Applied Energy 189 (2017) 602–612

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Study on a Pi-type mean flow acoustic engine capable of wind energy harvesting using a CFD model

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HIGHLIGHTS

- A Pi-type mean flow acoustic engine CFD model was built and the operation performance of the engine was obtained.
- The acoustic characteristics and hydrodynamic characteristics were analyzed.
- Running the engine in the first hydrodynamic and acoustic mode is most efficient in converting energy.
- Pressure wave phase differences between two resonators were obtained and analyzed.
- Pi-type mean flow acoustic engine differs from cross-junction mean flow acoustic engine in phase lag.

ARTICLE INFO

Article history:
Received 19 October 2016
Received in revised form 4 December 2016
Accepted 6 December 2016

Keywords:
Mean flow acoustic engine
Thermoacoustic
Transducer
Wind energy
Acoustic oscillation

ABSTRACT

A mean flow with remarkable kinetic energy passing deep cavities excites stable acoustic oscillations at certain mean flow velocity ranges. Based on this aerodynamic effect, a mean flow acoustic engine (MFAE) can be built to convert wind energy or other fluid energy into acoustic energy. The MFAE without mechanical moving parts has potential applications in driving thermoacoustic refrigerators and transducers to provide cooling power and electrical power, respectively. With two resonators spaced on one side of the driver, a Pi-type MFAE can be built. A computational fluid dynamics model with large-eddy simulation of turbulence was used to simulate the operation performance of a Pi-type MFAE. With mean flow velocity below 62.22 m/s, five acoustic modes with different pressure wave frequencies were observed in the Pi-type MFAE. Pressure amplitudes in the resonators, phase lags between two resonators, hydrodynamic vortices shedding and non-dimensional Strouhal numbers were presented. We found that the maximum pressure amplitude happens at the third acoustic mode with mean flow velocity 49.98 m/s. The maximum non-dimensional pressure amplitudes at four acoustic modes were found at Strouhal number close to 0.4 indicating the first hydrodynamic mode. The Strouhal number suggests an optimal working condition to harness wind energy. Furthermore, it is found that the phase difference between the pressure waves at the front resonator and at the rear resonator of the Pi-type MFAE differs from the cross-junction MFAE. Appropriately utilizing the phase difference between two resonators could enhance the energy exploitation.

1. Introduction

Wind power could be harnessed in a variety of ways including pumping water [1], grounding grain, segregating particles [2], generating electricity [3], etc. These approaches in general convert the kinetic energy of the airflow into mechanical energy of the mechanical parts (such as windmill). Wind energy nowadays was typically used to drive wind turbine in order to generate electricity. Studies on wind energy utilization were generally focused on improving the efficiency of the turbine [4–6]. Mean flow acoustic engine (MFAE) is a new engine harvesting wind energy and its mechanism differs from traditional ways of exploiting wind energy: it converts a one-way airflow with remarkable kinetic energy into a reciprocating airflow. The direction of the reciprocating airflow usually is perpendicular to the direction of the one-way airflow, and the reciprocating airflow induces a notable standing wave acoustic field in MFAE. This stable acoustic pressure at certain mean flow velocities can then be used to generate electricity

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http://dx.doi.org/10.1016/j.apenergy.2016.12.022
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Nomenclature

p	air gauge pressure (Pa)
p_{amp}	pressure amplitude (Pa)
c_0	speed of sound (m/s)
ρ_0	ambient density (kg/m^3)
m	acoustic mode number
h	hydrodynamic mode number
k_w	wave number
k	heat conductivity (W/(m $\cdot$ K))
e	internal energy (J)
R	universal gas constant (J/(kmol $\cdot$ K))
T	absolute temperature (K)
q	computable heat flux (W/m^2)
St	Strouhal number
Re	Reynolds number
H	width (m or mm)
W_{eff}	effective diameter of the resonator entrance (m or mm)
L	length (m or mm)
f	frequency (Hz)
U_{con}	convective velocity of the vortex
U_{mean}	mean flow velocity
t	time (s)
λ	wavelength (m)
ρ	air density (kg/m^3)
τ	stress (Pa)
σ	stress tensor (Pa)
μ	dynamic viscosity (kg/m $\cdot$ s)
ω	vorticity (1/s)
ϕ_{ac}	acoustic phase shift between vortex convection and acoustic oscillation

Subscripts

i, j	vector notation
n	mode number of natural frequency
R	resonator
D	driver

Headlines

–	spatial filtering operation
~	density-weighted filtering operation

using piezoelectric effect [7], provide cooling or heating power using thermoacoustic effect [8–11], measure velocity of the fluid in a novel way [12] and prospectively drive piston to provide mechanical energy. Moreover, a startup company in Spain recently built bladeless wind turbines applying the mechanism of the vortex induced vibration. If the company successfully commercializes this technique, the conventional wind turbine with moving blades could be replaced in the future [13,14]. Analogous to this industrialization example, MFAEs have a great application prospect in harvesting wind energy in a very simple way. According to the geometry of the flow pipes, MFAEs include T-junction, cross-junction, Pi-type, and other uncommon structures. Among them, T-junction and cross-junction MFAEs have been widely investigated [15–20], but the performance of Pi-type MFAE was rarely reported [15,21].

The working mechanism of MFAE is that airflow passing a deep cavitation induces vortex shedding and then excites acoustic oscillations in the deep cavitation. The purpose of early studies on acoustic oscillation induced by mean flow is to reduce the noise of pipelines, damp structure vibrations, and prevent fatigue rupture [22]. Rockwell and Naudascher categorized aerodynamically self-sustained oscillations into three types: fluid-dynamic, fluid-resonant, and fluid-elastic [23]. From then on, the fluid-resonant oscillation drew researchers' attentions due to its mono-frequency characteristic and remarkable acoustic energy density [8,16]. Slaton and Zeegers first built a thermoacoustic heat pump driven by a MFAE and obtained a maximum acoustic power of approximately 32 W [8] which is comparable with a standing wave thermoacoustic engine [24]. Devices based on piezoelectric effect were widely used in multiple fields [25–27]. The piezoelectric transducer and alternator driven by acoustics [28–30] suggest that MFAE can convert mean flow energy into electric power.

Acoustic amplitudes excited by mean flow passing deep cavitation can be classified into three levels [21]: low amplitude ($p_{amp}(L_R)/\rho_0 c_0 u_{mean} \leqslant 10^{-3}$), moderate amplitude ($10^{-3} \leqslant p_{amp}(L_R)/\rho_0 c_0 u_{mean} \leqslant 10^{-1}$) and high amplitude ($p_{amp}(L_R)/\rho_0 c_0 u_{mean} = O(1)$), where $p_{amp}(L_R)$ is the pressure amplitude at the end of the deep cavity, c_0 is the speed of sound, ρ_0 is the mean flow density and u_{mean} is mean flow velocity of the airflow. At different levels of acoustic amplitudes, researchers considered a variety of models to describe the behavior of shear layer rolling up and forming vortices. At low acoustic amplitudes, Elder [17] and Howe [31] established a shear layer model in which the oscillation amplitude of shear layer increases exponentially with the distance from the upstream edge. At moderate acoustic amplitudes, discrete vortices form in the resonator entrance and nonlinearity affects the growth of shear layer perturbations [21]. At high acoustic amplitudes, acoustic field strongly affects the formation of vortex [15]. Most models are based on Nelson's empirical model [32] for Helmholtz resonator assuming that vortex is concentrated into line vortices. Point-vortex model proposed by Bruggeman et al. [21] and Howe [31] overestimated oscillation amplitudes because the vortex is not concentrated into a point and the vortex path deviates from straight line. Krasny proposed a vortex-blob method [33] applied by Kriesels et al. [34], which supposes that acoustic power is equal to the losses brought by visco-thermal, radiated and non-linear effects. For high acoustic amplitude, Hofmans [35] exaggerated acoustic oscillation by 30% for a single side branch tube. To our knowledge, few if any modeling works have yet investigated the operating characteristics and performance of Pi-type MFAE at a wide range of mean flow velocities.

Fluid-related mechanics were broadly studied using numerical and analytical methods and computational fluid dynamics (CFD) was widely used to investigate the fluid flow characteristics, such as liquid desiccant [36,37], droplet dynamics [25,38,39], airflow field [40,41], phase change materials' melting process [42,43], moisture transportation in polymer composites [44–47], micro-scale particle transportation [48–51], gas reservoirs [52,53], and combustion process [54–57]. Recently, CFD model was used to simulate a MFAE with a cross-junction structure [20,58]. The result agrees with the experiment [19] in respects of acoustic mode, hydrodynamic mode, pressure amplitude trend, etc. Although the magnitude of pressure amplitude in the simulation is higher than experiment, the CFD model can predict the acoustic mode and the pressure amplitude variation with mean flow velocity.

The acoustic and hydrodynamic characteristic of MFAE with cross-junction structure has been investigated extensively for the past decades. Little study [15,16] was found in studying the Pi-type MFAE with two spaced branches on the same side of the trunk