Benchmark Test for Human Respiratory Airflow: Vortex Dynamics and Boundary Condition Validation

by

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Introduction

The past COVID-19 pandemic has highlighted the need for accurate Computational Fluid Dynamics (CFD) modeling of human exhalation processes (Xu et al., 2022). While violent respiratory activities like coughing and sneezing were traditionally considered higher-risk transmission events (Bourouiba et al., 2014; Dudalski et al., 2020), normal activities such as speaking and breathing may pose equal or greater risks due to their high frequency and production of long-lasting airborne droplets (Morawska et al., 2009; Mao et al., 2020).

Current CFD simulations suffer from limitations in boundary condition specification. Most studies use simplified constant velocity or sinusoidal functions, with few implementing actual human exhalation profiles (Faleiros et al., 2022). This benchmark investigates whether simplified boundary conditions using constant parameters (such as bulk velocity and injection time) can replace complex time-varying velocity profiles without sacrificing accuracy.

Drawing from the analogy between exhalation flows and impulsive jets, two distinct flow regimes were also discovered (Figure 1): Regime A (shorter formation time with rapid vortex ring breakdown) and Regime B (longer formation time with trailing jet and vortex shedding) (Xu et al., 2025). The benchmark also evaluates advanced CFD methods, particularly LES and other high-fidelity turbulence modeling approaches, to capture complex vortex dynamics in human exhalation flows.

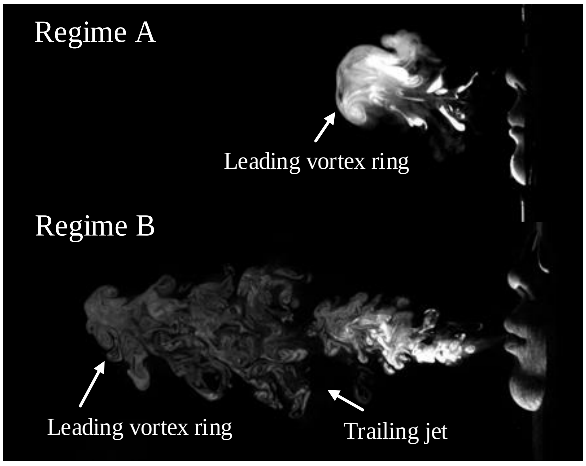

Figure 1. Two distinct regimes: A (pronouncing /ə/ with leading vortex ring) and B (normal expiration with leading vortex ring and trailing jets).

The benchmark seeks to bridge the gap between experimental observations and practical CFD modeling, providing validated tools for studying airborne disease transmission during normal respiratory activities.

Experimental Characterization of Turbulent Vocalization Flow

Experimental method

The benchmark test data originates from experimental studies using two complementary flow analysis methods: smoke visualization for flow shape and propagation characteristics, and PIV for quantitative velocity distribution and turbulence features. The experimental setup (Figure 2) consisted of a semi-enclosed transparent plastic box (484 × 484 × 500 mm) with a small round hole (diameter 0.12 m) for subject exhalation. The 2D PIV system included a high-speed camera (Phantom VEO640, 500 Hz) and 13 W continuous laser. Six healthy young adult subjects participated under controlled conditions (22 ± 1°C, 40-55% humidity, 2 h^{-1} air change rate). Ten phonemes were tested: vowels (/ɑ/, /i/, /ə/), fricatives (/v/, /θ/), affricatives (/dʒ/, /tʃ/), plosives (/b/, /t/), nasal (/m/), plus normal expiration. More details of the experiment setup can be found in Xu et al. (2025).

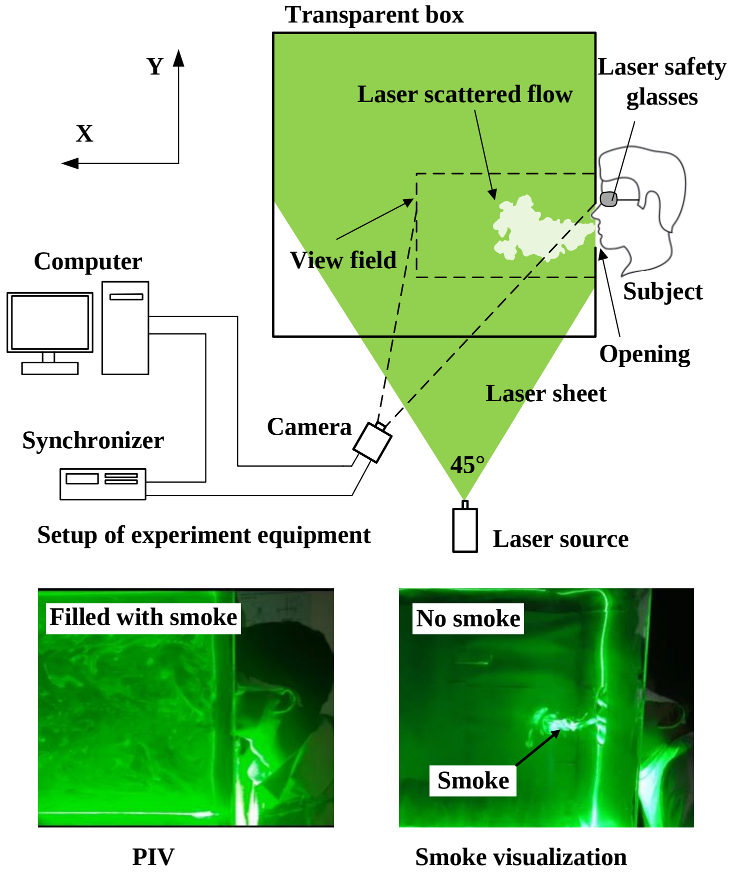

Figure 2. Experimental setup for PIV measurement and smoke visualization.

Key experimental findings

Analogous to impulsive jets (Gharib et al., 1998), the bulk velocity U_b is defined as the average of instantaneous exit velocity $u(t)$ from the mouth or nose:

$$U_b = \frac{1}{t_{inj}} \int_0^{t_{inj}} u(t) \mathrm{d}t \tag{1}$$

The formation time t^* and the maximum formation time t^*_{inj} is defined as:

$$t^* = \frac{U_b t}{D} \tag{2}$$

$$t^*_{inj} = \frac{U_b t_{inj}}{D} \tag{3}$$

where, D is the hydraulic diameter of mouth or nose opening.

When fluid discharge stops at t_{inj} (injection duration), t^* reaches its maximum for starting jet, termed the maximum injection formation time t^*_{inj}.

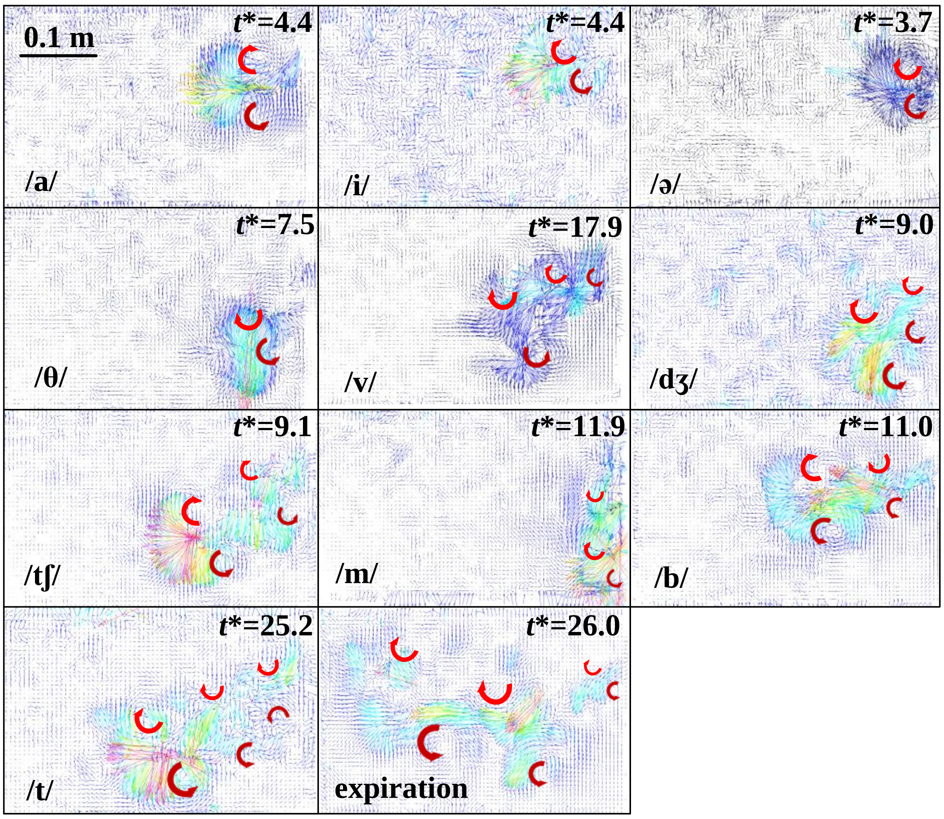

Figure 3. Vortex structure of all phonemes at the interrupted jet phase (the phase after the exhalation injection stops).

According to the impulsive jet theory, there exists a formation number, a dimensionless parameter indicating when a vortex ring reaches maximum circulation and begins shedding a series of smaller trailing vortex rings (Rosenfeld et al., 1998). Based on the relationship between t^*_{inj} and the formation number Fn, the exhaled flow exhibits two distinct vortex structures as a piston jet (Gharib et al., 1998). As shown in Figure 3, affricates, plosives, nasal sounds, and expiration consistently display trailing jets, indicating their t^*_{inj} exceeds Fn. Conversely, vowels and fricative /θ/ exhibit only leading vortex rings with minimal trailing jets, suggesting their

t^*_{inj} is below Fn. Figure 3 reveals a structural transition from /θ/ to /dʒ/: /θ/ forms single vortex rings while /dʒ/ develops trailing jets, indicating Fn lies between their t^*_{inj} values. Further analysis of the vorticity evolution of leading vortex ring over t^* reveals that in respiratory flows, formation numbers ranging from 5.5 to 9.0 correspond to a critical vorticity of around 70 s^{-1} (Xu et al., 2025).

Two flow regimes identified through experiments

Based on image and video observations (https://doi.org/10.1016/j.scs.2025.106340) and above theoretical analysis, two flow regimes are found during vocalization (Figure 1):

- Regime A (shorter formation time, $t^*_{inj} < \mathrm{Fn}$): Leading vortex ring formation → evolution and breakdown → turbulent diffusion and dissipation
- Regime B (longer formation time, $t^*_{inj} > \mathrm{Fn}$): Leading vortex ring formation → trailing jet with vortex shedding → vortex evolution and breakdown → turbulent diffusion and dissipation

Problem Definition

Observations show that flow regime type is determined by the relationship between t^*_{inj} and Fn rather than specific temporal velocity variations $u(t)$. This finding suggests potential for computational simplification, as t^*_{inj} depends on bulk parameters (U_b, t_{inj}, and D) instead of detailed time-varying profiles. Meanwhile, present RANS-based studies may not efficiently estimate exhalation propagation distances and cannot capture transient vortex evolution due to time-averaging of flows. To address these computational challenges and advance respiratory flow modeling, two benchmark problems are proposed:

1. Can simplified boundary conditions (U_b and t_{inj}) replace $u(t)$?
2. Can LES or other numerical methods simulate both vortex flow states of exhalation (Regimes A and B)?

Numerical Methods and Boundary Conditions

To validate these two questions, we provide data from real human subjects for boundary condition setup, including injection times, mouth scales, flow directions, velocities, Reynolds numbers, and dimensionless time parameters. The following requirements are proposed for the simulations:

CFD Code

- Employ CFD models with both simplified boundary conditions (constant U_b and t_{inj}) and transient velocity $u(t)$ boundary conditions for comparative analysis
- Implement high-fidelity numerical methods such as Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS) to accurately capture transient vortex structure evolution
- Ensure the code has capabilities for handling unsteady boundary conditions and complex geometries

- Utilize second-order or higher spatial and temporal discretization schemes for improved accuracy

Grid

- Generate sufficiently fine mesh resolution to capture vortex ring formation and evolution details, particularly near the mouth exit region
- Ensure y+ values satisfy turbulence model requirements
- Conduct grid independence studies to validate mesh adequacy

Computer Simulated Person and Mouth Structure

- Free
- Use the mouth scale through measurements

Quality of CFD Prediction

Comments should be made on the quality of the predictions as:

- Numerical method (RANS, LES or DNS)
- Boundary condition with transient velocity $u(t)$ or simplified boundary conditions (U_b and t_{inj})
- Discretization scheme order
- Turbulence model
- Grid quality should be considered and studied i.e. in terms of different grid sizes or distribution of y+ values

Results

It is convenient to report the simulation results at the following aspects and compare them with experimental results:

- Velocity decay over time for various speech intensities
- Propagation distance with time for different vocalizations
- Vortex ring formation, evolution patterns, and turbulent structures for different vocalization types if use LES or DNS

Measurement data

The measurement data from human subjects including test conditions, mouth scales, exhalation duration (injection times, t_{inj}), propagation directions, propagation distances, velocities (initial instantaneous velocity, peak velocity, bulk velocity), Reynolds numbers, and dimensionless time parameters (t^*_{inj}) can be downloaded in an Excel spreadsheet from https://www.en.build.aau.dk/web/cfd-benchmarks.

Literature and references

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