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Wavelet analysis on the turbulent flow structure of a T-junction

Bo Su[a], Yantao Yin[a], Shicong Li[a], Zhixiong Guo[b], Qiuwang Wang[a], Mei Lin[a,*]

[a] School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] Department of Mechanical and Aerospace Engineering, Rutgers, The State University of New Jersey, NJ 08854, USA

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ABSTRACT

Experimental measurements in a T-junction with one inlet and two outlets mimicking the airflow in a high-speed train ventilation system were carried out using well-resolved Hot-Wire Anemometry (HWA). Continuous wavelet transform (CWT) is used to analyze the time-frequency contents of the instantaneous streamwise velocity; and the discrete wavelet transform (DWT) is employed to determine the multi-resolution energy characteristics. The measurements and analysis are carried out at three representative streamwise locations, i.e., upstream, mid-center, and downstream of the T-junction. The results show that the normalized time-average velocity at the mid-center of the T-junction is the largest near the wall region. Comparing the CWT data in the region near the wall, it is found that the dominant frequency of the periodic high energy coherent structures increases along the streamwise direction, and the wavelet energy magnitude at mid-center of T-junction decreases with the increase of velocity ratio. The DWT results show that apparent wavelet energy peak appears at the upstream and downstream of the T-junction for different scales from 2^6 to 2^{10}, but not at the mid-center. However, the energy at scale 2^{11} abruptly rises in all flow regions at all the three streamwise locations and this energy decreases with the increase of the velocity ratio. Therefore, a higher velocity ratio is preferred for suppressing the generation of large-scale coherent structures to reduce drag forces and skin frictions for high-speed trains.

1. Introduction

Optimizing the ventilation system is critical for improving high-speed train's comfort, efficiency and safety. Fig. 1a shows the actual physical unit of a high-speed train ventilation system, where the vanes are fixed to block the wild debris into the train's cabin. Some fresh air flowing through the ventilation port is sucked into the facility cabin by the axial fan. Thus, turbulence and fluctuating forces will be generated at the downstream of the ventilation port on train's surface. These increase train's surface frictions and flow drags. The domain marked by the dotted rectangle in Fig. 1a is the test section in this study. Fig. 1b shows the plane graph of the ventilation port. Since it is difficult to perform a 1:1 scale experiment in laboratory, a small size model with the scale of 1:4.8, will be used to conduct the experimental study. The velocity ratio, which is the ratio of the suction velocity to the train's velocity, is a key parameter in ensuring the flow pattern similarity (Cambonie et al., 2014; Silva et al., 2003). On the contrary, Reynolds similarity is not strictly adopted due to high Reynolds number in the scaling analysis (Morii, 2008). In actual applications, the range of velocity ratio is from 0.08 to 0.15. The experimental model of the ventilation port is shown in Fig. 1c. It is necessary to understand the flow dynamics on the ventilation port in order to control the skin friction and total drag and further improve the efficiency of high-speed trains.

In experimental studies, the ventilation flow system in a wind tunnel can be modeled as a T-junction channel (Wu et al., 2015), as shown in Fig. 2a. The airflow in the cross tube is regarded as the ambient high-speed airflow passing through train's surface and part of the airflow in the cross tube is driven into the branch tube. The velocity in the branch tube, u_b, is much lower than the velocity in the cross tube, u_c. The ratio of these two flow velocities, $R = u_b/u_c$, is the aforementioned velocity ratio, controlling the flow rate ratio.

In the literature there are a number of researches on T-junction tubes, spanning a wide range of industrial applications (Mitchell, 2001; Bodnar et al., 2008; Kumar et al., 2011; Alam et al., 2012). The T-junction diverging flows have been studied under laminar, turbulent, steady, or unsteady conditions. The early experiments of laminar-flow T-junction by Liepsch et al. (1982) using Laser Doppler Anemometer (LDA) discussed the effect of the Reynolds number and mass flow ratio on the velocity field, local shear stress and pressure drop. Meanwhile, they performed numerical simulations and a good agreement between simulation and experiment was found. Neary and Sotiropoulos (1996) numerically carried out calculations for various Reynolds numbers, discharge ratios and duct aspect ratios for steady laminar flow through 90° diversion of rectangular cross-section. The result showed that even

* Corresponding author.
E-mail address: janeylinm@mail.xjtu.edu.cn (M. Lin).

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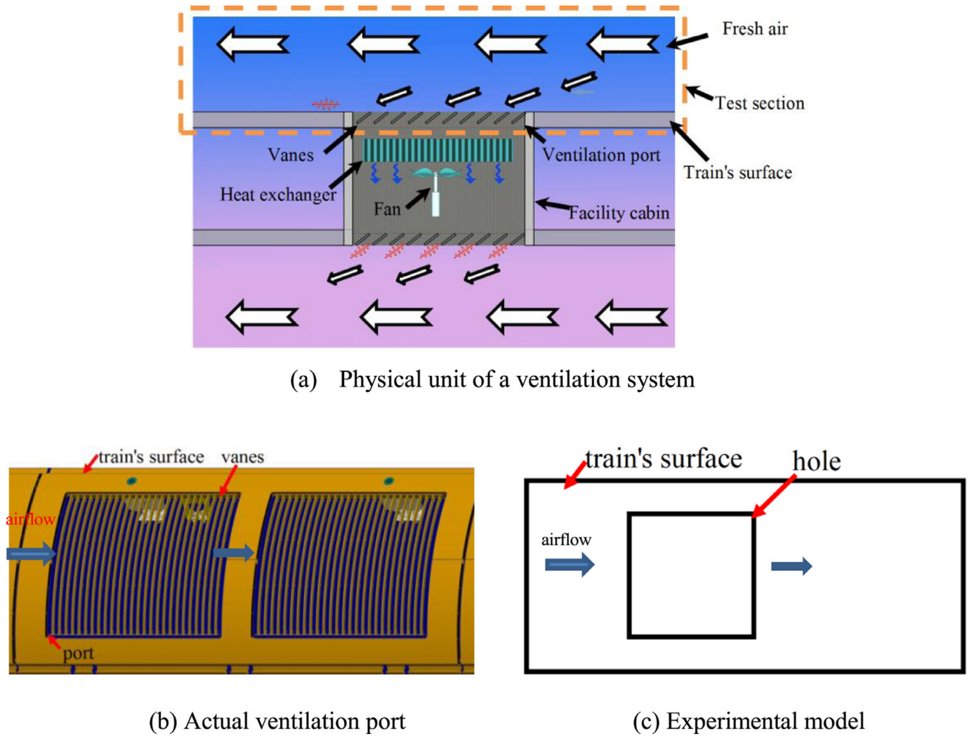

Fig. 1. Sketch of a ventilation system.

for large aspect ratio ducts, the flow at the symmetry plane is significantly affected by the distant top and bottom solid boundaries. Neofytou et al. (2014) simulated the shear-thinning and shear-thickening effects of laminar flow in a T-junction of rectangular ducts. Unsteady inlet condition is of interest for both the industrial and bioengineering applications. Anagnostopoulos and Mathioulakis (2004) numerically studied the pulsating flow field in a square T-junction duct with equal branch flow rate. The flow can sustain much higher adverse pressure gradients during acceleration before separating, compared to the steady inlet condition. Afterward Miranda et al. (2008) carried out steady and unsteady laminar flows in a two-dimensional (2D) T-junction for Newtonian and non-Newtonian fluids. Matos and Oliveira (2013) applied a generalized Newtonian fluid model in planar 2D T-junction tubes having a dividing or bifurcating flow arrangement (one main channel with a side branch at 90°), and also analyzed the competing effects of inertia, shear thinning and extraction ratio for non-Newtonian inelastic flows. Chen et al. (2015) conducted a global linear sensitivity analysis of a complex flow through a pipe T-junction, focusing on near the first Hopf bifurcation flow with Reynolds number at 560.

Many other studies have also involved T-junction turbulent flows. Sierra-Espinosa et al. (2000a, 2000b) experimentally and numerically investigated the turbulence structure of a water flow in the branch exit of a tee pipe junction, in which the Reynolds number was 1.26×10^5. Three turbulent models of the standard k-ε, renormalization group (RNG k-ε), and Reynolds stress model (RSM), were used. A disagreement between predictions and measurements in the reattachment region was observed. Also, the predictions did not reproduce the detachment region of the reverse flow as observed in the experiment. Costa et al. (2006) investigated the edge effects on the T-junction flow, and measured the pressure drop of a Newtonian fluid flow with sharp and round corners. It was found that the rounding corners reduce the energy losses whereas the straight flow basically remains unaffected. Beneš et al. (2013) dealt with the numerical solution of laminar and turbulent flows of Newtonian and non-Newtonian fluids on branch channels with two outlets. The channels considered were constant square or circular cross-sections. Some other mathematical models of tube junction were also reported by Oka et al. (2005) and Stogler (2006). Numerical results showed that the explicit algebraic Reynolds stress (EARSM) turbulence model was capable of capturing the secondary flows in channels of rectangular cross-section.

A number of literatures can be found on T-junction flows because of the mixing flow or separating flow for multi-phase systems in chemical and power engineering field (Georgiou et al., 2017; Wang and Lu, 2015; Sakowitz et al., 2014; Solehati et al., 2014; Poole et al., 2013; Elazhary and Soliman, 2012; Silva et al., al.,2010).

It should be noticed that the aforementioned studies did not discuss the multi-resolution turbulent coherent structures on T-junction diverging flows, which is closely related to high wall-friction drag (Gad-el-Hak, 2000). Understanding the coherent structures is the key for controlling turbulence drag reduction (Kravchenko et al., 1993).

In the present study, the flow structure in the cross tube T-junction channel is similar to the train surface flow structure. The time series of the streamwise velocity components are collected at three representative streamwise locations, i.e., the upstream, the mid-center, and the downstream of the T-junction with one inlet and two outlets. Various flow conditions with different velocities and velocity ratios are examined. The experimental measurements are validated with published data in the literature. The wavelet transform is used to analyze the time-frequency characteristics of a cross tube T-junction flow, and the energy cascade process of the coherent structures is discussed for different scales. These results will guide us to design an optimal ventilation system for high-speed trains.

2. Theory of wavelet analysis

Wavelet transform is a more accurate time-frequency domain analytical method as compared to the Fourier transform. The Fourier analysis transforms the signal into the frequency domain in the whole time domain. Thus, the frequency characteristic of the signal could be fully revealed whereas the time characteristic could not be found. Therefore, the Fourier transform is sufficient for analyzing stationary signals. For non-stationary signals, however, it is difficult to extract the signal feature through a Fourier transform. An improved Fourier