# A Novel Flow Tube with Wide Dynamic Range and Low Flow Rate Measurements Applicable for Spirometers and Breath Analysers

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## Abstract

**Chronic Obstructive Pulmonary Disease (COPD)** remains a major global health challenge and is currently the third leading cause of death worldwide. In 2019, an estimated 392 million individuals were living with COPD, contributing to over 3.5 million deaths annually.

Spirometry remains the standard method for assessing COPD. However, its high cost, limited portability, and dependence on clinical infrastructure restrict its accessibility, particularly in primary care settings. Moreover, recent evidence suggests that spirometry alone may not provide a comprehensive diagnosis of COPD, as factors such as smoking history can significantly influence lung function outcomes.

Quantifying exhaled biomarkers, including indicators of smoking exposure, prior to spirometry assessment could enhance diagnostic accuracy and interpretation.

We present *SPIROLUFT*, a novel diagnostic system centered on an innovative **Breath Flow Tube (BFT)** that unifies gas analysis and spirometry into one integrated measurement platform.

## Introduction

Chronic respiratory diseases such as COPD continue to pose major global health challenges, demanding diagnostic tools that are accurate, affordable, and suitable for frequent clinical use. Standard spirometry and breath gas analyzers often exist as separate systems, which increases equipment cost and complicates clinical workflows.

To overcome these limitations, this work introduces **an integrated approach** that combines airflow measurement and gas concentration sensing in a single compact unit. The system is designed to capture detailed respiratory characteristics such as airflow patterns, volume dynamics, and exhaled gas concentration within one synchronized measurement cycle. This integration allows clinicians to assess both mechanical and biochemical aspects of respiration, supporting improved evaluation of airway obstruction, smoking exposure (via CO levels), and overall lung health. The closed-loop gas analysis design further enhances response time and signal stability, offering a promising direction for next-generation COPD screening and respiratory monitoring systems.

## FlowTube Design

- **Architecture**: Perforated-orifice flow element integrated in a straight tube for low resistance and linear ΔP–Q response. Fig 1a and Fig 1b.
- **Perforation array**: 329 holes arranged on a circular plate.
- **Dimensions**: Hole diameter (Ø): 0.8–1.1 mm (graded set; manufacturing tolerance ±0.05 mm), tube inner diameter (ID) is 30 mm, and overall length is 120 mm.
- **Ports**: Pressure tap downstream (Ø ~4–5 mm) aligned to differential pressure sensor; electronics pod mount centered beneath.
- **Cleanability**: Smooth internal surfaces; no moving parts; compatible with alcohol wipes and disposable mouthpiece.
- **Intended flow range**: 0–16 L/s (meets ATS/ERS 2019 resistance target < 0.15 kPa·L⁻¹·s⁻¹).

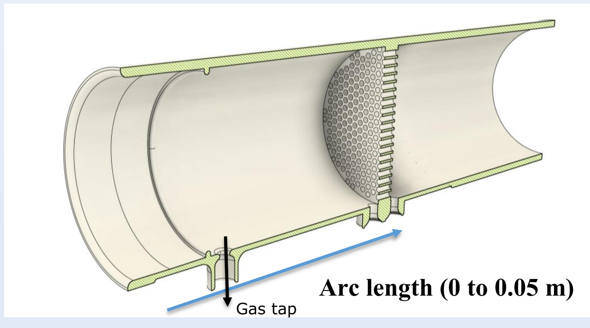



Figure (1a): Cross section of the perforated flow element integrated in the tube; electronics pod mount below; gas tap shown near inlet.

Figure (1b): Circular plate with 329 micro-orifices (Ø 0.8–1.1 mm) providing uniform flow conditioning and sensitive ΔP at low flows.

## Methodology

- The flow tube geometry was modeled and simulated using a CFD tool.
- Laminar flow analysis performed at 0.1 L/s (low-flow), 1 L/s (medium flow) and 14 L/s (high-flow) inlet velocities.
- Pressure and velocity profiles were computed along the central axis to evaluate tube performance.
- Experimental calibration and waveform validation conducted with *Hans-Rudolf series 1120 flow-volume simulator*.

## Fluid Dynamics Simulations Comparison

- 0.1 L/s simulation (fig 2a)
  - ✶ Velocity range: ~0 – 0.024 m/s.
  - ✶ Pressure drop: ~0.82 Pa.
  - ✶ Smooth, laminar regime.
- 1 L/s simulation (fig 2b)
  - ✶ Velocity range: ~0 – 0.84 m/s.
  - ✶ Pressure drop: ~26.64 Pa.
  - ✶ Showing good linearity with the 0.1 L/s case (≈ 0.82 Pa) nearly proportional to flowrate squared (as expected for laminar to transitional regime through small holes).
- 14 L/s simulation (fig 2c)
  - ✶ Velocity magnitude: peaks near 8 m/s, confirming expected flow acceleration.
  - ✶ Pressure drop: ~3253 Pa across tube length.
  - ✶ Flow remains stable with limited vortices, ensuring measurement consistency even at peak expiratory flow conditions.
  - ✶ Demonstrates device integrity and dynamic capability up to 16 L/s.

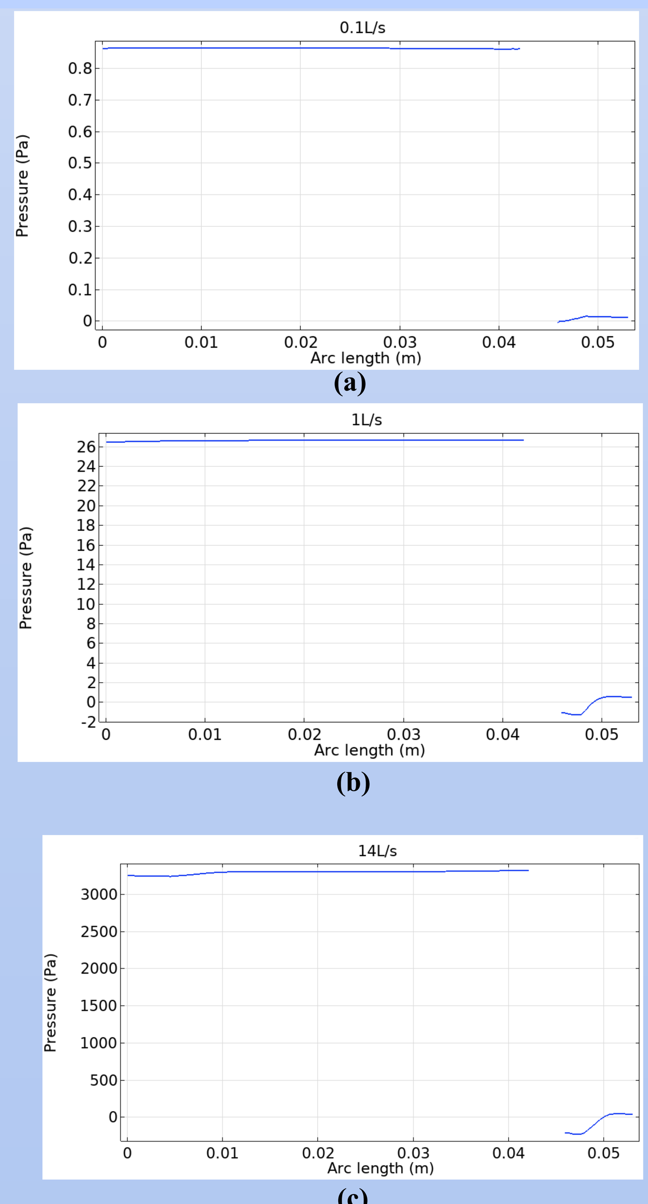



Figure (2): Pressure distribution from CFD simulations at (a) 0.1 L/s (b) 1 L/s [b], and (c) 14 L/s.

**Description and Analysis:**

- The table 1 compares measured pressure drops from the SPIROLUFT prototype with simulated CFD results across three flow regimes low (0.1 L/s), medium (1 L/s), and high (14 L/s).
- At low flow (0.1 L/s), results closely match, confirming excellent low-flow sensitivity and laminar stability.
- At 1 L/s, both datasets follow the expected quadratic ΔP–flow relationship, indicating predictable transitional behavior.
- At high flow (14 L/s), the CFD-predicted pressure drop is about 45% higher than experimental values, mainly due to idealized simulation conditions versus real-world factors such as minor turbulence damping, sensor averaging, and surface tolerances.
- Despite these differences, both results exhibit the same nonlinear ΔP ∝ Q² trend, validating the model's accuracy. The lower experimental pressure drop at high flow suggests reduced resistance, improving patient comfort—a desirable feature for clinical spirometry.

Table 1: Experimental vs. Simulated Pressure Drop Across Flow Rates

| Flowrate (L/sec) | Measured (Pa) | Simulated (Pa) |
|---|---|---|
| 0.1 | 1.0 | 0.82 |
| 1.0 | 18.40 | 26.40 |
| 14 | 1773.0 | 3253 |

## Integrated approach

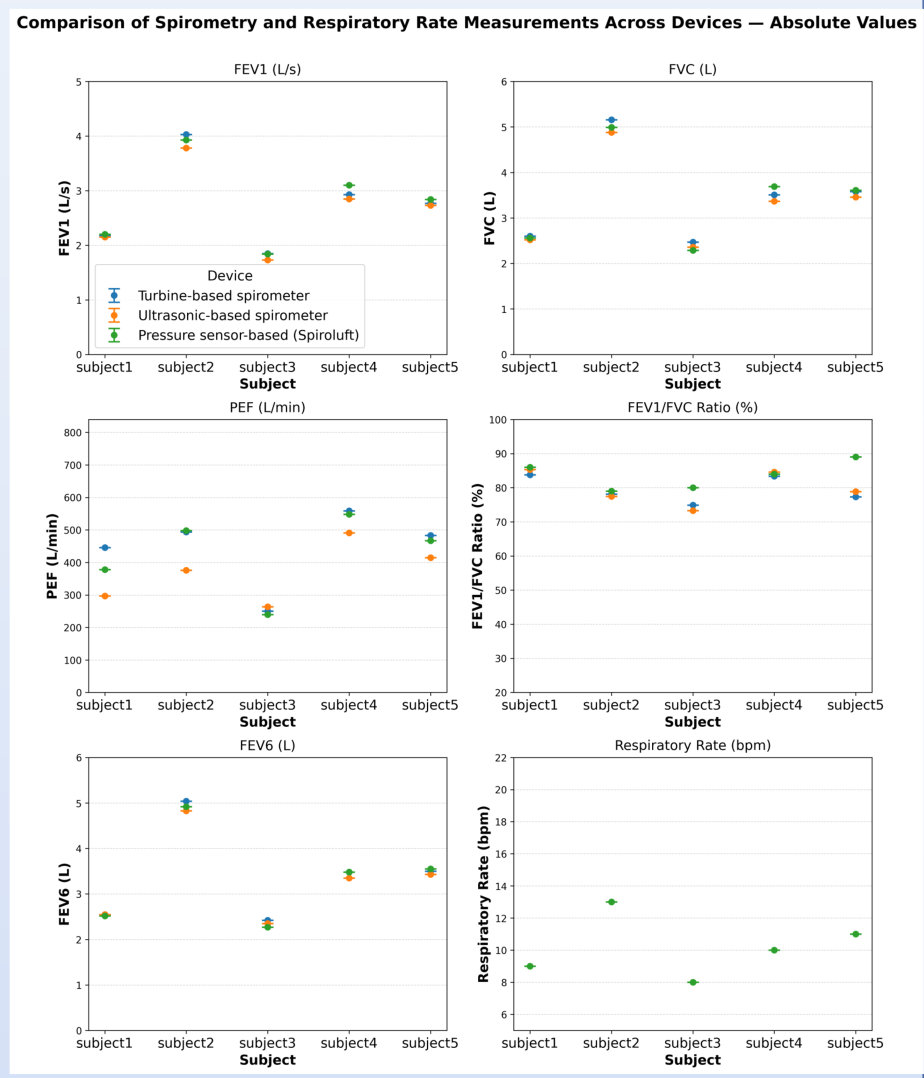
- To realize an integrated approach of measurement, a custom gas sensing module was designed to evaluate the sensor's response dynamics under open-loop and closed-loop configurations. A gas tap was designed to access the exhaled gas as shown in figure 1a.
- In an open-loop design, gas flows through the chamber once and is vented, causing slower stabilization due to dilution, whereas in a closed-loop design, gas recirculates within the chamber, allowing rapid concentration equilibrium.
- Experimental observations show that the closed-loop configuration reached steady-state CO concentration significantly faster than the open-loop setup.
- This improvement demonstrates the closed-loop design's superior response time, repeatability, and efficiency for real-time gas sensing applications integrated with the SPIROLUFT system.
- Both configurations confirmed reliable sensor performance and compatible with our **BFT.**

## Results

Spirometry measurements obtained from the Spiroluft pressure-sensor device were compared against a turbine-based spirometer and an ultrasonic spirometer across five subjects. The parameters evaluated included $FEV_1$ (L/s),FVC (L), PEF (L/min), $FEV_1$/FVC ratio (%), $FEV_6$ (L), and respiratory rate (bpm).

### Spirometry:

- $FEV_1$ and FVC values from Spiroluft closely matched reference devices with minor variation (<5%), confirming the accuracy of pressure-based flow estimation.
- Peak flow measurements were consistent, with slightly lower peak values observed for Spiroluft, attributed to smoother low-resistance flow dynamics inherent to its perforated-orifice design.
- The $FEV_1$/FVC ratio exhibited linear reproducibility across all devices, underscoring the Spiroluft system's ability to capture proportional volume dynamics accurately.
- $FEV_6$ values showed negligible variance, reaffirming Spiroluft's capability to handle full exhalation profiles.
- Respiratory rate derived from Spiroluft's continuous pressure waveform correlated well with the manual count, validating its utility for real-time breathing pattern analysis.



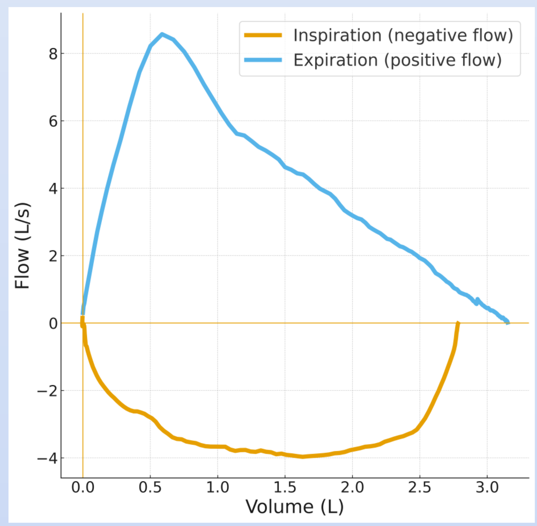




Figure (3): Flow-volume curve.

Figure (4): Comparison of spirometry and respiratory rate measurements with other commercial devices using different technologies shows that *SPIROLUFT* delivers comparable or superior performance, with the added advantage of integrated respiratory rate measurement.

### Gas Analysis:

- Analysis was performed according to ATS/ERS standard of constant flow of 45 -60 mlps
- Fractional exhaled carbon monoxide (FeCO) concentrations were measured using the Spiroluft breath analyzer for five human subjects.
- FeCO levels ranged between 2–5 ppm, consistent with values expected in non-smoking subjects.
- The 3 ppm calibration control was accurately reproduced, confirming precise sensor calibration and signal stability.
- Each subject's readings (mean ± SD) demonstrated high repeatability with minimal intra-subject variability.

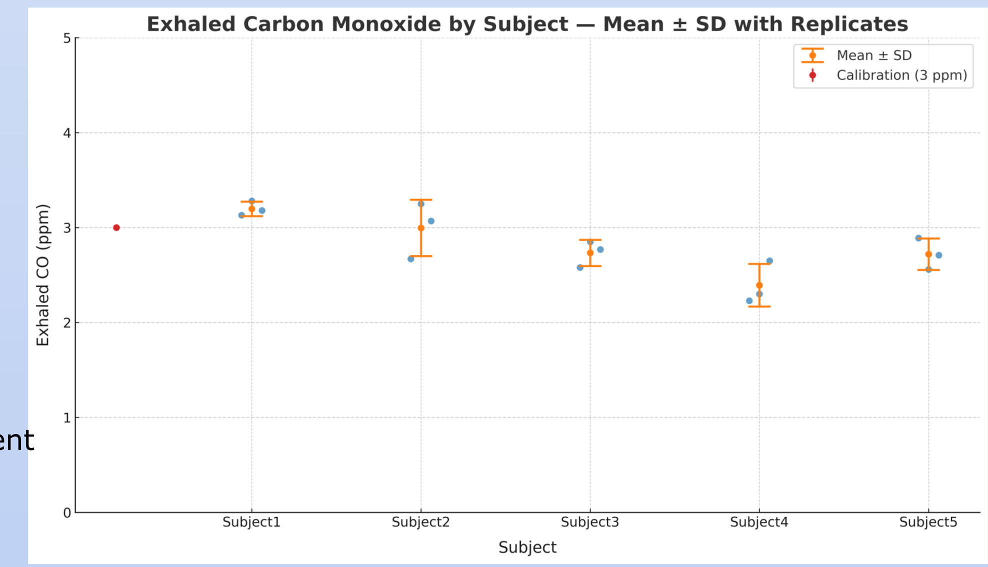



Figure (5): Exhaled CO levels for five subjects measured using the *SPIROLUFT* breath analyzer. Orange points show the mean ± SD for each subject; individual replicates are shown as dots. The red point indicates the 3 ppm calibration control performed using a standard 3 ppm gas bottle.

## Conclusion

- A novel dual-purpose flow tube was successfully developed for simultaneous spirometry and exhaled CO gas analysis.
- The design achieves low resistance (<0.15 kPa·L⁻¹·s⁻¹) and a linear flow response (0–16 L/s), fully compliant with ATS/ERS 2019 standards.
- High sensitivity at low flow rates (<0.1 L/s) and 100 Hz sampling enable precise, real-time respiratory monitoring.
- The closed-loop gas chamber provides faster rise time and better repeatability compared to open-loop configurations.
- Experimental results strongly correlate with CFD simulations, confirming design reliability and reproducibility.
- The system offers compact, biocompatible, and low-cost construction, suitable for clinical integration and mass manufacturing.
- This innovation enhances COPD detection, diagnostic accuracy, patient monitoring, and supports advanced pulmonary research.

Spiroluft

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