Journal of Zhejiang University-SCIENCE A

Flow field patterns in train compartments based on jet ventilation under variable air volume system: isothermal conditions

Songbo WU, Tian LI, Jiye ZHANG

State Key Laboratory of Rail Transit Vehicle System,
Southwest Jiaotong University, Chengdu, China

Key Findings

- Attached jet, Free jet flow patterns
- Significant correlation with Reynolds number
- Entrainment flow rate depends on initial flow and opening width
- Classical velocity distribution laws apply

- **Cite this as: Songbo WU, Tian LI, Jiye ZHANG, 2025. Flow field patterns in train compartments based on jet ventilation under variable air volume system: isothermal conditions. *Journal of Zhejiang University-SCIENCE A*, 26(12):1258-1272. https://doi.org/10.1631/jzus.A2500022**

Research Background and Significance

Variable Air Volume Systems in Trains

- Widely used for effective energy savings in air conditioning
- Achieves reduced ventilation energy consumption compared to fixed-volume systems
- Essential for maintaining thermal comfort in enclosed compartments

Current Research Limitations

- Design phase typically conducted at fixed airflow rates
- Mismatch between expected and actual flow fields
- Limited understanding of flow field evolution under variable conditions

Research Objectives

- Analyze flow field characteristics at variable airflow rates under isothermal conditions
- Establish correlation equations between airflow and flow field parameters
- Provide theoretical foundation for intelligent ventilation control systems

$Re \geq 2650$

Critical Reynolds number for classical flow behavior

Research Methodology Overview

Numerical Simulation

- **Realizable *k-ε*** turbulence model
- Enhanced wall function for near-wall surface
- SIMPLE algorithm for pressure-velocity coupling
- *Re* range: **990-3310**

Theoretical Analysis

- Prandtl turbulence hypothesis
- Classical jet flow theories
- Dimensionless analysis of flow parameters
- Correlation equations for ***Re* ≥ 2650**

Data Analysis

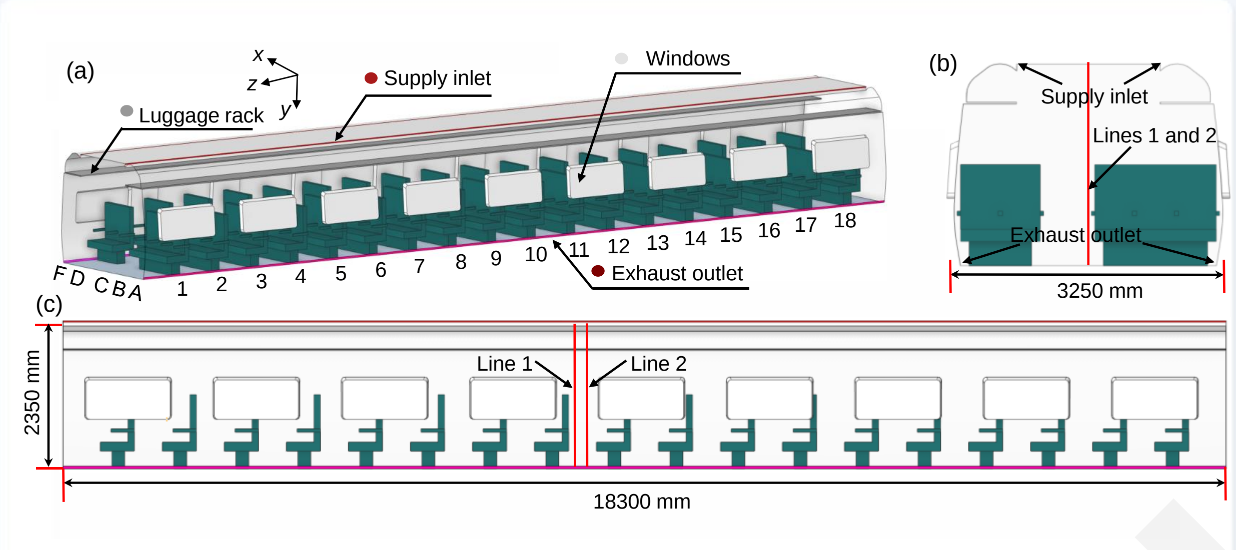
- Velocity field distribution analysis
- Vorticity field characterization
- Jet entrainment flow rate calculation
- Reynolds number dependency evaluation

Research Process

1. **Model Development**
2. **Grid Independence Verification**
3. **Numerical Simulation**
4. **Flow Field Analysis**
5. **Theoretical Derivation**

Computational Model and Boundary Conditions

Geometric Model

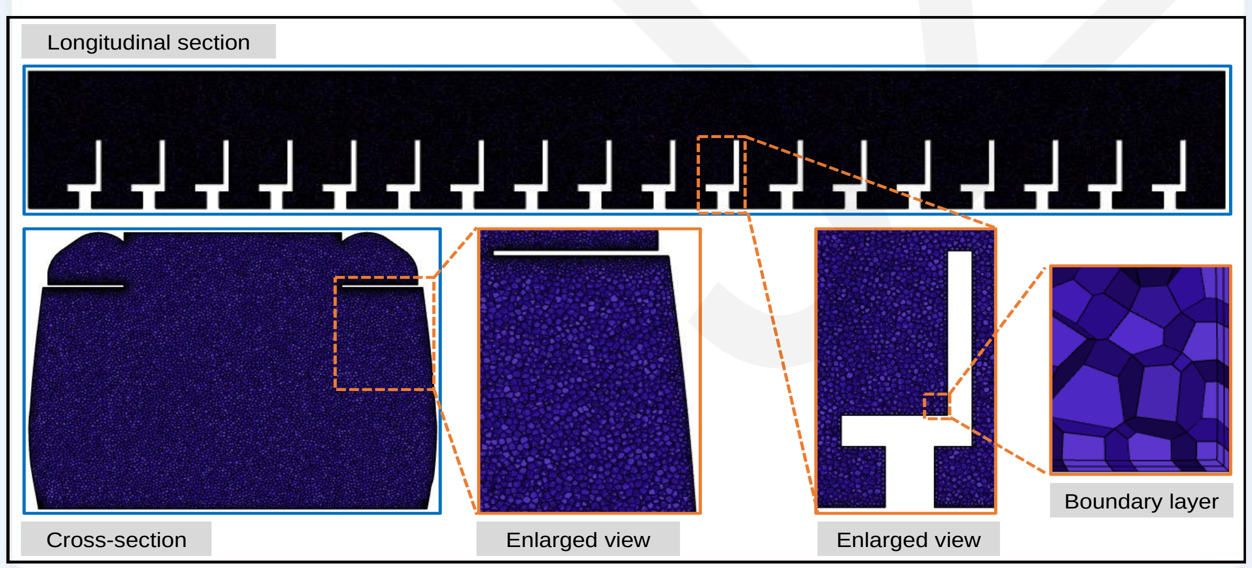


Dimensions: 18.3 m×3.2 m×2.3 m, L×W×H

Occupancy: 90 passengers, 3+2 seating

Air Supply: Ceiling slots b=20 mm

Air Exhaust: Floor outlets on both sides



Boundary Conditions

Supply inlet: Velocity-inlet (u_o=0.735-2.449 m/s)

Exhaust outlet: Outflow automatically adjusted

Temperature: 22℃ isothermal conditions

External: 35℃, 800 W/m ²solar radiation

Mesh Independence Verification

Three grid sets: 6.8M, 21.7M, 34.5M cells

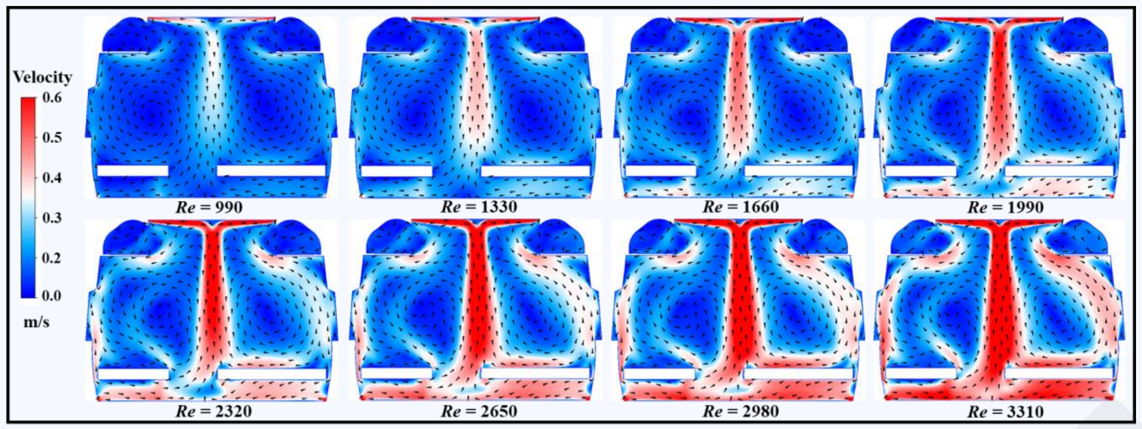
Maximum body grid size: 36mm, 28mm, 20mm

Two-layer boundary layer, first layer: 2mm

Selected: Medium grid, 21.7M cells for balance

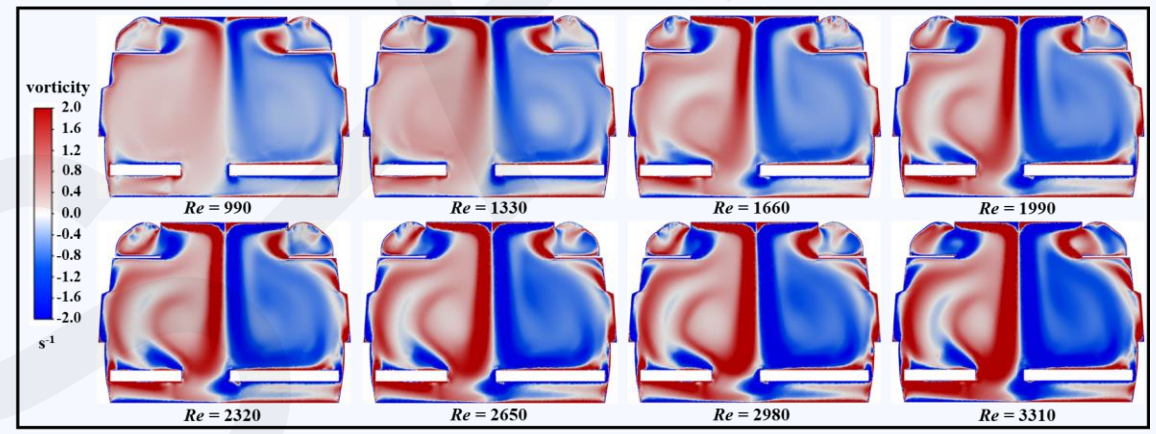
Air Flow Characteristics Analysis

Velocity Field Distribution



- **Jet attaches to ceiling** due to Coanda effect
- **Velocity positively correlated** with Reynolds number

Vorticity Field Distribution



- Vortex strength **increases** with Reynolds number
- Enhanced **entrainment capability** at higher *Re*

Flow Field Patterns

Attached Jet Region	Free Jet Region	Vortex Structures
Initial airflow conforms to wall-attached jet characteristics with Coanda effect	A|er converging at mid-ceiling, airflow exhibits free jet characteristics	Two large-scale circulation patterns form in passenger area

Parameter-Flow Field Theoretical Calculation

Axial Velocity Distribution

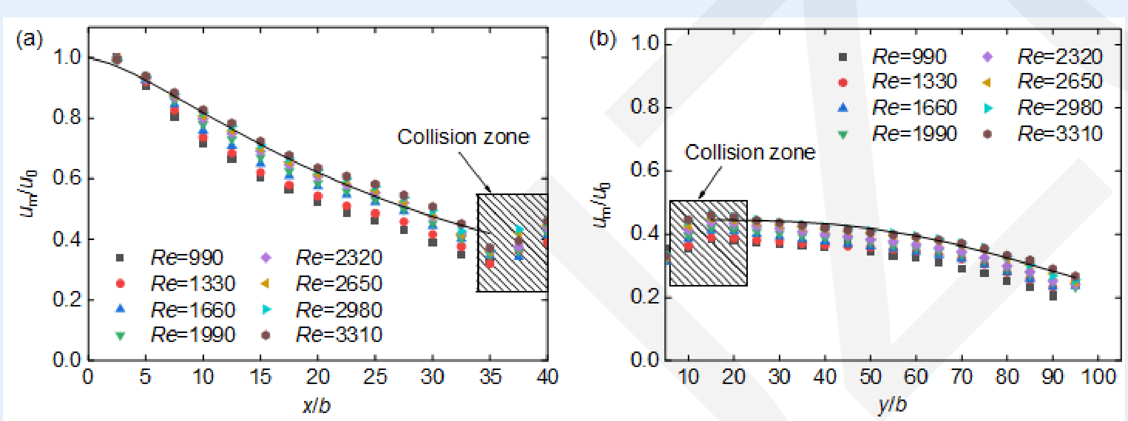
$$u_m / u_0 = 1./(0.007(x/b)^{1.46} + 1)$$

Attached jet region $Re \geq 2650$

$$u_m / u_0 = 0.446/(3.37 \times 10^{-8}(y/b)^{3.7} + 1)$$

Free jet region $Re \geq 2650$

- Follows classical $u_m / u_0 \sim (x/b)^r$ law
- Decay rate **independent of Re** when $Re \geq 2650$



Section Velocity & Jet Thickness

$$u / u_m = 1.48(0 y/\delta 0.5)^{1/7}[1 - \mathrm{erf}(0.68 y/\delta 0.5)]$$

Attached jet Verhoff

$$u / u_m = 0.86 \exp[-0.621(x^* / \delta 0.5)^2]$$

Free jet Tollmien

$$\delta_{0.5} = 0.1(x - 0.05) + 0.9b$$

Attached jet characteristic thickness

- Section velocity follows **exponential & Gaussian** distributions
- Jet characteristic thickness shows **linear distribution**

Key Finding

When $Re \geq 2650$, flow field characteristics become independent of Reynolds number and follow classical jet theory, allowing for standardized prediction models for train ventilation systems.

Impact of Reynolds Number on Flow Field

Flow Field Characteristics at Different *Re*

Low $Re \leq 1330$: Higher entrainment efficiency, stronger vortex structures

Medium *Re* 1660-2320 : Transition region with developing flow patterns

High $Re \geq 2650$: Reynolds independence, stable flow characteristics

Flow Parameters vs Reynolds Number

Jet thickness growth rate: Decreases with increasing *Re*

Vorticity strength: Increases with Re but gradient diminishes

Velocity profiles: Become increasingly similar at higher *Re*

Critical Reynolds Number

$$Re \geq 2650$$

Above this threshold, flow field characteristics becomeindependent of Reynolds number and follow classical jet theory

990-1330

Low *Re* : Enhanced entrainment, thicker jets, stronger vortex structures

1660-2320

Medium *Re* : Transition zone with developing flow patterns

2650-3310

High *Re* : Reynolds independence, classical velocity distributions

Entrainment Flow Analysis

Σ Entrainment Flow Calculation

$$Q_a / Q_0 = (0.109(x+9b-0.05)) / (b(0.007(x/b)^{1.46}+1))$$

Attached jet $\mathrm{Re} \geq 2650$

$$Q_f / Q_0 = (0.086(y+48.9b-0.3)) / (b(3.37*10^{-8}(y/b)^{3.7}+1))$$

Free jet $\mathrm{Re} \geq 2650$

- Entrainment flow rate **increases** with distance from jet origin
- Growth rate **higher** in free jet region than attached jet region

Key Parameters Impact

Initial Flow Rate (Q_0)

Directly proportional to entrainment capacity

Air Opening Width b

Critical factor for jet development

Vortex Structure

Enhances entrainment efficiency

Entrainment capacity **improves** ventilation efficiency

- Higher entrainment rate leads to **better air mixing**
- Optimal design of air supply parameters **enhances** thermal comfort

Key Insight

The entrainment flow rate is primarily related to the initial flow rate and air opening width. This relationship provides a theoretical foundation for optimizing ventilation system design in high-speed trains, enabling better thermal comfort and energy efficiency.

Conclusions

Key Findings

- Airflow initially exhibits **attached jet** characteristics, then transitions to **free jet** behavior
- Flow field characteristics show **significant correlation** with Reynolds number
- When ***Re*≥ 2650**, classical velocity distribution laws apply
- Entrainment flow rate primarily depends on **initial flow rate** and **air opening width**

Theoretical Contributions

- Established **correlation equations** between airflow and flow field parameters
- Developed **mathematical models** for attached and free jet regions
- Validated **classical jet theory** in confined space of train compartments
- Identified **critical Reynolds number** threshold for flow field independence

Design Optimization

Informs ventilation system design for high-speed trains

Energy Efficiency

Enhances energy savings through optimized VAV control

Thermal Comfort

Improves passenger comfort through better air distribution

This study provides a theoretical foundation for intelligent ventilation control systems, bridging the gap between fixed-volume design and actual variable operating conditions in high-speed trains.

Research Perspectives

Study Limitations

- Focused on **isothermal conditions** **o**nly
- Limited to **numerical simulations** without experimental validation
- Simplified **passenger model** without thermal effects
- Excluded **dynamic environmental factors** during train operation

Future Research Directions

→ **Investigate** non-isothermal conditions and thermal effects

→ Develop **experimental validation** of numerical findings

→ Study **contaminant dispersion**under VAV systems

→ Create **intelligent control algorithms** based on flow field characteristics

System Design

Optimized ventilation structures based on flow field patterns

Smart Control

Adaptive VAV control responding to real-time flow field changes

Machine Learning

Predictive models for thermal comfort and energy efficiency

This research provides a foundation for developing next-generation ventilation systems that can dynamically adapt to changing conditions while maintaining optimal thermal comfort and energy efficiency in high-speed trains.