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Performance comparison of jet pumps with rectangular and circular tapered channels for a loop-structured traveling-wave thermoacoustic engine

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HIGHLIGHTS

- Three evaluating parameters are proposed to characterize performance of a jet pump.
- The performances of jet pumps with rectangular and circular tapered channels are compared.
- Thickness-to-diameter ratio can change the magnitude and direction of the time-averaged pressure drop of jet pump.
- A jet pump with rounded circular tapered channel can work more efficiently.

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ABSTRACT

Gedeon streaming can considerably deteriorate the thermal efficiency of a traveling-wave thermoacoustic engine employing a loop configuration. Introducing a jet pump into the loop configuration is one of the effective ways to suppress Gedeon streaming. This paper focuses on the performance comparison between the jet pumps with rectangular and circular tapered channels, by numerically simulating and analyzing the time-averaged pressure drop induced by the jet pumps. Three parameters, i.e., the coefficient of time-averaged resistance, the coefficient of overall resistance, and the coefficient of effectiveness, are proposed to evaluate the performance of a jet pump. The emphasis is put on the effects of cross-sectional shape, thickness-to-diameter ratio, and rounding radius of the tapered channels. In absence of rounding the edge of the tapered channel, the jet pump with a rectangular tapered channel is more efficient to produce the time-averaged pressure drop at a large thickness-to-diameter ratio, while the jet pump with a circular tapered channel is more efficient at a small thickness-to-diameter ratio. However, it should be noted that the directions of the induced time-averaged pressure drops in these two cases are opposite. Rounding the edge of the small opening of the tapered channel can effectively improve jet pump's performance. Upon rounding, the jet pump with a circular tapered channel can produce a higher time-averaged pressure drop and work more efficiently than the one with a rectangular tapered channel.

1. Introduction

A thermoacoustic engine generally consists of pipes and heat exchangers, without any moving parts except for the oscillating fluid inside, which is inherently advantageous in its simple structure, reliability and longevity. Such an acoustic prime mover also has the potential to be powered by low-grade thermal energy, which are abundantly available including the industrial waste heat and solar energy. Much research and development effort has been focused on the prospective applications, such as producing electricity [1–3] and refrigeration [4,5] driven by the thermoacoustic engines with gaseous working fluid. Similar systems involving liquid–vapor two-phase oscillating flow, whose output hydraulic work can be used for water pumping, circulation and pressurization, have also attracted much interest [6–12].

Due to the perfect thermal contact between working fluid and solid boundary in the regenerator, a traveling-wave thermoacoustic engine is theoretically more efficient than a standing-wave one [13,14]. The thermoacoustic Stirling engine developed by Backhaus and Swift [15,16], one of the typical traveling-wave

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Nomenclature

a	area of opening of jet pump (mm^2)
A	pipe cross-sectional area (m^2)
c_p	specific heat at constant pressure (J/(kg K))
d_e	equivalent diameter of the small opening of the tapered channel (m)
D	diameter of the pipe (m)
k	coefficient of resistance
K	minor loss coefficient
l	thickness of the jet pump (m)
M	mass flow (kg/s)
p	pressure (Pa)
r	rounding radius (mm)
R	radius of the pipe (m)
T	time period (s) or temperature (K)
u	velocity (m/s)
U	volumetric velocity (m^3/s)
w_o	total power loss of fluid flow through the jet pump (W)

Abbreviations

CFD	Computational Fluid Dynamics
EXP.	Experimental Data
JP-CTC	jet pump with a circular tapered channel
JP-RCTC	jet pump with a rounded circular tapered channel
JP-RRTC I	jet pump with a rounded rectangular tapered channel I
JP-RRTC II	jet pump with a rounded rectangular tapered channel II
JP-RTC	jet pump with a rectangular tapered channel
RANS	Reynolds averaged Navier–Stokes equation
RKE	realizable κ–ε
SIM.	simulation results

Greek

α	Womersley parameter $\alpha = R(\omega/\nu)^{1/2} = \sqrt{\omega'}$
ε	coefficient of effectiveness (Pa/W)
ν	kinematic viscosity (m^2/s)
Π	wetted perimeter (m)
ρ	density (kg/m3)
ω	angular frequency (Hz)

Subscript

a	time-averaged
b	big
c	cold heat exchanger
con	contraction
exp	expansion
h	hot heat exchanger
jp	jet pump
loop	looped pipe where the jet pump locates
m	mean
o	total
s	small
1	amplitude
2,0	second-order time-averaged
+	forward fluid flow
−	backward fluid flow

thermoacoustic engines, achieved a thermal efficiency as high as 0.3, which brought a prosperity in the field of thermoacoustic engines [17–22]. So far, the thermoacoustic Stirling engine and the multi-stage looped traveling-wave thermoacoustic engine can both attain an exergy efficiency up to about 0.5 [20,22].

The traveling-wave thermoacoustic engine usually has a loop configuration, which may cause an acoustic streaming named as Gedeon streaming [23]. An oscillating flow circulates throughout the loop in a time-averaged manner, which can directly bring heat from the hot heat exchanger to the cold heat exchanger without involving the thermoacoustic conversion, therefore inducing the valueless heat loss and deteriorating the system's efficiency [15,16]. The Gedeon streaming can be expressed as $M_{2,0} = Re[\rho_1 U_1]/2 + \rho_m U_{2,0}$, where U_1 is the volumetric velocity amplitude, $U_{2,0}$ is the second-order time-averaged volumetric velocity, ρ_1 is the density amplitude, and ρ_m is the mean density. The heat loss due to Gedeon streaming is $Q_{\text{loss}} = M_{2,0} c_p (T_h - T_c)$, where c_p is the specific heat at constant pressure, T_h and T_c are the temperatures at the hot and cold heat exchangers, respectively.

A "jet pump", schematically shown in Fig. 1, was introduced into the loop configuration by Backhaus and Swift [15,16] to suppress the Gedeon streaming. The jet pump is characterized by a rectangular tapered groove with different inlet and outlet opening areas, which can produce a time-averaged pressure drop in the oscillating flow, because the pressure drop through the jet pump is asymmetric between the forward and backward flows in each of their half time periods. Such a time-averaged pressure drop can effectively suppress the Gedeon streaming.

So far, the time-averaged pressure drop caused by a jet pump is usually calculated by the formula proposed by Backhaus and Swift [16]. Following Iguchi's hypothesis [24] that at each instant the time-dependent oscillating flow with large amplitude can be considered as a steady flow, they deduced the expression of the time-averaged pressure drop as follows

$$\Delta p_a = \frac{\rho_m |U_{1,jp}|^2}{8a_s^2}\left[\left(K_{\exp,s} - K_{\text{con},s}\right) + \left(\frac{a_s}{a_b}\right)^2 \left(K_{\text{con},b} - K_{\exp,b}\right)\right], \qquad (1)$$

where ρ_m is the mean density of working fluid, $U_{1,jp}$ is the volumetric velocity amplitude where jet pump locates, a_s and a_b are the areas of small and big openings of jet pump. $K_{\exp}$ is the expansion loss coefficient, and $K_{\exp} = 1$ when $A_{\text{loop}} \gg a_s$ and a_b (A_{loop} is the cross-sectional area of the pipe where the jet pump locates). K_{con} is the contraction loss coefficient, and $K_{\text{con}} = 0.5$ when $A_{\text{loop}} \gg a_s$ and a_b with a sharp edge. K_{con} decreases as a function of rounding radius r at the edge of channel opening.

Eq. (1) indicates that the pressure drop of flow in the converging direction (i.e., from the big opening to the small opening of the

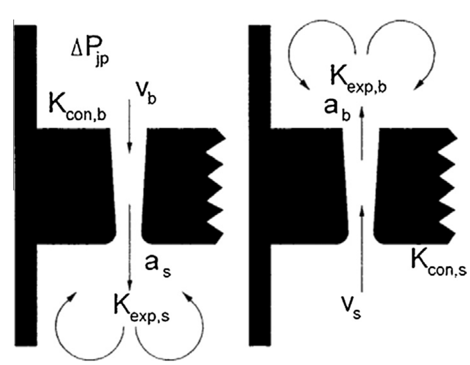

Fig. 1. Schematic diagram of a jet pump [16].