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Combined hardware/software method for measuring heat source reserves applied to waste heat recovery of industrial furnaces

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Abstract– In order to reduce CO_2 emissions from industrial heating processes, evaluation of the amount of heat that can be extracted from the heat source when constructing waste heat power generation systems is important; however, at present there is no established method to quantitatively measure the heat source characteristics and the amount of heat that can be extracted from a heat source. A new heat flow modulation method using semiconductor thermoelectric conversion devices generates a modulated heat flow wave that propagates as if it were a radio wave propagating in a waveguide. By processing and analyzing the reflected heat flow signal characteristics (frequency and phase) of this modulated heat flow wave using a combined hardware/software method, the amount of heat that can be extracted from the heat source (extractable heat quantity) can be calculated.

1. Introduction

In Japan, the Paris Agreement to limit temperature rise to within 1.5°C has set Japan's CO_2 reduction targets of "60% reduction from 2019 levels by 2035" and "carbon neutrality by 2050". The total amount of energy used in industrial manufacturing processes that use heating is extremely large. This needs to be reduced but the "lack of precise measurements of the thermal characteristics" makes energy-saving measures difficult. In the construction of waste heat power generation systems to reduce CO_2 emissions from industrial heating processes, it is important to evaluate the amount of heat that can be extracted from the heat source, but at present, no method has been established to quantitatively measure the heat source characteristics and the amount of heat that can be extracted from it. In this study, we developed a device for measuring the thermal impedance characteristics and an algorithm to calculate the amount of heat that can be harvested by quantitatively expressing how much energy can be transferred from a high-temperature heat source to a low-temperature region.

2. Extractable Heat Capacity Measurement Device using a Thermal Modem Analyzer

Fig. 1 shows the components of the measurement device used to obtain the extractable heat capacity from a heat source and the thermal circuit model. In the extractable heat capacity measurement device, heat is drawn from the heat source of an industrial furnace through a heat exchanger and directed to a cooling source through a metal heat transfer path, a sensing device, and thermal bonding components.

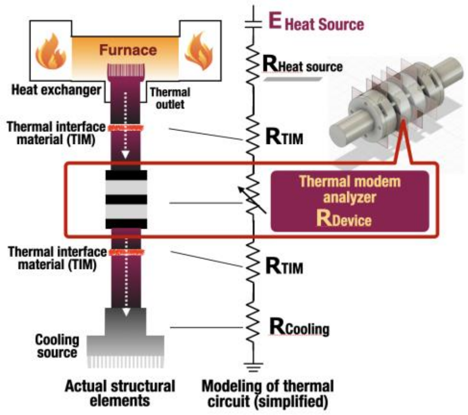

Figure 1 Schematic illustration for extractable heat capacity measurement unit, including a thermal modem analyzer

The measurement device incorporates a thermoelectric device capable of electronic cooling/heating and has a heat flow modulation function to measure the thermal impedance characteristics of the heat transfer path. The heat flow modulation function in the measurement device (variable and modulated heat flow through the thermoelectric device) is replaced by a variable resistor in the equivalent electrical circuit model, and the power supply voltage characteristics associated with the heat source can be estimated by analyzing this circuit model. This can be used to estimate the power supply voltage characteristics which correspond to the heat source. Specifically, if the heat exchanger characteristics, heat transfer path, thermal bonding agent and cooling characteristics are known, and only the measurement device part changes, the power supply voltage characteristics can be estimated and calculated by parametric analysis of the circuit. We consider that the capacitive component of the supply voltage represents the amount of

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heat that can be supplied in the thermal circuit, that is, it is possible to estimate the amount of heat available in the heat source.

Figure 2 shows an example of the operation of the extractable heat capacity measurement unit equipped with a thermal modem analyzer and the test heat source. The thermal modem analyzer consists of three thermoelectric modules sandwiched between cylindrical aluminum parts.

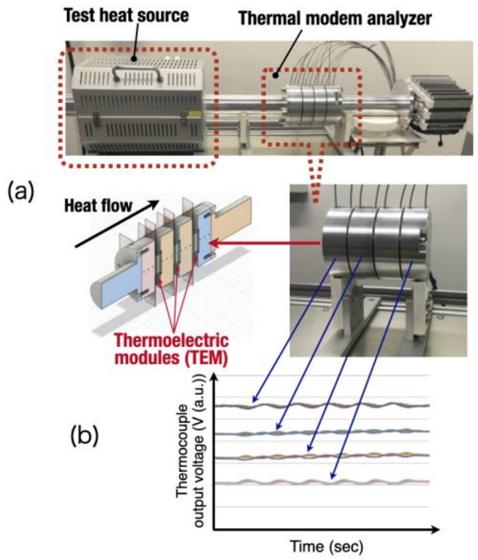

Figure 2 (a) Test heat source for the extractable heat capacity measurement unit with a thermal modem analyzer. (b) Voltage waveforms observed.

The thermoelectric modules are installed between cylindrical aluminum parts and are used to observe the heat flow changes in the measurement device, the state of heat flow modulation by the thermoelectric module, and the superposition of modulated heat flow waves and reflected waves. (Fig. 2-(a))

Figure 2-(b) shows an example of the voltage waveforms in a heat flow modulation and sensing device observed after a certain time when sine wave heat flow modulation is applied to the thermoelectric module using a four-quadrant bipolar power supply. The in-phase sine wave applied to the three thermoelectric modules is electrically converted into heat absorption and heat generation in the thermoelectric module, resulting in heat flow modulation, which propagates both towards the heat source and the heat sink, changing the phase and magnitude of the sine wave. In addition, a portion of the propagating sine wave is observed to have a return component due to reflection.

To analyze the waveforms observed by the thermal modem analyzer, an electrical circuit analogous to the thermal circuit was used. A diagram of the heat transfer model of the extractable heat capacity measurement unit including the thermal modem analyzer and the equivalent electrical circuit model corresponding to the thermal circuit.

The heat flowing in from the heat source is connected to the thermal modem analyzer by aluminum connecting rods, and there is thermal resistance between the heat source and the thermal modem analyzer; the thermal resistance of the thermoelectric elements is higher than that of the metal parts, and the thermal modem analyzer is guided to the cooling section by an aluminum connecting rod. In the equivalent electrical circuit, the thermal resistance, heat flow, and temperature difference in the thermal circuit are replaced by electrical resistance, current, and voltage,

The TEMs mounted in the thermal modem analyzer are driven by a four-quadrant bipolar power supply during operation, so in the equivalent electrical circuit, the circuit elements are arranged to be AC power supplies that generate sine waves. The TEMs are arranged as shown in the equivalent electrical circuit, taking account of the fact that the TEMs are in series along the heat flow path. The three AC power supplies representing the three TEM components are all set to operate in phase with the sine wave that is actually applied during operation of the thermal modem analyzer.

The waveforms observed at each monitoring location originate from in-phase sine waves emitted from the TEMs, but the phase and amplitude of the sine waves eventually change due to the spacing of the TEMs, the thermal conductivity of the metal parts between the TEMs and the shape of the parts, as well as the decoupling effect of heat flow waves propagating and reflecting through the metal parts inside the measurement unit.

To analyze the waveforms observed by the thermal modem analyzer, an electrical circuit analogous to the thermal circuit was used. The equivalent electrical circuit and an environment was constructed to reproduce the operation of the thermal modem analyzer. In the calculated waveforms shown in Fig. 4-(b), the heat flow from the heat source starts to gradually increase from the initial state, and as time passes, the heat flows from the heat source to the cooling source through the TEMs with heat flow modulation. At present, we have not yet reached a situation where we can accurately calculate the observed waveforms because we have not yet constructed an equivalent electrical circuit model that fully reproduces the heat output from the actual test heat source. On the other hand, the waveforms at each monitoring location in the vicinity of the TEMs are thought to reproduce similar trends in the phase variation of the sinusoidal modulation caused by the TEMs, but closer agreement in the behavior of the amplitudes is needed to set up thermal circuit elements and equivalent electrical circuit parameters.

3. Summary

A heat capacity measurement unit was developed for estimating the extractable heat capacity of industrial heat sources, and an instrument for software analysis of the heat transfer path characteristics was developed.