DOI 10.5162/sensor2015/D3.4

Multimode Laser Doppler Velocimeter for Flow Measurements in the Manifold of a Fuel Cell Stack

S. Burgmann[1], F. Schmieder[2], M. E. Kinaci[1], L. Büttner[2], J. Czarske[2]
[1]Zentrum für BrennstoffzellenTechnik GmbH (ZBT),
Carl-Benz-Straße 201, 47057 Duisburg, Germany,
s.burgmann@zbt-duisburg.de
[2] Technische Universität Dresden, Prof. für Mess- und Prüftechnik,
Helmholtzstr. 18, 01069 Dresden, Germany

Abstract:

Fuel cell stack performance strongly depends on the uniformity of the flow distribution over the fuel cells. Typically, numerical flow simulations are used to design the small flow geometries of a stack but experimental validation of the simulated flow is mostly lacking. To measure the flow distribution within these small geometries a specific Laser Doppler Velocimeter has been developed that uses light with low spatial coherence (multimode light) and fluorescent tracer particles. A spatial resolution of less than 100 µm even close to the wall is achieved. Comparing the measurement results of this MM-LDV-sensor with other experimental and numerical data revealed a very good agreement for a model configuration. Therefore, this tested and validated sensor was applied to the flow within the real geometry of a fuel cell stack manifold to gain a deeper knowledge of the flow configuration and to generate a benchmark for CFD-based fuel cell design.

Key words: Fuel cell stack, flow distribution, multimode laser-light, fluorescent tracers, MM-LDV-sensor

Scientific Problem

Fuels cells are currently entering the market in many technical areas complying different tasks such as uninterruptible power supply (UPS), power unit for mobile applications (emobility), combined heat and power plant (CHP) and portable power plant. Precisely spoken, these fuel cell power plants usually consist of several fuel cells that are electrically connected in series to achieve usable voltage and power. This configuration is called fuel cell stack. Since fuel cell stacks are fluidic systems (air or oxygen on the cathode side and hydrogen or reformate gas on the anode side) the gaseous educts have to transported through the stack. From a fluidic point of view, gases are passing the fuel cells inside the stack in a parallel configuration via small channels within the bipolar-plates of the anode and cathode, respectively. Therefore, the channels of the fuel cells are usually connected by a distributing and a collecting manifold (see Fig. 1). The educts have to be distributed homogeneously throughout the stack. Chang et al. [1] demonstrated for a 100-cell-stack that a misdistribution of 15 % at the cathode leads to a voltage drop of 50 % between the best and the worst cell. Since the weakest cell governs the overall fuel cell stack performance, misdistribution should be avoided. The individual mass flow rate of the cells inside the stack depends on the pressure distribution and is difficult to predict [2, 3, 4].

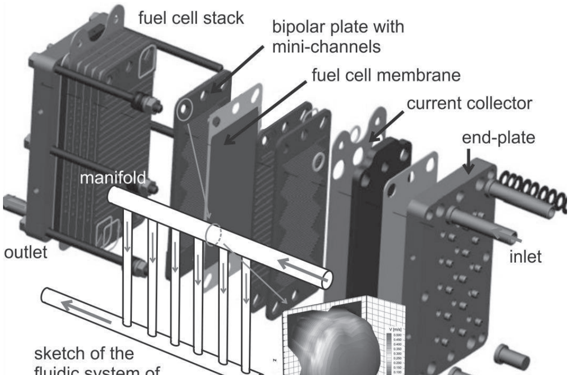

Fig. 1. Illustration of the configuration of a fuel cell stack showing the different components and the fluidic system of the manifolds and the fuel cell channels

Usually computational fluid mechanics (CFD) is used to design the flow structures of cells and manifold. As already demonstrated by several authors [5, 6], simulation of the flow inside a fuel cell stack strongly depends on type and spatial resolution of the numerical grid and the turbulence model. Experimental validation is lacking in most cases. Hence, the real flow distribution within the manifolds and the cells is usually not known, since measuring inside these small structures is difficult.

In the past, some authors investigated the flow inside the manifold of a scaled or abstracted fuel cell stack model by means of laser-optical measurement techniques such as Particle Image Velocimetry (PIV) [5, 6]. However, this technique requires relatively large optical access to the system which is why this technique has not been applied to real fuel cell stack geometries. The solution could be Laser Doppler Velocimetry (LDV). There is only one single publication on LDV-measurements in fuel cells [7]. Although LDV measurements leverage the advantage that only one single and small optical access to the system is needed, this work already shows the drawbacks and limits of LDV in small geometries. Since the measurement volume of a typical LDV-system is in the range of 1 mm only few data points with high signal-to-noise ratio can be gained.

Therefore, a measurement technique with a spatial resolution of less than 100 µm and high fidelity has to be developed that allows for in-situ measurements in fuel cell stacks. In this paper we present a new measurement system that fulfils these requirements, which is validated and successfully applied to the real geometry of a fuel cell stack.

Approach

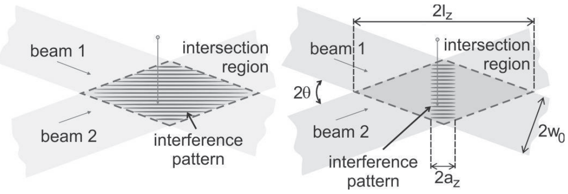

Fig. 2. Illustration of the interference pattern of classical LDV (left) and LDV with multi-mode laser-light (right)

The applied measurement principle is based on the LDV-technique, which uses two intersecting coherent laser beams. The crossing-section of the beams forms the measurement volume where an interference pattern is generated. The interference fringes possess the distance *d*. A particle that passes this pattern leads to a temporal modulated intensity signal ("burst") with frequency f_D that can be detected by a photo diode. This frequency is directly proportional to the particle-velocity. Typically, due to the coherent laser light, the interference fringes appear within the whole intersecting region which has a size of approximately 1 mm. Using laser light with low spatial coherence, the extent of the interference pattern can be strongly reduced (see Fig. 2). The spatial coherence of the laser beams is governed by the light source and optical fiber that is used to couple light source and sensor-optics. Multi-mode light with low spatial coherence can be realized by choosing appropriate components such that the interference pattern only covers a small section in the center of the intersection region of the two laser beams (see Fig. 2). This region may only cover 1 % of the intersection region. The modulated intensity signal of passing particles can be only detected within this small region. The measurement principle of the Multi-mode-(MM)-LDV has been developed and previously presented in [8, 9]. Since now it has been improved and adopted to the specific parameters of the small geometries of a fuel cell stack manifold and the corresponding optical restrictions. The set-up of the developed sensor is depicted in fig. 3.

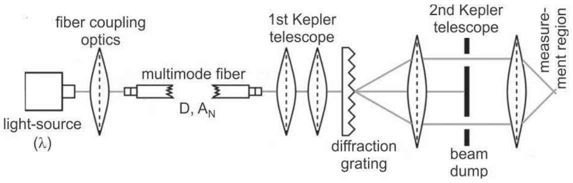

Fig. 3. Sketch of the multimode LDV set-up

In a first step the best parameters of the different components regarding low spatial resolution and high fidelity have been identified. Since the ratio ξ of intersection area length l_z and interference pattern length a_z depends on the beam quality factor M^2 parameters that influence M^2 have been tested. Combining a broad area laser diode (λ=635 nm) with a multimode optical fiber with a core diameter D of 50 µm and numerical aperture A_N of 0,22 a spatial resolution of 65 µm in air and 92 µm in water has been achieved. Minimum relative measurement uncertainty was detected to be $7 * 10^{-4}$. The sensor is designed to enable measurements in backward scatter mode [10]. Additionally, to be able to perform measurements close to walls the application of fluorescent particles has been analyzed. Reflections on the walls may hinder the detection of the intensity signal of particles. Since there is a small deviation between absorption and emission wavelength for fluorescent particles wall reflections can be suppressed by the use of optical filters. It has been shown that the typical offset due to reflections of the intensity signal can be reduced to zero. However, the degree of modulation of the intensity signal drops by approximately 20 % in the investigated case. Therefore, the quality of the optical access to the fluidic system has to be high in case of applying fluorescent particles [11].

Results and Discussion

In a first step to validate the sensor measurements have been performed in a model of the fluidic system of a fuel cell stack. This model consists of two Plexiglas-tubes of 7 mm diameter representing the manifolds that are connected by 32 small tubes of 1 mm diameter that resemble the fuel cell channels (compare sketch of the fluidic system in fig. 1). Two characteristic operating points of a real fuel cell stack are investigated that correspond to a stoichiometry of λ=2 leading to Reynolds numbers of Re_A=1500 and Re_B=3000. The first case represents a laminar flow and the latter one a turbulent flow. Considering fluid mechanical analogy measurements were performed in water, reason being simplification of the experiment. Velocity profiles at distinct points along the manifold tube are measured by MM-LDV by traversing the sensor perpendicular to the tube axis. To validate the MM-LDV measurements additionally Particle Image Velocimetry (PIV) is applied. In the model optical access is granted for this technique which is not given for the real fuel cell geometry. Planar velocity distribution in the center line of the manifold tube is measured by PIV which is transformed into local velocity profiles that can be directly compared with the results of the MM-LDV measurements. Fig. 4 illustrates the measurement performance with MM-LDV and PIV at the model system.

Additionally, CFD simulations are performed to compare experimental and numerical results and to quantify the reliability of numerical simulations of flow distribution for fuel cells.

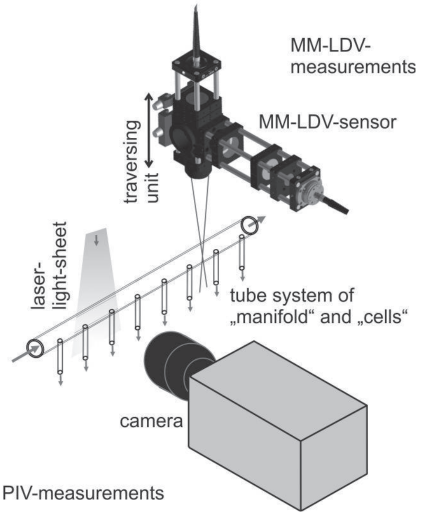

Fig. 4. MM-LDV and PIV measurements at the model system of the fuel cell stack

In fig. 5 results for the turbulent case (Re_B=3000) are shown. Velocity profiles at distinct locations along the axis of the model manifold are presented which are measured by MM-LDV and PIV, respectively and calculated by CFD based on two different turbulence models. The first one is the well known and often used *k-ε*-model. The second is the relatively new *k-ζ-f*-model which is a 4-equation turbulence model [12]. As can be seen the experimentally gained data agree very well except for the last case (position 32), which is at the and of the model manifold, where very low velocity appear and small differences between the measurement location (axial and lateral position) lead to strong deviations.

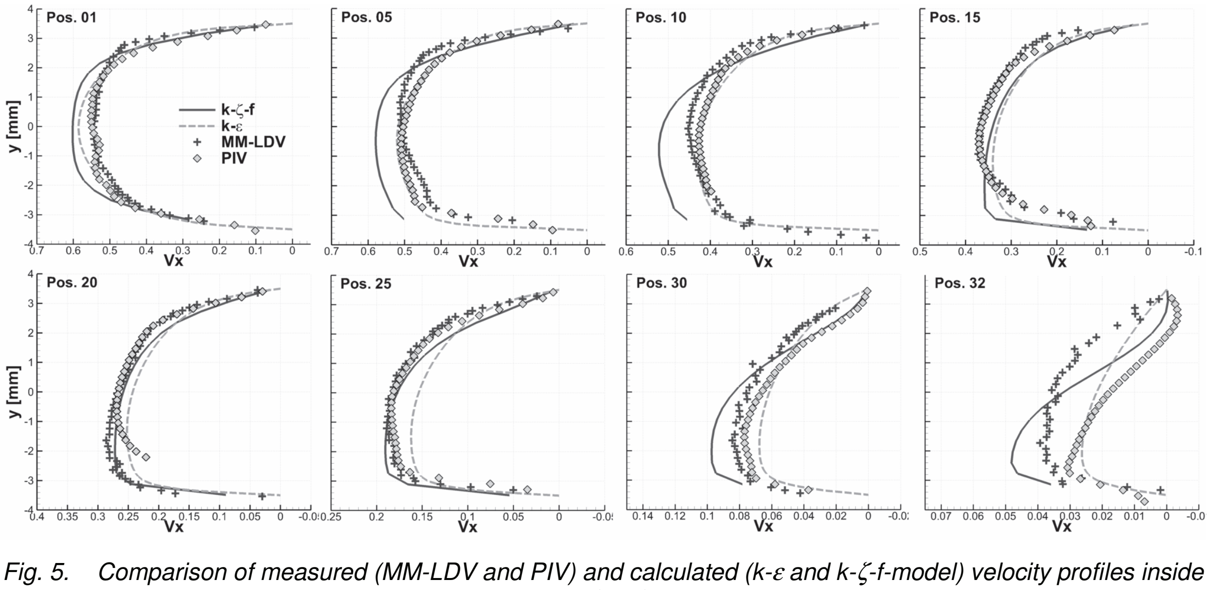

Fig. 5. Comparison of measured (MM-LDV and PIV) and calculated (k-ε and k-ζ-f-model) velocity profiles inside the model manifold for Re_B=3000

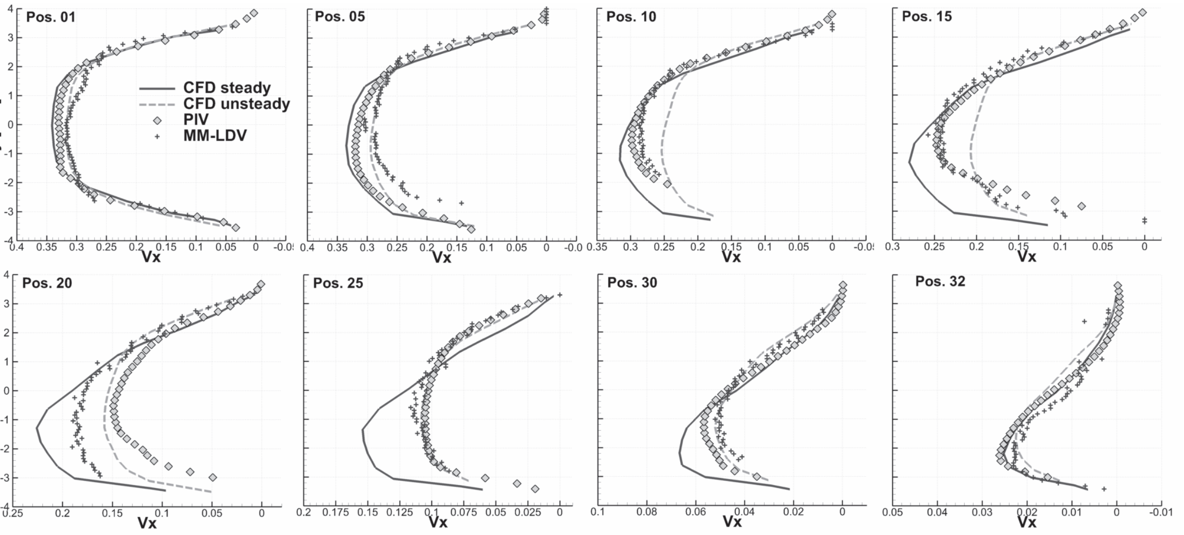

Fig. 6. Comparison of measured (MM-LDV and PIV) and calculated (steady simulation and temporal mean of unsteady simulation) velocity profiles inside the model manifold for Re_A=1500

On the other hand, for the turbulent case depicted in fig. 5 CFD results differ from experimental data. Obviously, in the inlet region of the model manifold the *k-ε*-model obtains more realistic results whereas in the end region *k-ζ-f*-model fits better. Another interesting finding can be gained from the analysis of the laminar case. PIV measurements showed strong unsteady flow phenomena at the rear end of the model manifold (vortices are passing by). Therefore, CFD-simulations have been performed in two ways: in a steady case and in an unsteady case (time step Δt= 10 µs, 10000 time steps). In the latter case the temporal mean of all time steps has been taken into account. Fig. 6 again shows that the experimental results (MM-LDV and PIV) agree very well even for the laminar case (Re_A=1500). Additionally, the results reveal that in this specific case, the temporal mean of the very extensive unsteady calculation provides more realistic results at the rear end of the model manifold, where the unsteady effects are present.

The comparison presented in figs. 5 and 6 clearly proves the MM-LDV-sensor to be able to measure in small geometries with appropriate robustness and precision. Furthermore, the results clearly show that numerical simulation on the one hand strongly depends on grid and turbulence model and on the other hand large scale velocity fluctuations require extensive simulation efforts. An experimental validation of the simulation results is a must at least for a fluid mechanical problem like the distribution of fluid via a manifold.

At this point of the project the MM-LDV-technique has been validated for a model configuration with known boundary conditions. Therefore, this measurement technique has been applied to the real geometry of a fuel cell stack, where no additional experimental data (e.g. by PIV) is available. Fig. 7 shows the manufactured fuel cell stack model which resembles the real flow geometry of a stack. Optical access to the manifold of this stack is provided by intermediate plates that contain small windows. In total five measurement locations along the manifold axis are available.

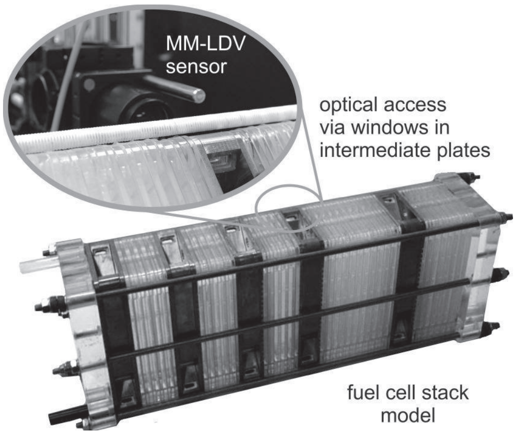

Fig. 7. Fuel cell stack model with real flow geometry and equipped with intermediate plates with windows to gain optical access for MM-LDV-measurements

In a first step again this fuel cell stack model is operated with water to simplify measurements. Fluid mechanical analogy again is considered. In this case only the turbulent case is investigated since unsteady CFD-simulations of the stack is beyond the limits concerning the available hardware. CFD simulations are again performed using the *k-ζ-f*-model. In order to save computation time the mini-channels inside the bipolar plates are replaced by porosities such that the number of grid points can be reduced. The Carman-Kozeny equation [13] is used to resemble the pressure drop of the mini-channels. However, the total stack geometry still requires more than 10 million grid points (see fig. 8).

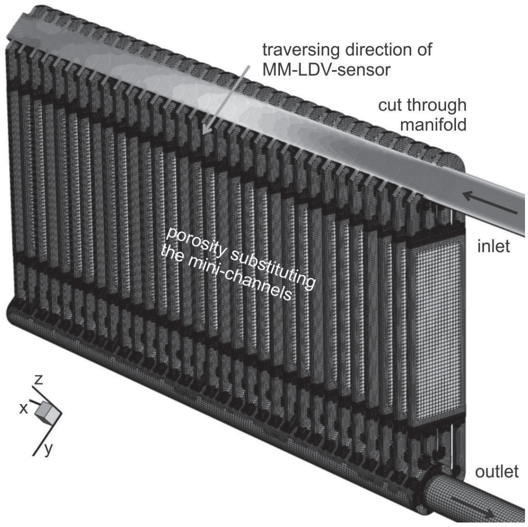

Fig. 8. Computational grid of the 32-cell fuel cell stack showing the velocity distribution in a cut through the inlet manifold and the porosities substituting the mini-channels of the individual cells

The flow inside the stack is simulated in all three dimensions. To compare the results with the measured MM-LDV-profiles a 2-D cut in direction of the measurement axis is selected from the CFD-results (see fig. 8). The comparison of the measured and calculated velocity profiles inside the real geometry of the fuel cell stack show sufficiently good agreement as can be deduced from fig. 9. It has been shown that the chosen configuration of small windows to provide optical access to the manifold flow is suitable for MM-LDV measurements.

In the next step not only the real geometry of the fuel cell stack is used but also the real fluid, i.e. air. Seeding the air with tracer particles is quite difficult for small flow geometries since the particles need to follow the flow precisely. Deviations of the flight path of the particles from the real streamlines of the flow may be in the same order of magnitude as the flow geometry if the particles are not small enough. On the other hand, the particles need to be large enough to generate a detectable intensity signal. Furthermore, for fuel cell applications the seeding particle material should not effect the electrochemical reaction inside the cell or should lead to deterioration. As analyzed and demonstrated in [14] and [15], seeding the flow with ethylene-glycol particles with a mean diameter of 1 µm and small diameter band width is applicable to the small geometries in operated fuel cells. Such a seeding is used in this work.

The comparison between MM-LDV measurements in air and water at the five window positions and k-ζ-f-model is presented in fig. 8 as normalized velocity profiles. Normalization is done by the relevant bulk velocity in each case ($v_{bulk,\ air}$ = 6.03 m/s, $v_{bulk,\ water}$ = 0.43 m/s). As can be seen, the MM-LDV measurement results agree very well. Deviations between the measurement results mainly stem from differences in the inflow conditions and difficulties in providing stable flow conditions during the measurements in water due to numerous interruptions for cleaning the tubing system.

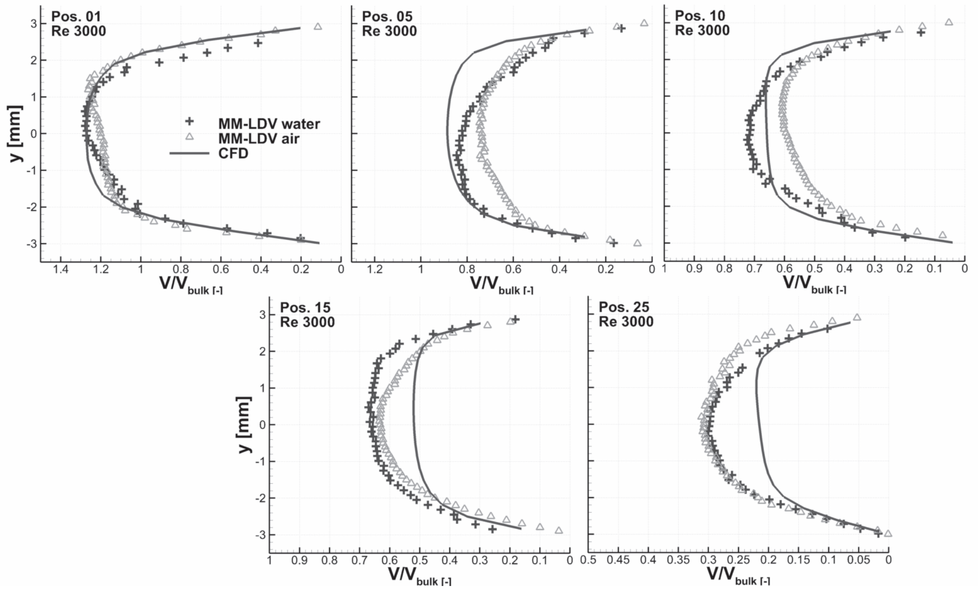

Fig. 9. Comparison of measured (MM-LDV) and calculated (k-z-f-model) velocity profiles inside the manifold of the fuel cell stack model for Re_B=3000 for measurements in water and air

In this work, it has been demonstrated that MM-LDV-measurements in water and air in small geometries are possible and can be performed with adequate accuracy. Furthermore, it has been shown that the spatial resolution of this measurement technique is sufficient to display the velocity profiles even very close to walls.

I.e., for the first time flow velocity measurements in air in real fuel cell stack geometry under realistic flow conditions have been successfully performed. It has been shown that experimental validation of CFD-results for flow distribution problems are essential since numerical simulation results strongly and unpredictably depend in (turbulence-) model and spatial grid resolution.

Outlook

As mentioned above the requirements for MM-LDV measurements in air in the manifold on the cathode side of a fuel cell stack are fulfilled regarding the seeding of the flow and the measurement robustness, spatial resolution and accuracy. Hence, in a next step measurements in the cathode manifold of an operated fuel cell stack will be performed. Based on the measurement results and accompanying CFD calculations the flow distribution in the manifold and the cells will be analyzed. In the future design changes of the manifold geometry can be deduced based on these findings that will lead to a homogeneous distribution of the reactants over the fuel cells of a stack without increasing pressure losses.

Acknowledgements

This research project (407 ZBG) has been funded by the AiF within the programme for sponsorship by Industrial Joint Research (IGF) of the German Federal Ministry of Economic Affairs and Energy based on an enactment of the German Parliament.

References

[1] P.A.C. Chang, J. St-Pierre, J. Stumper, B. Wetton, Flow distribution in proton exchange membrane fuel cell stacks, *Journal of Power Sources*, 162(1): 340-355 (2006)

[2] C.H. Chen, S.P. Jung, S.C. Yen, Flow distribution in the manifold of PEM fuel cell stack, *Journal of Power Sources*, 173: 249–263 (2007)

[3] R.J. Kee, P. Korada, K. Walters, M.A. Pavol, Generalized model of the flow distribution in channel networks of planar fuel cells, *Journal of Power Sources*, 109: 148-159 (2002)

[4] J.H. Koh, H.K. Seo, C.G. Lee, Y.S. Yoo, H.C. Lim, Pressure and flow distribution in internal gas manifolds of a fuel-cell stack, *Journal of Power Sources*, 115: 54–65 (2003)

[5] L. Grega, M. McGarry, M. Begum, B. Abruzzo, Flow Characterization of a Polymer Electronic Membrane Fuel Cell Manifold and Individual Cells Using Particle Image Velocimetry, *Journal of Fuel Cell Science and Technology*, 4: 272-279 (2007)

[6] J. Lebaek, M.B. Andreasen, H. Andresen, M. Bang, S.K. Kaer, Particle Image Velocimetry and Computational Fluid Dynamics Analysis of Fuel Cell Manifold, *Journal of Fuel Cell Science and Technology*, 7, 031001-1-031001-10 (2010)

[7] D.J.L. Brett, A.R. Kucernak, P. Aguiar, S.C. Atkins, N.P. Brandon, R. Clague, L.F. Cohen, G. Hinds, C. Kalyvas, G.J. Offer, B. Ladewig, R. Maher, A. Marquis, P. Shearing, N. Vasileiadis, V. Vesovic, What Happens Inside a Fuel Cell? Developing an Experimental Functional Map of Fuel Cell Performance *ChemPhysChem*, 11: 2714 – 273 (2010)

[8] L. Büttner, J. Czarske, A multimode-fibre laser-Doppler anemometer for highly spatially resolved velocity measurements using low-coherence light, Meas. Sci. Technol., 12: 1891-1903 (2001)

[9] L. Büttner, J. Czarske, Multimode fibre laser Doppler anemometer (LDA) with high spatial resolution for the investigation of boundary layers, Selected paper from the 11th Lisbon Symposium, Exp. Fluids, 36: 214-216 (2004)

[10] S. Burgmann, M. E. Kinaci, L. Feierabend, F. Schwarzer, J. König, L. Büttner, J. Czarske, „Laser-Doppler-Anemometer mit geringer örtlicher Kohärenz zur Strömungsmessung in kleinen Rohrleitungen am Beispiel eines Brennstoffzellen-Stapels,“ *GALA-meeting "Laser Methods in Flow Meaurement Techniques",* pp. 47.1-47.9, Sept. 03-05, 2013.

[11] F. Schmieder, S. Burgmann, M. E. Kinaci, L. Büttner, J. Czarske, „Optische Strömungsmessung im realen Manifold eines Brennstoffzellenstapels mit Hilfe eines Multimode-Laser-Doppler-Anemometers“, *GALA-meeting "Laser Methods in Flow Meaurement Techniques"*, pp. 30.1-30.1, Sept. 09-11, 2014

[12] K. Hanjalic, M. Popovac, M. Hadziabdic, A robust near-wall elliptic-relaxation eddy-viscosity turbulence model for CFD, *Int. J. Heat Fluid Flow*, 25: 1047–1051 (2004)

[13] P.C. Carman, Fluid flow through granular beds, *Transactions, Institution of Chemical Engineers*, London, 15: 150-166 (1937)

[14] S. Burgmann, N. van der Schoot, C. Asbach, J. Wartmann, R. Lindken, Analysis of tracer particle characteristics for µPIV in wall-bounded gas flows, *La Houille Blanche* 4: 55–61 (2011)

[15] S. Burgmann, M. Blank, O. Panchenko, J. Wartmann, µPIV measurements of two-phase flows of an operated direct methanol fuel cell, *Exp Fluids*, 54: 1513 (2013)