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Clarification of relationship between temperature distribution in the stack and energy conversion in a two-phase fluid thermoacoustic engine

二相流体熱音響エンジンのスタック内部温度分布とエネルギー変換の関係性の明確化

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1. Introduction

The temperature required to drive the thermoacoustic engine is about 200°C. However, most of industrial waste heat temperature is below 150°C.[1] To effectively utilize this low-temperature waste heat, the critical temperature to start the oscillation of thermoacoustic engine should be lowered. In techniques to lower the critical temperature, the two-phase fluid thermoacoustic engines are included.[2]

In the conventional study, the temperature gradient in a stack is almost approximated by the constant slope of a straight line connecting the temperatures at both ends, and the effect of lowering the critical temperature is discussed. However, the thermoacoustic phenomenon occurs due to the volume change by thermal expansion or compression while the fluid moves along the temperature gradient.[3] Thus, it is required to consider the effect of lowering the critical temperature by considering the temperature distribution in the stack.

Kuroki *ea al*. have focused attention on the temperature gradient in a stack with water added, how the temperature gradient in the stack with water added affects the energy generation is theoretically investigated.[4] In the paper of Kuroki *et al*., the energy generation in the stack was calculated based on Rott's equation which did not consider the two-phase condition although the two-phase fluid thermoacoustic engine was used for the experiment. Therefore, the consideration for two-phase fluid is insufficient. Hence, in this report, the energy generation in the stack is calculated based on Raspet's equation considering the two-phase condition, and the consideration of the effect of lowering the critical temperature in the two-phase fluid thermoacoustic engine is deepened.

2. Experiments

The diagrammatic view of the thermoacoustic engine used for the experiment is shown in Fig. 1. The travelling-wave type thermoacoustic engine

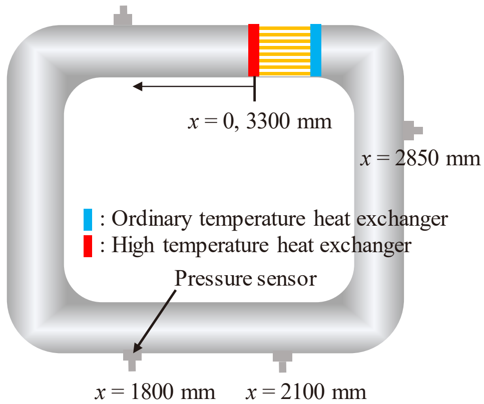

Fig. 1　Schematic of experimental system.

with a 3300 mm total length and a 42 mm inner diameter is used. The stack made of honeycomb ceramics with the flow path radius of 0.35 mm and the length of 50 mm is employed. By installing an ordinary temperature heat exchanger at one end and a high temperature heat exchanger at another end of the stack, the temperature difference is given between both ends. The coordinates are set based on the position of the high temperature heat exchanger. The experiment was carried out under dry and wet conditions. A sufficiently dried stack was used in the dry condition. 7.49 g of water was added to the stack and 100% relative humidity in the system is achieved in the wet condition. Inserting K-type thermocouples into the flow path in the stack, the temperatures in the stack are measured at points with an interval of 10 mm as well as at both ends. The sound pressure in the tube is measured with crystal-type pressure sensors. The pressure sensor was installed at the positions of x = 350, 1800, 2100, 2850 mm.

3. Results

It is confirmed that the frequency of self-excited vibration is the fundamental resonance frequency of 103 Hz in both conditions. The temperature distribution in the stack at self-excited vibration in both conditions is shown in Fig. 2. The critical temperature under dry and wet conditions were 149°C and 82°C, respectively. The critical temperature using a stack with water added decreased by 67°C compared to the dry stack. The temperature rise was biased toward the heating end side in both conditions.

4. Discussion

The effect of lowering the critical temperature under the wet condition is considered focusing on the work source. The work source means the work in a unit volume per a unit time. The work source concerning dry conditions W_D is expressed by the following equation.[3]

$$W_{\mathrm{D}} = \frac{1}{2}\mathrm{Re}[p\tilde{u}\beta_{\mathrm{E}}]\frac{dT}{dx} \quad (1)$$

where p is the sound pressure, u is the particle velocity, β_E is the effective thermal expansion coefficient, and T is the temperature. Kuroki *et al* calculated the work source under the wet condition using Eq. (1).[4, 5] However, the wet condition is not taken into consideration in Eq. (1), so in this report, the work source is calculated under the condition. Here, the work source concerning wet conditions W_W is derived as the following equation.

$$W_{\mathrm{W}} = \frac{1}{2}\mathrm{Re}\left[p\tilde{u}\beta_{\mathrm{E}}\left\{1+\frac{lp_{\mathrm{W}}}{R_0 T p_\alpha}\right\}\right]\frac{dT}{dx} \quad (2)$$

where l is latent heat, R_0 is gas constant, p_w is the saturated vapor pressure and p_α is the partial pressure of air. Compared with Eq. (1), Eq. (2) has an additional term of $1+lp_W/R_oTp_\alpha$. The term 1 indicates the work source by air, and the term lp_W/R_oTp_α indicates the work source by the phase change of water and water vapor. The work source distribution in the stack in both conditions at the steady state is shown in Fig. 3. The temperature at the heating end under the wet condition is lower than that under the dry condition. However, the work source was largely reversed near the heating end in the wet condition and the dry condition. The local increase of the work source on the heating end side under the wet condition is due to the effect of the term lp_W/R_oTp_α. In particular, it was confirmed that the saturated vapor pressure p_W had a large effect.

5. Conclusions

The critical temperature to start the oscillation of thermoacoustic engine was compared using a dry stack and a stack with water added. As a result, the critical temperature using a stack with water added decreased by 67°C compared to the dry stack. The saturated water vapor pressure on the heating end side has a great influence on the critical temperature drops in the wet condition.

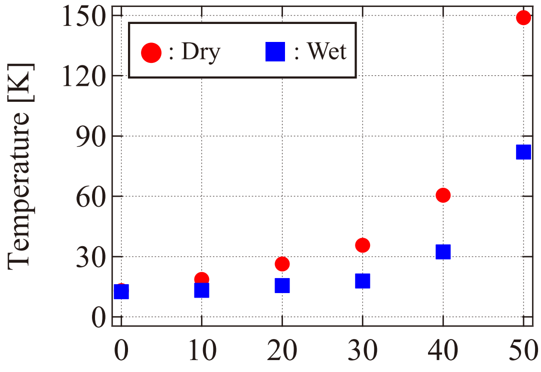

Fig. 2 Temperature distribution in the stack at self-excited vibration.

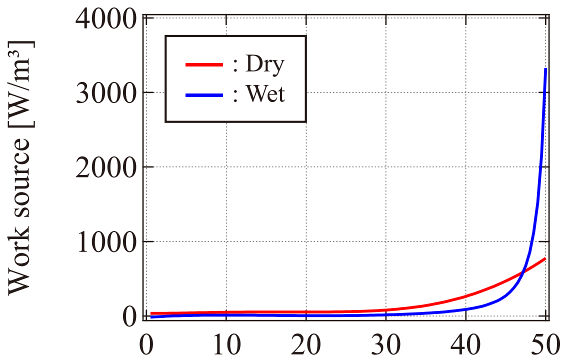

Fig. 3 Work source distribution in the stack at the steady state.

Acknowledgment
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