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Comparison of temperature difference measurement technologies used in vehicular heat exchangers

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ABSTRACT

In the vehicle industry, thermal balance experiments have been extensively conducted on engines to determine energy distribution from fuel to engine power. The temperature differences between the hot and cold sides of the vehicular heat exchanger are the key parameters used to calculate the heat quantity. However, in certain gas–liquid heat exchangers, the temperature difference of the liquid side is significantly smaller than that of the gas side. Measurement errors can be increased if an inappropriate measurement method is adopted. To minimize the measurement errors, a new temperature difference measurement method based on compound thermocouple (CTC) is introduced in this study. This method is calibrated using a thermostatic oil tank. An empirical formula is used to evaluate cases in which the basic temperature ranges from 20 °C to 120 °C, and a temperature difference of less than 20 °C is gained. The proposed method has been implemented in a practical thermal balance experiment using a vehicle radiator, and the results are compared with that of pairing calibrated resistance temperature detectors (RTDs). The results show that the CTC-based method can reduce the averaged thermal balance error in vehicular cooling systems to less than 4%.

1. Introduction

Thermal balance experimentation is one of the most important means of studying energy distribution in engines [1]. The energy produced by the combustion process in chamber is mainly transferred into engine power, cooling heat, and exhaust dissipation [2]. To evaluate the heat dissipation from the cooling system, the temperature difference between the inlet and outlet must be measured. Temperature sensors are normally used for such a purpose. However, in certain vehicular heat exchangers, such as lubricating oil coolers and water radiators, the temperature difference in the liquid side is considerably smaller than that in the airside, and thus the measurement accuracy can easily influence the tested difference value, thereby affecting the thermal balance error in the engine [3]. Furthermore, as the power density in engine development increases, the mass flow rate $(\dot{m})_{coolant}$ of liquid coolant in the heat exchangers increases as well; the error in temperature differences (ΔT) is thus amplified when calculating heat dissipation ($\dot{Q}$) in coolant using $\dot{Q} = (c_p)_{coolant}\dot{m}\Delta T$, where $(c_p)_{coolant}$ is the specific heat capacity of the liquid coolant. Meanwhile, the error of thermal balance (Err) is increased further due to the deviation of heat dissipations between cold and hot sides. Therefore, ensuring precise temperature difference measurement is a key factor in engine thermal equilibrium experiments.

Several techniques have recently been introduced to improve the accuracy of temperature difference measurement. The most common method is often based on a temperature difference transmitter. Alternatively, pairing resistance temperature detectors (RTDs) by means of calibration is an effective method to minimize testing errors [4].

Temperature difference transmitters employ hardware to process the temperature signals between two measuring points. Such transmitters consist of the gate circuit, holding circuit, and A/D circuit. The accuracy of this approach mainly depends on the temperature signals at the input terminal, and it therefore has a considerably high requirement for the temperature sensors. Furthermore, this method is based on the principle of signal transmission, which implies a certain amount of transmission error. Typically, when the accuracy of the temperature difference transmitter is approximately 1% F.S, the measurement error ranges from 0.5 °C to 2 °C. However, in vehicular heat exchangers, given that relatively small temperature difference and high mass flow rates

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Nomenclature

A	heat transfer area (m^2)	ΔT	temperature difference (°C)
C^*	heat capacity rate ratio (–)	T_n	temperature at the measuring plane (°C)
C_{min}	minimum heat capacity rate (–)	U	Total heat transfer coefficient ($W \cdot m^{-2}$ °C^{-1})
C_{max}	Maximum heat capacity rate (–)	V_i	molecular specific volume ($mol \cdot m^{-3}$)
c_p	specific heat capacity ($kJ \cdot kg^{-1}$ °C^{-1})	V_{air}	volume flow rate of air ($m^3 \cdot s^{-1}$)
c_{pL}	specific molecular heat capacity ($kJ \cdot mol^{-1}$ °C)	ε	effectiveness (–)
E	thermoelectric potential (mV)	δ	relative measuring error (%)
ΔE	thermoelectric potential in ΔT (mV)	μ	Thomson coefficient (μV °C^{-1})
Err	error of thermal balance (%)	υ_H	specific volume ($m^3 \cdot kg^{-1}$)
H_{air}	absolute humidity of air (g)	ρ	density ($kg \cdot m^{-3}$)
$\dot{m}$	mass flow rate ($kg \cdot s^{-1}$)	ϕ	relative humidity (–)
p	pressure (Pa)		
p_g	saturated water vapor pressure (kPa)	*Abbreviations*	
p_0	standard atmospheric pressure (kPa)	A/D	analog to digital transfer
p_a	local atmospheric pressure (kPa)	A, B	thermocouple material
$\dot{Q}$	heat transfer rate (kW)	CTC	compound thermocouple
S	Seebeck coefficient (μV °C^{-1})	RTD	resistance temperature detector
T	temperature (°C)	TC	thermocouple
T_{base}	basic temperature (°C)	NTU	number of heat transfer unit

in the liquid side, the actual temperature difference between the import and export is less than 10 °C. Therefore, the measurement inaccuracy significantly affects the calculation of thermal balance, which could exceed 5% error.

The aim of pairing RTD sensors is to minimize the measurement error by identifying two temperature sensors with the same positive or negative error deviations. In this method, all temperature sensors are calibrated in the same batch. Particular sensors with the same shift direction and the closet calibration values are selected to form the pairing sensors for measuring the import and export temperatures, respectively, of the same heat exchanger. Thus, the error resulting from opposite trends or inconsistency among the sensors can be minimized. However, the process of calibration and selection are too complicated to be widely used in industry.

In order to ensure the measurement accuracy and to simplify the operation, a new method based on compound thermocouple (CTC) is introduced in this paper. The principle of this method is described in Section 2, and the empirical formulas used in practical applications are derived in Section 3. In addition, an experimental validation is presented by comparing with the means of pairing RTD sensors in wind tunnel experiments. The present results show that the new method based on CTC is more convenient and accurate in measuring the temperature differences in vehicular heat exchangers.

2. Principle of the measurement method

The structure of the compound thermocouple configuration is shown in Fig. 1. X_1 and X_2 represent two thermocouples composed of $A_1 + B_1$ and $A_2 + B_2$, respectively, in which A and B denote different thermocouple materials, A_1 and A_2 are made of the same material A, whereas B_1 and B_2 are made of the same material B. The test terminals of B_1 and B_2 are joined together (E_B represents the corresponding thermoelectric potential) to form the CTC circuit. In application, the sensors of X_1 and X_2 are placed at the required test points ($T_1 + \Delta T$ and T_1 represent the tested temperatures, $\Delta T > 0$). A_1 and A_2 are the measuring cables of the CTC (E_{A1} and E_{A2} represent their respective thermoelectric potentials). Note that the three terminals E_{A1}, E_{A2}, and E_B are kept at the same environmental temperature T_0 [5].

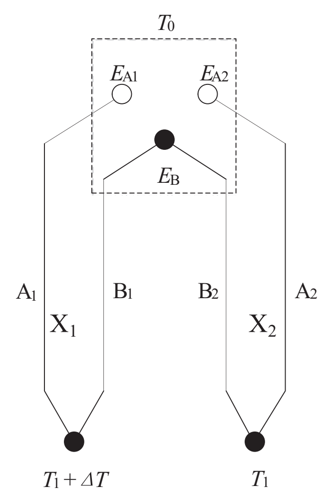

Fig. 1. Sketch of the compound thermocouple configuration.

The thermoelectric potentials of the reference points in the compound thermal couple are given by:

$$E_{A_1A_2} = E_{A_1B} - E_{A_2B}, \tag{1}$$

in which

$$E_{A_1B} = \int_{T_0}^{T_1+\Delta T} S_{AB}(T)dT \tag{2}$$

and

$$E_{A_2B} = \int_{T_0}^{T_1} S_{AB}(T)dT, \tag{3}$$

where S_{AB}(T) denotes the Seebeck coefficient [6] generally determined by the thermocouple materials A and B, and can be calculated using the following formula:

$$S_{AB}(T) = \int_0^T \frac{\mu_A(t) \cdot \mu_B(t)}{t} dt, \tag{4}$$

where μ is the Thomson coefficient obtained by independent experiments.