heat recovery becomes possible through an efficient thermoelectric generation system at high temperatures. I think this R&D effort is a milestone, but what is the greatest issue that must be overcome in the future?

Answer (Ryoji Funahashi)

They are mass production and improved reliability of the module. Of course, search for new materials is necessary because of the current low conversion efficiency, but I think the immediate task is to build a market for thermoelectric conversion that can be realized at the current performance.

3 Prospect for n-type thermoelectric material development

Question (Naoto Kobayashi)

I understood that in this R&D, compared to the high-performance p-type thermoelectric oxide material, the performance of n-type thermoelectric oxide material is not so good, and this is a major issue in the future research. Please explain the strategy and prospect for the future development of n-type thermoelectric material.

Answer (Ryoji Funahashi)

We have two strategies for material development. One is development of material to be used in the thermoelectric conversion market that will be developed in the near future. This is not development of totally unknown material, but we plan to improve the performance of Ni and Mn oxides that were described here through element addition and process technologies. Moreover, current performances of both p- and n-types are insufficient to expand the thermoelectric conversion market. It is necessary to create a totally new substance using crystal structure control by nanotechnology or high-efficiency search by combinatorial technology.

4 Efficacy of heat recovery system from high temperatures

Question (Naoto Kobayashi)

For the development of small cogeneration system, I think it was highly significant that you conducted verification of the system. Also, this small-size verified system is most likely effective for general heat energy use such as electric conversion at high temperatures, heat use in medium temperature, and use of high-temperature steam. In actual practical application, other than water heater, how do you the think heat recovery from high temperature by topping can be used?

Answer (Ryoji Funahashi)

Basically, I think it can be installed in any system that involves heat exchange with water. For example, I think it can be used for boiler fin, which is much larger than home water heater. The important point is not to depart from the main objective of the original system. Also, I think solid oxide fuel cell (SOFC) is a candidate. The operating temperature of SOFC is decreasing every year with technological progress. Therefore, the temperature margin is formed on the high temperature side. I think this margin can be used effectively for thermoelectric conversion.

5 Effect of the result of this research on thermoelectric generation market

Question (Naoto Kobayashi)

Concerning the effect of the result of this research on thermoelectric generation market, what level of innovation do you think will be introduced to the market compared to current technologies and products?

Answer (Ryoji Funahashi)

There is no market for thermoelectric generation yet. Therefore, as explained in the paper, we must assess the value of thermoelectric generation from a different angle to build the thermoelectric market. We are planning to establish a venture company to do this.