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Research paper

Experimental verification of heat transport by acoustic wave

Shinya Hasegawa [a, *], Keisuke Kondo [b], Yasuo Oshinoya [a]

[a] *Department of Prime Mover Engineering, Tokai University, Kanagawa 259-1292, Japan*
[b] *Course of Mechanical Engineering, Tokai University, Kanagawa 259-1292, Japan*

HIGHLIGHTS

- We confirmed the heat transport by acoustic wave experimentally.
- We propose a parameter G dominating the effective thermal conductivity κ_D.
- G is shown to obey a universal curve specified by dimensionless parameter r_0/δ.
- κ_D is proportional to the square of the displacement amplitude.
- Maximum κ_D is 1600-fold higher than that without oscillation.

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ABSTRACT

Heat transfer between two liquid reservoirs maintained at different temperatures and connected to each other by a capillary bundle is known to be markedly enhanced by oscillatory flow in the bundle. In this study, heat transport by an acoustic wave was experimentally investigated. On the basis of the results, a parameter is proposed that expresses the quantity of heat transported by an acoustic wave in order to characterize this phenomenon. This parameter is depended on the normalized channel radius of the regenerator divided by the thermal penetration depth. Furthermore, the effective thermal conductivity is confirmed to increase proportionally to the square of the displacement amplitude. In regard to this point, even when a compressible gas was used as the working fluid, the result was the same as when a liquid was used.

1. Introduction

Improving the radiation performance of heat-generating devices is a challenge in various technologies, such as electric devices and automotive devices. Devices with high heat transport performance are required for heat removal from heating-generating elements. Heat pipes that utilize phase transitions are one means by which heat can be transported, and the saturation temperature of the fluid provides the operating range of the heat pipe. Generally, it is difficult to control the amount of heat transported from the outside of the heat pipe.

The "dream pipe" is the name of a heat transport device proposed by Kurzweg and Zhao [1]. It has a simple internal construction and high heat transport performance. The dream pipe consists of hot and cold liquid reservoirs connected by a capillary bundle. If the liquid columns in the bundle oscillate with a displacement amplitude smaller than the bundle length, the heat flow rate from the hot to cold reservoir increases remarkably depending on the amplitude and frequency of the oscillatory liquid flow. According to Kurzweg and Zhao's experimental results, the largest effective thermal conductivity obtained was 27-fold that of copper. The concept behind the dream pipe goes back to theoretical studies by Chatwin [2] and Watson [3]. They reported that an oscillating flow in a tube induces extraordinary mass diffusion. Jaeger and Kurzweg [4] demonstrated this phenomenon experimentally. Watson [3] investigated this extraordinary mass diffusion due to the oscillatory motion of the fluid in the pipe, and obtained an analytic solution for the effective mass diffusivity. Nishio et al. [5] derived an equation by using Watson's analytic solution and substituting mass diffusivity for the thermal diffusivity. These theoretical results agree well with the experimental results for the dream pipe. After the report by Kurzweg and Zhao [1], Kurzweg [6] conducted a numerical analysis showing that the oscillatory flow in the tube facilitated heat transport. Rocha and Bejan [7] theoretically studied

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* Corresponding author. Tel.: +81 0463 581211; fax: +81 0463 598293.
E-mail address: s.hasegawa@tokai-u.jp (S. Hasegawa).

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the optimal tube size, and Nishio et al. [8] reported the optimal conditions for the dream pipe, including liquid properties, tube diameter, and oscillation conditions, and proposed the phase-shifted oscillation-controlled heat transport tube. The dream pipe can be operated at any temperature so long as the working fluid does not undergo a phase transition. Another advantage of the dream pipe is that its heat transport performance can be controlled by the displacement amplitude or driving frequency. A disadvantage, however, is that it requires an external power supply. Furthermore, to obtain a high effective thermal conductivity several tens of times that of copper, vibration must be applied with displacement amplitude of approximately 10 cm and frequency of approximately 8 Hz [1]. This frequency is high when applying a large displacement amplitude to oscillate a liquid having a large mass.

In previous research on the dream pipe, a liquid was used as the working fluid. However, the range of operating temperatures is limited to those where the working fluid remains in the liquid phase. Furthermore, the driving frequency is limited to the order of several hertz, as in the experiments of Kurzweg and Zhao [1] (2–8 Hz). Accordingly, we propose using a gas working fluid in order to overcome these limitations. If a gas is used as the working fluid, driving frequencies of several hundred hertz with displacement amplitudes of several ten centimeters can be achieved. Moreover, if gas is used as the working fluid, the possibility arises of generating an acoustic wave in the dream pipe by thermoacoustic self-oscillation [9,10] without the use of an external power supply.

A thermoacoustic engine is an acoustical device that utilizes the spontaneous oscillation of a gas column subjected to a steep temperature gradient. Thermoacoustic energy conversion between the axial heat flow and acoustic power results from thermal interactions between gas parcels and solid walls of flow channels. In addition, by forcing the gas inside the narrow ducts to oscillate, the temperature gradient in the narrow ducts can be used for thermoacoustic refrigeration [11,12]. When a gas is used as the working fluid, heat transport by oscillatory flow can be categorized into two types depending on the direction of the heat flow [13]. The first type is heat flow from low to high temperature (the heat pump effect), which is used to generate low temperatures in thermoacoustic refrigerators and pulse tube refrigerators [14]. A thermoacoustic refrigerator built by Luo et al. achieved a refrigerating temperature of −64.4 °C [12]. The second type is heat flow from high to low temperature as in simple heat conduction (the thermal diffusion effect), which is what occurs in the dream pipe. The dream pipe, which uses gas, is thought to have several advantages as described above. However, verification experiments have not been performed on the thermal diffusion effects of gas oscillation. Thus, we chose air as the working fluid and experimentally investigated whether the heat transport performance for air is comparable to that for liquids. We also experimentally investigated operating conditions under which large heat transport can be obtained.

2. Verification of heat transport by acoustic wave

2.1. Experimental apparatus and method

Fig. 1 shows a schematic of the experimental apparatus used to investigate heat transport by an acoustic wave. The apparatus consists of four units: two woofer speakers (FW108N, Fostex) facing each other, two stainless tubes with inner diameter of 4.0×10^{-2} m, two copper heat exchangers, and a capillary bundle. The air in the apparatus is under atmospheric pressure. The capillary bundle that we used was a cylindrical ceramic honeycomb catalyst support with numerous square channels (Fig. 2), hereinafter referred to as the regenerator. We prepared three regenerators that had the same axial length ($L = 3.0 \times 10^{-2}$ m) but different flow channel diameters of $2r_0 = 0.67$, 1.18, and 2.11 mm and porosities of $\varepsilon = 0.833$, 0.863, and 0.69, respectively. A heat exchanger was set at each end of the regenerator. The heat exchangers consisted of pairs of copper plates aligned in parallel with a 2-mm gap between them. Each plate was 1 mm thick and 30 mm in axial length (Fig. 3). The hot heat exchanger temperature was kept at $T_H = 403$ K by fitting a sheath heater to the exchanger and adjusting the applied voltage using a DC power supply (PWM800M, KIKUSUI). The ambient heat exchanger temperature T_C was maintained at room temperature $T_C = 303$ K by circulating cooling water around the exchanger. The total length of the experimental apparatus was 2.69 m, with a 1.3 m-long stainless tube connecting a woofer speaker to a heat exchanger on each side of the regenerator. The unit formed by the two heat exchangers and the regenerator was placed in the center of the apparatus.

First, in the absence of an acoustic wave, we measured the input electric power (Q_0) required to establish a temperature difference ΔT $(=T_H - T_C) = 100$ K across the regenerator from one end to the other. Next, the woofer speakers on both sides were driven at the same frequency by using a two-channel function generator (DG4062, RIGOL) and a power amplifier (P1000S, YAMAHA). Here, the oscillatory pressure inside each stainless tube was measured using three pressure transducers (PD104K-30K, JTEKT). The mean displacement amplitude and acoustic impedance at the regenerator

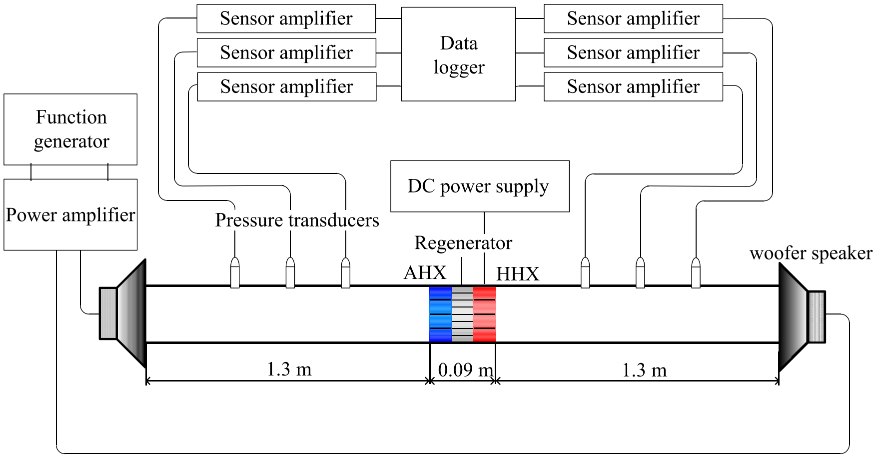

Fig. 1. Schematic of experimental apparatus (AHX: ambient heat exchanger; HHX: hot heat exchanger). The two heat exchangers and the regenerator each had an axial length of 0.03 m, for a total of 0.09 m.

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