Applied Thermal Engineering 122 (2017) 339–349

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Investigation on the flow noise propagation mechanism in pipelines of shell-and-tube heat exchangers based on synergy principle of flow and sound fields ☆

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HIGHLIGHTS

- The flow and sound fields are coupled to investigate the flow noise propagation process.
- The field synergy principle for sound energy transfer process is developed.
- The silencing effect increases with the increase of synergy between flow and sound fields.

ARTICLE INFO

Article history:
Received 26 December 2016
Revised 23 March 2017
Accepted 15 April 2017
Available online 8 May 2017

Keywords:
Field synergy principle
Flow noise propagation
Numerical simulation
Fluid flow

ABSTRACT

As major equipment for implementing technological process, Shell-and-Tube Heat Exchangers are widely used in modern industries. Because the noise propagation in pipelines in shell-and-tube heat exchangers can't be ignored, it is a key point to investigate the transfer mechanism of sound energy in pipelines and develop high efficiency mufflers with low penalty of pressure drop. Different with the traditional method, this study is focused on the flow and sound fields synergy principle to investigate the flow noise propagation mechanism in pipelines. In this study, theoretical analysis and numerical simulation methods are coupled to investigate the pipeline noise propagation process. Based on the momentum and the energy equations in the sound field, the synergetic relationship between the flow field and the pressure gradient field is deduced, and the field synergy theory is established. The flow noise propagation process of noise in the pipeline is studied by numerical simulation. The synergy is verified by analyzing the calculating results of flow and sound fields. The results show that with the increase of synergy between flow and sound fields, the work done by the fluid on the wall increases, which means the exchange of sound energy between the wall and the fluid increases.

1. Introduction

Since humans entered the industrial era, energy issues affect people's life and economic development and energy conservation becomes more and more important. As a traditional equipment for implementing technological process, Shell-and-Tube Heat Exchangers (STHXs) are widely used in various modern industries. According to relevant reports, shell-and-tube heat exchangers accounted for 35–40% in the total share of the world market of heat exchangers, and even can account for as much as more than 70% in the petrochemical industry [1]. So the study about the flow and heat transfer mechanism in the shell-and-tube heat exchangers to improve the performance is significant for energy saving [2]. In recent years, scholars have done a lot of research on the shell-and-tube heat exchangers, but most of them are focused on the heat transfer enhancement and flow resistance weakness [3], few of them are focused on the flow noise propagation mechanism. In order to investigate the noise propagation mechanism in the process of fluid flow, the flow noise mechanism in shell-and-tube heat exchangers based on flow and sound fields synergy principle is investigated.

As an environmental problem, noise problems occur widely in internal combustion engines, gas turbines, blowers, vacuum pumps, compressors, heat exchangers and other devices, as shown

☆ Presented at the 19th Conference Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction (PRES'16), 2016.08.28-08.31, Prague, Czech Republic. Original Paper Number: 701.

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http://dx.doi.org/10.1016/j.applthermaleng.2017.04.057
1359-4311/

Nomenclature

A	area, m^2
A_{in}	inlet area, m^2
A_{out}	outlet area, m^2
c	sound velocity, m s^{-1}
c_p	specific heat capacity in constant pressure, J kg^{-1} K^{-1}
D	diameter, mm
D_{in}	inlet diameter, mm
D_{out}	outlet diameter, mm
D_{mid}	middle part diameter, mm
f	force, N
F	frequency, Hz
k	thermal conductivity of fluid, W m^{-2} K^{-1}
L	length, mm
L_{in}	inlet length, mm
L_{out}	outlet length, mm
L_{mid}	middle part length, mm
P	fluid pressure, Pa
p	sound pressure, Pa
p'	small variation of pressure
q	quality force, N
Re	Reynolds number
s	entropy, J K^{-1}
TL	sound transmission loss
T	temperature, K
v	velocity, m s^{-1}
W	sound power, W
x,y,z	coordinate directions, m

Greek symbols

α	intersection angle between velocity and temperature gradient, °
γ	specific heat capacity, J kg^{-1}
θ	field synergy angle, °
∇p	pressure gradient, Pa
ρ	density, kg m^{-3}

Subscripts

i	i_{th}, i = 1,2,3...
in	inlet
out	outlet
max	maximum
mid	middle part

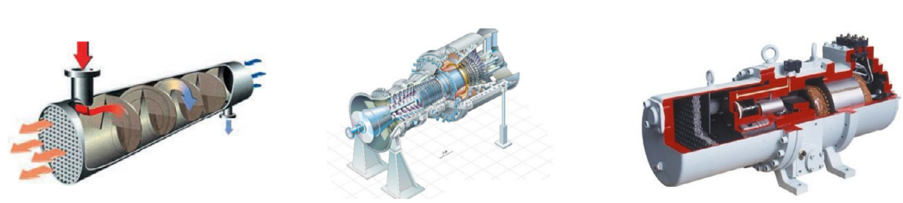
Abbreviations

AML	automatic matched layer
CFD	computational fluid dynamics
STHXs	shell-and-tube heat exchangers

in Fig. 1 [4]. With the development of economy and science technology, while enjoying the convenience of modern society, human demands a better living environment. People want to work and live in a quieter environment, but the noise pollution become more common and severe due to the continue increase of a variety of machine power. In the traditional industrial design concept, the noise problem is usually downplayed, but the design of the heat exchanger highly influences the noise [5]. At this time the cost of local repair will be expensive and the product development cycle will also be delayed [6]. Therefore, in order to satisfy the increasingly stringent noise emission regulations and achieve sound quality as a competitive advantage in the design phase, the noise problem should be taken into account. The design of the heat exchanger highly influences the noise. Noise control mainly depends on the three aspects of sound source, propagation process and receiver. This paper is mainly focused on the noise propagation process.

Focused on the sound propagation process, noise is usually reduced by arranging the mufflers. The traditional mufflers can be divided into resistive mufflers and dissipative mufflers respectively [7,8], as shown in Fig. 2. Due to their desirable broadband noise attenuation characteristics, the expansion chambers are widely used in the ducting systems for pulsating flows [9]. Selamet Radavich [10] investigated in detail the effect of the length on the acoustic attenuation performance of concentric expansion chambers with fixed inlet and outlet ducts, fixed chamber diameters and varying chamber length to diameter ratios from 0.2 to 3.5. Selamet and Ji [11] also investigated the acoustic attenuation performance of circular expansion chambers with extended inlet/outlet. Middelberg et al. [12,13] studied the acoustic performance of various simple expansion chamber mufflers with computational fluid dynamics analysis. Bilawchuk and Fyfe [14] compared the various numerical methods used for calculating transmission loss in muffler systems and concluded that the finite element method (FEM) is better suited for this kind of application. Hu and McLaughlin [15] investigated the flow and acoustic properties of low Reynolds number under expanded supersonic jets. Mishra et al. [16] developed a computational fluid dynamic model to study the effect of muffler geometry modification on key exhaust parameters of an engine. Jiang et al. [17] investigated the sound transmission through tube arrays in power boilers based on phononic crystals theory. Currently, the noise reduction measurements in pipelines are mainly based on the perspective of sound propagation, focused on the transmission medium impedance matching characteristics and the dissipative process of sound energy in the propagation medium, but few are on the synergy between flow and sound fields.

Guo et al. [18] developed the field synergy principle to improve heat transfer performance in 1998, which stated that the overall



(a) heat exchanger (b) gas turbine (b) compressor

Fig. 1. Principal equipments with flow noise.