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Computational Simulation of Thermoelectric Generators in Marine Power Plants

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In thermoelectric generation applications, the two indispensable conditions are the hot source and the cold source to provide the temperature difference for the generator. Thus, the waste heat recovery from various high temperature gas or steam turbines on ships by thermoelectric generators (TEG) is promising because the ocean naturally plays a role as an infinitely large cold source. Among other options, a pilot study of the applicability of thermoelectric generation to the boiler section of marine power plants is presented through CFD (Computational Fluid Dynamics) modeling. It is found that more than 600 W power may be produced from the waste heat of a 300 kW boiler but without an obvious loss of the system safety. [doi:10.2320/matertrans.E-M2011813]

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1. Introduction

The large-scale application of TEG in power plants such as gas turbines, steam turbines, engines, as well as incinerators, has recently attracted a lot of attention. If the huge energy dissipation of exhaust heat therein can be recovered in part into electricity by the noiseless, pollution-free, reliable and easy-to-use TEG, obvious benefits will be obtained. In terms of both fuel saving and CO_2 reduction, some general technical and economizer parameters have been shown in the previous studies.[1,2)]

In thermoelectric generation applications, the two indispensable conditions are the hot source and the cold source to provide the temperature difference for the generator. In other words, the larger the temperature difference between the hot and the cold, the better power performance of the TEG. In this sense, the waste heat recovery from various high temperature gas or steam turbines on ships by TEG is very promising because the ocean naturally plays a role as an infinitely large and almost zero cost cold source. In these marine power plants, in principle it is easier to build and keep the precious temperature difference for TEG. Additionally the isolation from the commercial electric grid during the cruising potentially makes a greater demand for TEG as a complementary DC power supply on ships.

Nowadays, for instance, steam turbines are extensively used for many large ships, in which the boilers burn the fuel to provide high temperature and high pressure steam as the working media for the turbine. Initially the thermal energy radiated from the fuel heats the water in the cooling wall of the furnace and converts the water into steam. Then the high temperature flue gas from the furnace passes through a series of heat exchanges such as superheaters and reheaters to eventually become low temperature exhaust. In such a system, the first possibility for TEG application is to utilize the big temperature difference between the combustor and its cooling water, and the second can be based on the relatively smaller temperature difference between the final exhaust and the steam.

In spite of a preliminary study regarding the application of TEG in on-ship incinerators in which potential benefits were conceptually estimated,[3)] more technical examinations on the realistic combination of TEG and marine power plants have not been reported. Since many advanced thermoelectric materials and cascaded devices are becoming available for high temperature range, a pilot study of the applicability of thermoelectric generation to the boiler section of marine steam turbines (among a great many other options), in particular the first application possibility mentioned above, is presented in this paper through the CFD modeling approach.

2. Modeling

When TEG are integrated into an established energy system, two issues should be of equal importance in the system design: the first is how much power TEG can generate, and the second is that how much the original system as well as its safety and performance are changed. In Ref. 4), the effect of TEG on the vehicle system is assessed experimentally, and it is found that the loss caused by the generator due to additional pumping loads is significant to the coolant system. For stove applications,[5)] the hot surface temperature could decrease with the increasing number of modules because the temperature depends on the stove's internal heat transfer and combustion characteristics. As the heat transfer through the surface increases in the vicinity of TEG, the local temperature decreases. Similarly experiments in Ref. 6) show that the hot reservoir temperature is considerably lowered as a result of the increased heat sink across the TEG. The phenomenon is also observed that when the TEG are attached to the combustor, the self-sustaining butane combustion (which has been achieved without TEG) is no longer possible.[7)]

For analyzing the overall performance change of energy systems brought by TEG, a simple way might be using 1-D analytical models. However, the marine power plants are essentially more complicated than all the above systems.[4–7)] Thus, a more careful examination about the influences of TEG on the systems is mandatory. In marine energy systems, usually the specific status of fluid heat sources (e.g., fuel or

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air delivery, fluid flow and heat transfer to a bank of tubes, and local steam or water flows, etc) is required to be analyzed together with the detailed electric parameters of using TEG. Obviously the key analysis technology would include the advanced CFD modeling, TEG modeling, and particularly their multidimensional integration. To furnish such an integration tool, a multidimensional TEG model has been implemented in the popular CFD package FLUENT, where the nonlinear thermoelectric equations can be numerically solved.[8] In this way, various CFD submodels of fluid flow and combustion in FLUENT can be immediately connected to the TEG model as if they are within a continuum domain.[9]

This paper extends the proposed modeling approach to the TEG application in the boiler section of marine steam turbines. For simplicity, the two dimensional (2D) model of a 300 kW swirl-stabilized burner in FLUENT tutorial[10] is utilized as the boiler paradigm. The burner has an octagonal body cross-section with a cylindrical exhaust duct, where the diameters are about 1 m and 0.3 m, respectively. The total height of the burner is close to 3 m. Furnace walls are water cooled, so that TEG can be installed therein to obtain the temperature difference to produce power. The natural gas fuel mainly consists of ch4 (96.5%), and various fuel compositions enter the burner through the same inlet with a single radial velocity. The combustion air enters the burner through another inlet with an axial velocity and a swirl velocity, which can improve the combustion efficiency. Other details of boundary condition and model setting of the boiler can be found in Ref. 10).

The TEG for such a boiler application must have high temperature characteristics to fit the environment. In this study, the high temperature module in Ref. 11) is selected as the TEG prototype, of which the geometry dimensions for p-type and n-type thermoelements, ceramic plate, and silver electrode are followed in the modeling. Since some parameters like temperature dependent material properties and contact resistances have not been available yet, without loss of generality, the bismuth telluride is assumed as the thermoelectric material. In previous studies,[8,9] the thermoelectric model in CFD has been demonstrated to be able to include the temperature dependences of all material properties. For simplicity, the values of bismuth telluride estimated at room temperature are used in this work, i.e., p- and n-type thermal conductivity are 2 W/mK, electrical conductivity 100000 S/m, and Seebeck coefficient $\pm 200\,\mu V/K$, respectively. The electrode material properties are also adjusted to fit the reported electrical resistance of the module.

The TEG module is multi-dimensionally modeled in FLUENT, and the temperature and electric potential profiles are shown in Fig. 1 and Fig. 2, respectively. We note that the potential in Fig. 2 is not the Seebeck potential but the potential distribution resulting from the current flowing in the device, i.e., Ohm's voltage drop, where the left top electrode (red color) is stipulated as the ground. In the both figures, the hot and cold boundary temperatures are stipulated as 1273 K and room temperature. The electrical boundary condition usually refers to the load, and here a resistance of 0.06 Ω is applied to approximately match the internal resistance.

In terms of the boiler size, the prototype module is prolonged to be approximately 1 meter and connected to the boiler model in the simulation, as is shown in Fig. 3. The TEG model is then able to run in conjunction with the fluidic thermal regime as well as the possible heat exchanger geometry of the marine boiler. The interface part is augmented in Fig. 4, where the non-uniform temperature profile of the boiler wall serves as the hot source for TEG. On the top side of the TEG, the coolant temperature is specified as the thermal boundary of the cold side.

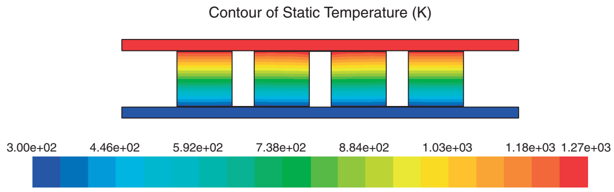

Fig. 1 Temperature profile of FLUENT simulation for the TEG module.[11]

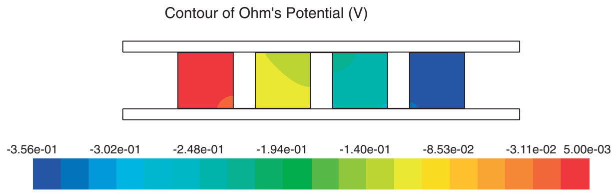

Fig. 2 Potential profile of FLUENT simulation for the TEG module.[11]

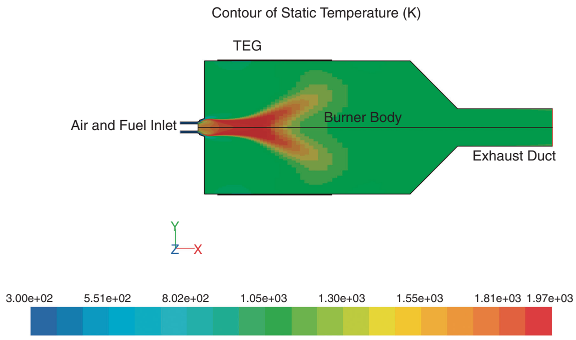

Fig. 3 Temperature profile of the co-simulation for the non-premix combustion TEG system.

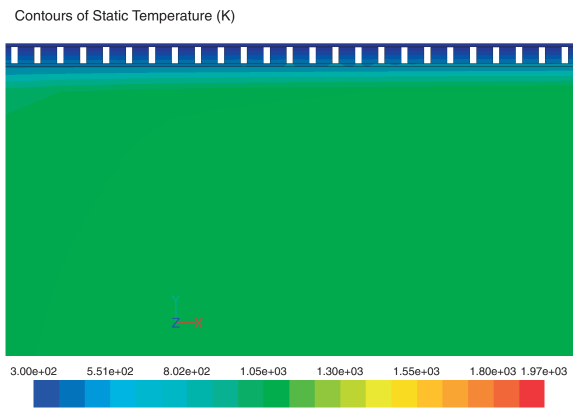

Fig. 4 Close-up of the interface part between the TEG and the boiler.

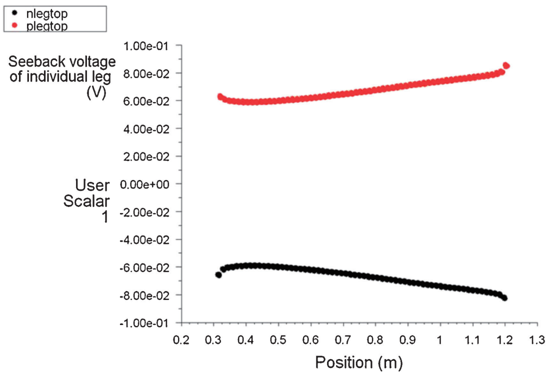

Fig. 5 Seebeck voltage generated by each TEG leg in terms of position.

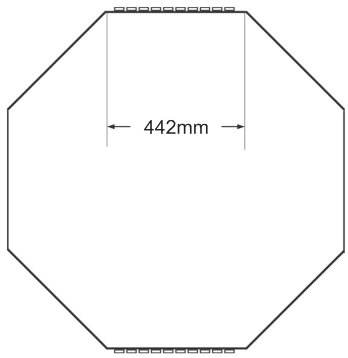

Fig. 6 Cross-section view of the boiler body and the TEG placement instance.

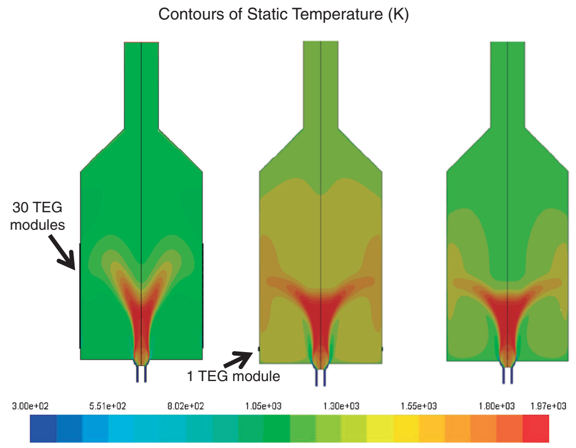

Fig. 7 Temperature profiles when the boiler wall is without any TEG (right), equipped with one TEG module (middle), and with 30 TEG modules (left).

3. Results and Discussion

Computational models of the two major components, i.e., the boiler combustor for steam generation and the TEG, are implemented respectively and simulated together as a whole in FLUENT. Figure 5 shows the Seebeck voltage generated by each p-type and n-type leg in terms of the horizontal position. Under the non-uniform temperature distribution of the boiler wall, it is obvious that, even though composed of the same thermoelectric materials, the generation abilities of the thermoelements are different at different positions. Therefore, further optimization of the TEG placement to seek the overall maximum performance of the system power would be critical.

In this 2D calculation, the “1 meter” TEG can produce an open voltage at a level of ~9 V with an internal resistance of ~2.5 Ω, hence the maximum power output is ~8.1 W provided that the load is close to 2.5 Ω. The octagonal cross-section of the boiler body is shown in Fig. 6, in which the width of every side is enough to accommodate at least 10 pieces of such TEG. Based on the design simulated where only the top and bottom surfaces have TEG installed (Fig. 6), the full three dimensional performance may be estimated as that more than 600 W electricity is extracted from the waste heat radiated by the 300 kW boiler. We note again that the calculation results are based on bismuth telluride properties measured at low temperature.

As is mentioned before, the other critical issue is that how the TEG integration affects the boiler performance and reliability. Figure 7 shows the comparison of temperature profiles when the boiler wall is without any TEG, equipped with one TEG module in Ref. 11), and with 30 such modules (“1 meter” TEG), respectively. Clearly the high temperature parts without TEG and with one TEG module are almost same. It can also be seen that with the “1 meter” TEG, the high temperature flame is more focused around the center line. In this connection, the new design including TEG does not reduce the safety of the boiler because the high temperature region is further to the wall, and thus more unlikely to destroy it.

4. Conclusions

In the design of modern power plants, normally even a tiny increase of efficiency is regarded as huge technical progress. The very difficult efficiency improvement of the marine power plants may however be attempted by the thermoelectric generation. With the help of the proposed CFD modeling approach, it is demonstrated in this paper that the optimal design of both TEG installation and the power plant itself can be carried out by a single simulator FLUENT. For the presented case, further optimization may include the effects of various convection and radiation conditions as well as the swirl velocity within the boiler on the TEG power performance.

The rest modeling challenge still lies in the interface part. Due to the size difference of the TEG and the power plants, grids of different scale should be used for the two modeling objectives, respectively. To deal with the flux accuracy, additional efforts on boundary condition transfer and iteration control will likely be needed, but with the knowledge already accumulated on other typical multi-scale issues, we are optimistic to solve it with a reasonable cost in the near future.

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