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Research Paper

Prediction and parametric analysis of acoustic streaming in a thermoacoustic Stirling heat engine with a jet pump using response surface methodology

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HIGHLIGHTS

- Response surface methodology is used to predict acoustic streaming in a TASHE.
- Analysis of variance is performed to identify the effect significance of factors.
- The regression model between objective functions and designing parameters is obtained.
- The interaction effects of jet pump's parameters on acoustic streaming are analyzed.

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ABSTRACT

Jet pumps are widely used in thermoacoustic Stirling heat engines and pulse tube cryocoolers to restrain acoustic streaming and improve the system performance. In this paper, a regression model is presented to predict the acoustic streaming in a thermoacoustic Stirling heat engine (TASHE) with different structure parameters of the jet pump. These parameters include position, length, inner diameter and tapered angle. Response surface methodology (RSM) is used to study the relationship between structure parameters of jet pump and acoustic streaming. A regression model is developed to predict the acoustic streaming. The analysis of variance (ANOVA) is conducted to describe the rationality of regression model and examine the statistical significance of factors. In addition, the relationship between acoustic streaming and structure parameters of jet pump is presented using 2D contour and 3D surface plot. It reveals that small position, length, tapered angle and large inner diameter can help suppress acoustic streaming. Eventually, four random confirmation tests are performed to verify that the regression model can predict acoustic streaming reasonably. This work provides theoretical guidance for controlling acoustic streaming using jet pump.

1. Introduction

Thermoacoustic technology which refers to time-averaged interaction between the thermodynamic and acoustic phenomena is basking in a great boom since the publications of Rott and Swift [1,2]. This novel technology can convert waste heat to mechanical/electrical power, or transfer heat from the cold end to the ambient end and generate cooling effect with a driver. The former type of the device that generates useful work is known as a thermoacoustic prime-mover. When the temperature gradient of the stack or the regenerator in the thermoacoustic system with a heat source exceeds the critical value, the gas will oscillate without any drivers. Besides, it also shows great advantages and promising prospects owing to its potential high efficiency and environmental friendliness compared to the traditional mechanical engine, especially in utilizing waste heat to combine with refrigerator, electric generator and so on [3–6].

In the light of the definition of acoustic power $W = \frac{1}{2}|p|\ |U|\cos\varphi$, the smaller phase difference φ between pressure and volume flow rate indicates more acoustic power. When sound propagates in form of traveling wave, the phase difference is close to zero. The use of a looped tube as the waveguide of a thermoacoustic engine has enabled the execution of a Stirling thermodynamic cycle by traveling waves. However, the improvement of efficiency was still limited because of the existence of acoustic streamings [7–10]. It was pointed out that there existed a non-zero time-averaged mass flux in the loop and one or more

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Nomenclature

a	cross-sectional area (m^2)
d	diameter of jet pump (mm)
L	length of PA (mm)
K	local resistance coefficient
H	enthalpy (W)
Δp	pressure drop (Pa)
D	diameter of tube (mm)
p	pressure amplitude (Pa)
T	temperature (K)
u	velocity (m/s)
x	variables
y	response
W	acoustic power (W)

Greek symbols

α	tapered angle of PA (°)
β	regression coefficient
φ	phase (°)
ρ	density (kg/m^3)
ε	statistical error

Subscripts

b	narrow end of PA
k	number of factors
2	second order
$+$	into the narrow end of PA
s	wide end of PA
1	first order
m	mean value
$-$	out of the narrow end of PA

Other

$\|\|$	amplitude

time-averaged mass fluxes about the thermal penetration depth in the thermal buffer tube (TBT). The former is called Gedeon streaming that carries heat away from the hot heat exchanger and generates unfavorable heat losses. The latter is named Rayleigh streaming that generates unnecessary heat leak by convecting heat from the hot end of the TBT to the ambient heat exchanger. Previous literatures had verified theses acoustic streamings could cause energy dissipation and lower the efficiency of heat and sound energy interconversion [11,12]. Therefore, it is necessary to predict acoustic streamings and take measures to eliminate their effect.

The Rayleigh streaming could be suppressed by using a simple tapered TBT, which is not discussed in this paper [2]. However, predicting and restraining Gedeon streaming are much more complicated. To achieve this goal, many studies have been carried out. Biwa et al. tactfully used the axial temperature distribution to qualitatively measure the acoustic streaming in annular thermoacoustic engines [13]. Paridaens et al. [10] carried out the study on the generation mechanisms of acoustic streaming in a thermoacoustic prime mover with different channels. The investigation showed that the mechanisms of acoustic streaming generation is different for wide and narrow channels. It's well known that jet pumps [2,14] and elastic membranes [15–17] can be used in thermoacoustic Stirling heat engines and pulse tube cryocoolers to suppress the acoustic streaming. Due to the limited lifetime of the membrane in the oscillatory flow, its reliability could not be guaranteed. In contrast, the jet pumps earned widespread respect for its high reliability. The jet pump has an orifice plate structure which generated the additional pressure drop by using the asymmetry of hydrodynamic end effects to counteract Gedeon streaming. In 1999, Swift first proposed a jet pump in the thermoacoustic Stirling heat engine (TASHE) [2]. Experiment showed that Gedeon streaming was reduced significantly and the Carnot efficiency was up to 40%. They also developed a software called Design Environment for Low-amplitude Thermoacoustic Energy Conversion (DeltaEC), which was a popular tool to predict the performance of thermoacoustic systems [18]. Subsequently, Barton et al. [19] revealed the influence of the Reynolds number, the length and radius rounding the edge of a cross section with sudden change on the time-averaged pressure drop and power dissipation. In his work, a parametric study was performed, e.g. two parameters were fixed while the third varied. Petculescu and Wilen [20] investigated the nonlinear effect and minor loss of the jet pump, and then discussed the influence of different cone half-angles. Results verified "the Iguchi hypothesis" that the quasi-steady assumption was applicable in many situations involving high amplitude time-dependent flow. However, these works only focused the performance of the jet pump, and didn't couple it with the TASHE and consider its influence on Gedeon streaming. Biwa et al. [14] applied a jet pump in a looped-tube thermoacoustic engine to measure the acoustic streaming, which indicated that the orientation of the jet pump had an important effect on decreasing the heat loss caused by the acoustic streaming. It has been accepted that the existence of Gedeon streaming did harm to the performance and the jet pump played a significant role in restraining Gedeon streaming in the TASHE. Nevertheless, how to predict the acoustic streaming and how parameters of jet pump affect Gedeon streaming are still not clear, and few studies was reported. Thus it is necessary to carry out studies on the prediction of the Gedeon streaming and jet pump's influence, which can provide guidelines for optimization design of jet pump.

The response surface methodology (RSM), firstly induced by Box and Wilson [21], is a method for the accurate prediction of engineering system input–output relationships by taking a full consideration for parameter interaction. It has been widely applied in numerous manufacturing fields for the design, development and formulation of new products, as well as in the improvement of existing product designs [22–24]. RSM can obtain the regression equation of factors and responses by limited experimental designs and intuitively display the relationship between factors and responses by contour plot and response surface. Therefore, the RSM is applied to predict the Gedeon streaming and analyze the influence of the jet pump's parameters.

The aim of the present study is the prediction and parametric analysis of acoustic streaming (Gedeon streaming) in the TASHE with a jet pump. The model of TASHE with a jet pump is developed using DeltaEC. The regression model to predict acoustic streaming is developed using RSM. Furthermore, analysis of variance (ANOVA) is applied to identify the parametric significance statistically. The influences of parameters on Gedeon streaming are presented in contour plot and 3D response surface. Finally, four verification deigns are performed to test the accuracy of RSM.

2. Model development

2.1. Model description of the TASHE with jet pump

Fig. 1 presents the schematic diagram of the TASHE with a jet pump. The TASHE is composed of a loop and a resonator. The main