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Research Paper

# Thermal diffusion effect of a regenerator with complex flow channels

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## HIGHLIGHTS

- Thermal diffusion is studied in uniform and complex flow regenerator channels.
- Heat flow due to the thermal diffusion effect was isolated by thermoacoustic theory.
- A maximum heat flow of 10.0 W was observed at acoustic power input of 0.1 W.
- Both regenerator types followed a universal curve for dimensionless parameter $r/\delta$.
- Complex channels can be treated as uniform to estimate the thermal diffusion effect.

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## ABSTRACT

The thermal diffusion effect caused by an oscillatory flow has a large effect on the thermal efficiency of a thermoacoustic engine. This study measures and compares the thermal diffusion effect caused by an oscillatory flow in regenerators with uniform and complex flow channels. In an experiment, a maximum heat flow originating from the thermal diffusion effect of 10.0 W is observed during the input of 0.1 W acoustic power in a regenerator with uniform flow channels at a temperature difference in the regenerator $\Delta T = 100$ K. $\mathrm{Im}[g_D]$, which is a parameter that governs the thermal diffusion effect, is found from the heat flow obtained in the experiment. Consequently, thermoacoustic theory for both regenerators with uniform and complex flow channels shows a good agreement. This result indicates that the regenerator with the random flow channels is equivalent to that with the uniform flow channels. Predicting the thermal diffusion effect according to the oscillatory flow is also possible.

## 1. Introduction

Thermoacoustic engines are basically built from pipes and a porous material with a temperature gradient (hereinafter referred to as the "regenerator"). Accordingly, these engines do not require moving parts, which have so far been indispensable in conventional thermal engines. In 1979, Ceperley theoretically posited that acoustic power is amplified when a traveling wave propagates in a regenerator with a temperature gradient [1]. In 1998, Yazaki et al. realized Ceperley's proposal as a loop-type thermoacoustic engine [2], which implies that regenerators are an important component in thermoacoustic engines. Thermoacoustic engine regenerators can be broadly classified into two categories. The first category comprises regenerators with uniform flow channels, including honeycomb ceramics with multiple square pores (Fig. 1), parallel plates, and pin arrays of bundled circular tubes. A regenerator with a flow channel radius smaller than the thermal penetration depth is necessary for a thermoacoustic engine to achieve high thermal efficiency [2]. However, manufacturing a regenerator with uniform flow channels, such as honeycomb ceramics, that produces small pores is difficult using the current technology. The second category comprises regenerators with complex flow channels. The equivalent to micro-pores can be comparatively and easily realized in regenerators with complex flow channels through stacking layers [3]. Fig. 2 shows stacks of metal meshes. Reticulated vitreous carbon (RVC) [4], steel wool, and the like are used in regenerators with complex flow channels. In practice, stacks of metal meshes are used in regenerators for thermoacoustic engines with a high thermal efficiency [5,6]. The quantification of acoustic propagation and heat flow properties with respect to complex flow channels is an important task in the practical application of the thermoacoustic phenomenon. The acoustic propagation and heat flow properties within a regenerator with uniform flow channels can be understood according to the thermoacoustic wave equation by Rott [7].

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## Nomenclature

*List of symbols*

| | |
|---|---|
| $A$ | cross-sectional area |
| $A_{\mathrm{Gas}}$ | cross-sectional areas of the gas |
| $A_{\mathrm{Solid}}$ | cross-sectional areas of the regenerator |
| $c$ | adiabatic sound speed |
| $c_p$ | isobaric specific heat |
| $D$ | flow path diameter of uniform channel |
| $D_h$ | hydraulic diameter of stacked screen mesh |
| $d$ | wire diameter of the wire mesh |
| $f$ | frequency |
| $L$ | axial length of regenerators |
| $P$ | complex pressure amplitude |
| $Q$ | heat flow |
| $Q_{\mathrm{prog}}$ | heat flow caused by the traveling wave component |
| $Q_{\mathrm{stand}}$ | heat flow caused by the standing wave component |
| $Q_D$ | heat flow caused by the thermal diffusion effect |
| $Q_\kappa$ | heat flow caused by the simple heat conduction |
| $Q_{\mathrm{Loss}}$ | heat leak |
| $r$ | flow channel radius |
| $r_{\mathrm{eff}}$ | equivalent flow channel radius |
| $s$ | complex entropy amplitude |
| $S_{g-s}$ | gas–solid contact surface area |
| $T$ | complex temperature amplitude of the gas |
| $T_C$ | ambient heat exchanger temperature |
| $T_H$ | hot heat exchanger temperature |
| $\Delta T$ | temperature difference between both ends of the regenerator |
| $T_m$ | mean density in a duct |
| $u$ | complex velocity amplitude |
| $\lvert\langle u\rangle_R\rvert$ | cross-sectional mean of the oscillatory velocity in the regenerator |
| $V_{\mathrm{gas}}$ | gas volume |
| $V_{\mathrm{holder}}$ | volume of the regenerator holder |
| $V_{\mathrm{solid}}$ | volume of the wires of the stacked-screen regenerator |
| $W$ | acoustic power |
| $Z$ | specific acoustic impedance |
| $\alpha$ | thermal diffusion coefficient |
| $\delta$ | thermal penetration depth |
| $\varepsilon$ | porosity |
| $\kappa$ | thermal conductivity |
| $\nu$ | viscosity coefficient |
| $\rho_m$ | mean density in a duct |
| $\sigma$ | Prandtl number |
| $\varphi$ | phase difference between pressure and velocity |
| $\chi_\alpha$, $\chi_\nu$ | thermoacoustic functions |
| $\omega$ | angular frequency |

Swift [8] and Tominaga [9] develop the thermoacoustic wave equation into thermoacoustic theory. Thermoacoustic theory is first applied to parallel plates and circular tubes. Arnott et al. developed thermoacoustic theory for equilateral triangular and rectangular flow channel geometries [10]. However, determining an accurate flow channel geometry for a regenerator with complex flow channels is difficult. For this reason, understanding the acoustic propagation and heat flow properties using thermoacoustic theory is usually difficult. It is necessary to empirically determine an equivalent flow channel diameter to understand the properties of a regenerator with complex flow channels. Wilen considered the RVC and found a thermoacoustic function for the acoustic propagation properties of a regenerator by measuring the amplitude from a speaker and the RVC internal and external pressures [11]. His comparisons with the analytical solutions for various flow channel geometries showed that this result was equivalent to that of a parallel plate. Furthermore, Ueda measured the pressure and velocity of a small-amplitude acoustic field around the inlet and outlet of a stacked-screen regenerator. He also compared the transfer matrix with that of a circular tube assembly [3], and found the following empirical formula for the equivalent flow channel radius $r_{\mathrm{eff}}$ of a stacked-screen regenerator:

$$r_{\mathrm{eff}} = \frac{\sqrt{D_h d}}{2}. \tag{1}$$

Here, $D_h$ is the hydraulic diameter, and $d$ is the wire mesh diameter. Half the hydraulic diameter ($D_h/2$) is employed as the characteristic radius $r$ of a stacked-screen regenerator. $D_h$ is defined as four times the ratio of the gas volume ($V_{\mathrm{gas}}$) to the gas–solid contact surface area ($S_{g-s}$) in a stacked-screen regenerator, that is,

$$D_h = \frac{4V_{\mathrm{gas}}}{S_{g-s}}. \tag{2}$$

$V_{\mathrm{gas}}$ is estimated from the equation $V_{\mathrm{gas}} = V_{\mathrm{holder}} - V_{\mathrm{solid}}$, where $V_{\mathrm{holder}}$ and $V_{\mathrm{solid}}$ denote the volumes of the regenerator holder and

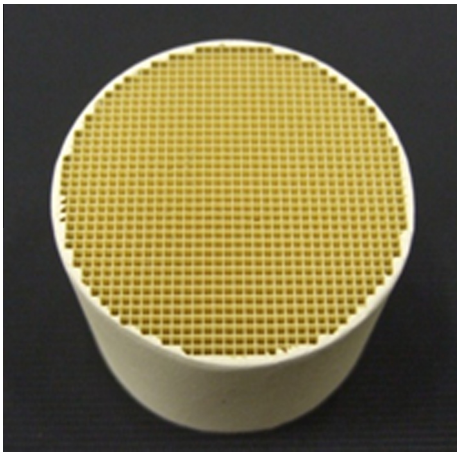

**Fig. 1.** Honeycomb ceramics used for regenerators ($2r_0 = 1.18$ mm for the regenerator in the photograph).

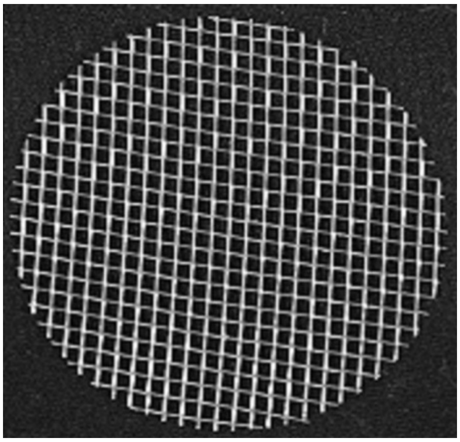

**Fig. 2.** Metal mesh used for regenerators (mesh #16 for the mesh in the photograph).