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Technical Note

# A quantitative method to describe the flow characteristics of an oscillating flow including porous media

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ABSTRACT

The flow characteristics of an oscillating flow including porous media are very important for designing oscillating-flow-based devices. A combined experimental and simulation study is carried out to provide a comprehensive quantitative understanding of the oscillating flows. The cycle rate through porous media, a particularly basic parameter, is proposed based on the dimensionless pressure drop as a correction factor for the similarity parameters of the oscillating flows. A modified dimensionless fluid displacement is introduced based on the cycle rate, and a correlation equation is proposed to calculate the cycle-averaged friction factor of porous media. Significant phase difference (7–71°) is observed between the movements of gas inside porous media and pistons, which increases with the increasing pressure drop of porous media. Another correlation equation is proposed to predict the phase difference. It should be noted that the pressure drop of porous media would also affect the flows inside other heat exchangers between cylinder and porous media. The mass flow rate next to the cylinder is very different from that adjacent to the porous media in terms of amplitude and phase difference. Mass flow rates at different cross sections vary linearly with the volume between the piston upper surface and the monitored cross section. Finally, a quantitative method is proposed to describe the flow characteristics of an oscillating flow including porous media, which is expected to improve the design methods of oscillating-flow-based devices.

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## 1. Introduction

Oscillating flow, whose flow direction reverses periodically [1], exists in many devices and heat exchangers, for example, Stirling engines [2], Stirling refrigerators [3], Cryocooler [4], coolers for electronic equipment [5], etc. Porous media is widely used in these devices, as a heat reservoir or as a means to enhance heat transfer, because of its large specific surface and intense mixing of the fluid flow [6]. The performance of these devices improves significantly with the presence of porous media. As a typical device, the Stirling engine is involved in the following discussion. It is not easy for a real Stirling engine to reach the expected performance from the design because less quantitative methods are available to describe the functional characteristics of the oscillating flows in heat-work conversion processes.

Generally, there are two groups of flow characteristics for oscillating flows in devices, related with porous media and with other heat exchangers (including heater, cooler and connection pipes in the oscillating flow). For the flow characteristics through porous media, many correlation equations of friction factor of porous media were proposed [7–13], which can be found in the report by Xiao et al. [14]. These correlation equations can be divided into two types according to the parameters they are based on. The first type is related to the Reynolds number. The second type is based on the similarity parameters of an oscillating flow, i.e., the kinetic Reynolds number and the dimensionless oscillation amplitude. The second type can be converted into the first ones, but the precondition is that the flow must be assumed as incompressible, according to the report by Xiao et al. [14]. In order to expand the application range, correction factors are strongly suggested to consider the effect of pressure drop when similarity parameters are applied.

Besides the friction factor, the phase difference between the pressure drop of porous media and piston velocity is also very important, which determines the start crank angle of the mass flow rate through porous media (the mass flow rate is in phase with pressure drop). Zhao and Cheng [10] observed significant phase difference, like the phase difference is 24° when the kinetic Reynolds number is $5.529 \times 10^{-2}$. However, Leong and Jin [7] observed a much smaller phase difference (3.7°) when the kinetic Reynolds number was 24.0. It was probably caused by the pressure drop of porous media, because the amplitude of pressure drop

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(between 30 and 45 Pa) was much smaller than that of Zhao and Cheng [10] (3000–3500 Pa). Thus, the effect of pressure drop or relative issues should be considered when a correlation equation is proposed. Based on the correction factors for the similarity parameters of an oscillating flow, the friction factor of porous media, and the phase difference between the pressure drop of porous media and piston velocity, the flow characteristics of porous media can at least be determined.

Many researchers [15,16] have made efforts on choosing a regenerator for the Stirling engine, while very few of them could provide a comprehensive and deep explanation about their choice. Gheith et al. [15] found that a regenerator with 85% porosity was the most suitable matrix for the tested Gamma-type Stirling engine among the tested samples. Most of the explanations for these results were attributed to the compromise of pressure drop and heat transfer of porous media, and the effects of porous media on the oscillating flow were seldom mentioned. It should be noted that the oscillating flow is a closed cycle and all heat exchangers inside interact with each other through the heat and mass transfer of an oscillating flow. Thus, the effect of porous media on the flow of other heat exchangers should also be considered.

Based on the previous study by Xiao et al. [14], the current work aims to develop a quantitative method to describe the flow characteristics of an oscillating flow including porous media. Experiments and numerical simulations by Fluent [17] have been performed to study the flow characteristics of porous media and other heat exchangers such as cooler and connecting pipes. The mass flow rates through porous media and at different cross sections have been analyzed. The phase difference between the movements of gas and piston has also been discussed. Finally, a logic link of these flow characteristics has been presented.

## 2. Experimental equipment and simulation model

### 2.1. Experimental equipment

A similar test rig, which has been reported by Xiao et al. [14], is used to investigate flow characteristics of an oscillating flow including porous media and provide data for model validation, as shown in Fig. 1(a). The velocity straighteners are removed in this test rig to reduce the pressure drop of the system comparing to previous experimental apparatus. Four types of wire screens (100 mesh, 200 mesh, 300 mesh and 400 mesh) are tested, and the detailed information can be found in the report by Xiao et al. [14]. The frequencies of 2, 4, 6 and 7.9 Hz are selected. Four pressure transducers with response frequency of 10 kHz are used to monitor the pressures in the oscillating flow. The bottom dead center of the left piston is set as 0°. The ends of porous media are named as left end and right end, respectively. The flow from left end to right end is defined as the forward flow, and the flow from right end to left end is defined as the reverse flow. The experiment is performed under atmospheric pressure and room temperature.

The porosity $\varphi$ is calculated based on the weight of the wire screens [18]. The definition of hydraulic diameter $d_h$, Reynolds number $Re_{(dh)}$, and friction factor of porous media $f$ from Zhao and Cheng [10] are as follows:

$$\varphi = 1 - \frac{V_{metal}}{V_{po}} \tag{1}$$

$$d_h = \frac{\varphi}{1-\varphi} d_w \tag{2}$$

$$Re_{(dh)} = \frac{d_h \rho u}{\mu} \tag{3}$$

$$f = \frac{\Delta P d_h}{0.5 * \rho u^2 L_{po}} \tag{4}$$

where $V_{po}$ is the volume of the housing of porous media; $V_{metal}$ is the volume of wire screens; $L_{po}$ is the length of the housing of porous media; $d_w$ is the wire diameter; $\varphi$ is the porosity; $\rho$ and $\mu$ are the density and dynamic viscosity of air, respectively; $\Delta P$ is the pressure drop through porous media; $u$ is the velocity of air in the porous media.

### 2.2. Numerical study

Fig. 1(b) shows the numerical model for an oscillating flow through porous media. The configuration of this model is similar to that reported by Xiao et al. [14]. Dynamic mesh is applied to simulate the movement of pistons according to Eq. (5). The right piston lags behind the left piston by 180°. The working condition is the same as that of the experiment. The porous media model in the Fluent is applied, and the detailed input parameters can be found in the report by Xiao et al. [14].

$$u_{pis} = \omega/2L_{pis}\sin(\omega t + \theta) \tag{5}$$

where $L_{pis}$ is the stroke of piston; $\theta$ is the phase difference between the pistons; $\omega$ is the angular frequency.

The uncertainties of the cycle-averaged pressure drop of porous media (ten cycles) and the crank angle for the variation of flow direction (phase difference) are 0.94–7.45% and 0.33–9.41% with a 95% confidence level, respectively. The pressures and mass flow rates at monitor 1–10 in the model are recorded. The peak angles and amplitudes of pressures (manometer pressure) and pressure drops agree well with the experimental data. The maximum deviations between the calculated cycle-averaged pressure drop of the porous media and experimental data are less than 13.6%, 8.9%, 6.46% and 9.5% for 100, 200, 300 and 400 mesh wire screens, respectively. The maximum deviations of the phase difference for each kind of wire screens are less than 15.2%, 6.41%, 6.6% and 3.76%, respectively.

## 3. Results and discussion

### 3.1. Flow characteristics of porous media

#### 3.1.1. Cycle rate through porous media

An oscillating flow is a closed cycle, and the amount of gas during the cycle is constant, which is different from a steady flow. The cycled amount of gas through porous media of half cycle is, in theory, equal to the amount of gas swept by pistons. A part of the gas cannot flow through the porous media within a given time, because of the pressure drop of porous media and other heat exchangers. Thus, the amplitude of the mass flow rate (close to a sine curve) through porous media will decrease, as shown in Fig. 2(a). The pressure drop of porous media accounts for about 73–97% of the overall pressure drop in this study, and here just the effect of the pressure drop of porous media is considered. Two parameters are proposed, namely cycle rate $\delta$ and the dimensionless pressure drop $\Delta P^*$. Cycle rate $\delta$ is defined as the ratio of actual cycled amount of gas through porous media $M_{cr}$ to the theoretical value $M_{ct}$. The dimensionless pressure drop $\Delta P^*$ is defined as the ratio of cycle-averaged pressure drop $\Delta P_{cycle}$ of porous media to the mean pressure $P_{mean}$. These two parameters are calculated for the tested four types of wire screens under different frequencies (2 Hz, 4 Hz, 6 Hz and 7.9 Hz), as shown in Fig. 2(b). The cycle rate is affected by the frequency and mesh size, which can be categorized as the effect of pressure drop, according to Eq. (4).The relationship between cycle rate and the dimensionless pressure

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