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Simultaneous Laser Doppler Velocimetry and stand-off Raman spectroscopy as a novel tool to assess flow characteristics of process streams

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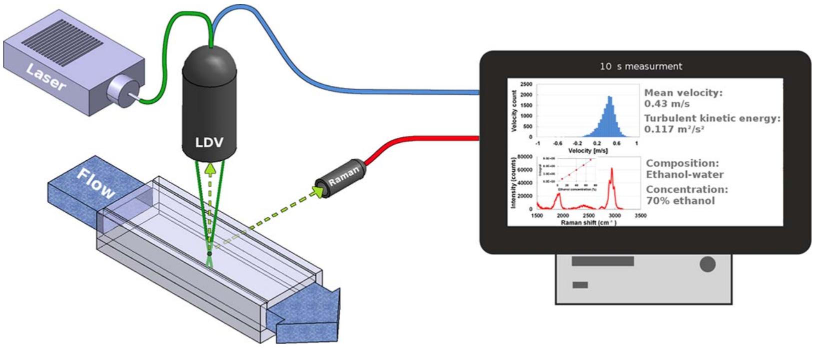
GRAPHICAL ABSTRACT



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ABSTRACT

Flow characteristics of process streams are important in industrial chemical plants. Online measurement of physical and chemical properties of such streams like velocity, turbulence, chemical composition, and concentration, plays a key role in adjustment and optimization of industrial processes. In transient processes with steep changes in the concentration and velocity (e.g. mixing of fluid with different viscosities or multiphase flows) it is important to monitor process parameters at the same time and position to be able to iterpret them correctly. In this work, a novel method for simultaneous measurement of velocity, composition, and concentration relying on two well-known methods, Laser Doppler Velocimetry (LDV) and Raman spectroscopy is presented and tested. Both techniques were combined using the same laser as light source, thus making sure sampling from exactly the same position at the same time is achieved. Experiments on mixing of water and ethanol streams in a custom-built T-junction geometry were performed using LDV to obtain velocity and Raman spectroscopy to measure concentration using the suggested method. Results are compared against Computational Fluid Dynamics (CFD) simulations using models for mixing of miscible, multi-species liquids at different flow regimes. CFD predicts turbulent diffusion to be the dominant phenomena in mixing in the T-junction since the turbulent diffusion coefficient ($\sim 0.02\,m^2/s$) is much higher than the molecular diffusion coefficient ($\sim 10^{-8}\,m^2/s$). A mean deviation of 8% between model and experiment for velocity and 10% for concentration evaluation was observed, which suggests the feasibility of this technique for simultaneous monitoring of process streams.

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1. Introduction

Process control and optimization are inseparable parts of every industrial process and plant. Regular measurements (e.g. online or offline at a suitable periodic schedule) of the actual status of the process to gain feedback from the system are common and necessary. As more information is provided, a better understanding of the process can be obtained, enabling a more efficient and economic process management. Usually, in process flow streams, velocity, velocity fluctuations (an indicator of mixing and turbulence), compositions and concentrations of key components are of utmost importance. Based on these properties it is possible to predict flow rates and process states. Furthermore, these properties can also be used for validation and calibration of different available models, e.g. the available models used in predictive process control or Computational Fluid Dynamics (CFD) [1].

There exists a variety of techniques for detecting chemical composition and measuring concentration in fluids, among which optical detection approaches are widely applied methods [2,3]. Different spectroscopic detection methods can be used for concentration and composition measurements, e.g. ultraviolet absorption (UV), thermal lens microscopy (TLM) and laser-induced fluorescence (LIF). In general, optical methods are capable of measuring chemical species without interfering with the flow [4]. Among these methods, LIF received special attention because of its accuracy and high sensitivity [5].

Funatani et al. [6] used a particle image velocimetry (PIV) system to measure the velocity field in the thermal flows and simultaneously used a two-color LIF to measure the temperature in a turbulent buoyant plume. Combining planar LIF (PLIF) and PIV, Charogiannis et al. [7] introduced a new method for investigation of hydrodynamic characteristics of thin liquid film flows. They added LIF to a PIV system to mask out particle reflections from raw images and in order to measure spatially and temporally resolved film thickness.

Although LIF as a detection technique is widely used, the main drawback is that usually, the components of the stream itself do not fluoresce and they need to be treated with either fluorescent particles or fluorescence tags, which requires extra effort and is expensive. Especially in multi-phase streams this is problematic, as different markers would be required, which have to follow the flow pattern of the original stream components.

Another well-established method for evaluation of chemical and structural properties of species is Raman spectroscopy. This technique is capable of analyzing non-fluorescent samples [5]. Park et al. [5] used confocal Raman microscopy (CRM) to study the mixing behavior in laminar micro-mixers and they compared the images from CRM to confocal fluorescence microscopy (CFM). Rinke et al. [8] utilized pulsed Raman imaging to analyze the concentration of two components (water and ethanol) at the outlet of a macro mixer. They compared their results with computational fluid dynamics simulations to show the validity of Raman imaging for measuring concentration profiles during a mixing. Beushausen et al. [9] combined two-dimensional molecular tagging velocimetry (2D-MTV) with planar spontaneous Raman scattering (PSRS) to investigate the velocity and concentration fields of water and ethanol in a micro-mixer. They also compared their results with standard μPIV. Wellhausen et al. [10] used a combination of PIV and Raman scattering to study the mixing in micro-mixers.

Among available velocity measurement techniques Laser Doppler Velocimetry (LDV) has received special attention because its capability of measuring instantaneous velocity without interfering with the flow, enabling accurate and reproducible measurements at different working conditions (e.g. high temperature) [11–13]. LDV is a direct measurement technique without the need of calibration: It measures the fluid stream velocity and velocity fluctuations based on the detection of scattered light by suitable seeding particles passing between two or more collimated, monochromatic and coherent laser beams [14].

Rottenkolber et al. [15] tried to combine the LDV with Phase Doppler Anemometry (PDA) to investigate the two-phase flow inside the spray of an SI-engine by adding fluorescent tracer particles to the gas phase. They managed to characterize time-resolved droplet motion and induced air flow. They also compared the results to the PIV. Quinzani et al. [16] combined LDV with Flow Induced Birefringence (FIB) to measure the stress and velocity fields of a viscoelastic solution through a planar abrupt contraction. Lemoine et al. [17] used a combination of LDV and LIF to measure the velocity and concentration in a turbulent submerged free jet and measured the average field of concentration, velocity, and local eddy diffusivity. Dibble et al. [18] did simultaneous LDV-Raman scattering velocity and scalars sampling in the turbulent flames. Using a LDV system with a two-color dual beam, real fringe system laser combined with a dye laser for Raman measurements, they also presented an analytical equation for generating unbiased velocity and scalar distributions using the data from seeding in only one stream. Moss [19] used LDV to study velocity in the open premixed turbulent flame and quantifying the scattered light he also analyzed the liquid concentration in the flame.

From these studies it was found that a combination of LDV and Raman spectroscopy could be capable of providing both velocity and composition of a process stream: LDV is suitable for higher measurement frequencies, which can provide the required turbulence data while Raman spectroscopy delivers composition and concentration information.

Using LDV and Raman spectroscopy integrated into one setup, information about the flow characteristics and the composition for the evaluation of a stream can be obtained at once. However, if these two methods are installed separately there is no guarantee that the process data provided is consistent and from the same fluid element at the same time – even if the focal points of the probes are aimed at the same position within the geometry. The authors believe that especially for more complex flows, including turbulent mixing or multiphase flows, this complicates the interpretation of the measured data and in some cases, may lead to misleading or even wrong results (e. g. considering the slip velocity of two non-mixing components inside a multiphase flow – if the velocity measurement is attributed to the wrong phase the overall evaluation will be degraded or flows with steep velocity or concentration gradients). Therefore, in this work we introduce a new method for combining these two technologies with the goal of obtaining information about the condition of the process at the same position and time. For simplicity, the first test setup for demonstrating the capability of the new approach was run with a single phase two component (water – ethanol) mixing system consisting of a T-junction.

CFD can provide a detailed spatial and temporal representation of the system. CFD is the numerical analysis of systems including fluid flow and related phenomena. CFD provides a powerful tool for having a detailed look inside dynamic streams, which are hard or impossible to experimentally evaluate or very expensive to analyze. Usually, it is used to further analyze phenomena inside a given geometry or optimize the process by adjusting parameters that are difficult to test in laboratories or pilot plants [20,21].

In this study, the T-junction measurement setup was simulated using well established CFD algorithms (e.g. transient simulation of multispecies fluids) and models (e.g. transitional turbulence model). The results of CFD simulations were compared to the measured velocities obtained with LDV and compositions obtained via Raman spectroscopy. Finding a reasonable agreement of the measured flow and concentration profiles with the simulated model supports the feasibility and suitability of the proposed method.

2. Theoretical background

2.1. Laser Doppler Velocimetry (LDV)

In the past, flow patterns were determined using dye injection into the fluid and observing dye streamlines [22]. This method was not applicable to very low and high velocity flows. In 1964 a new method