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NUMERICAL MODELING OF THE FLOW PAST AN AIRFOIL CHARACTERIZED BY A LAMINAR SEPARATION BUBBLE

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ABSTRACT

This paper discusses the RANS and URANS modeling possibility of a complex three-dimensional flow field forming around an airfoil which is characterized by the presence of a short laminar separation bubble on its suction side and a turbulent separation in the vicinity of the trailing edge. The wing section is placed in a confined computational domain that models the closed test section of a wind tunnel, or also can be interpreted as a duct. The flow is modeled by using the k-ω SST turbulence model with the γ-Re_Θ laminar/turbulent transition model that is supposed to be applicable for predicting laminar separation-induced transition which is of major importance in the present case.

1. INTRODUCTION

The investigation of the flow past airfoils is one of the basic topics of the research in fluid dynamics. The main operational area of airfoils is the aircraft industry where wings and other lifting surfaces are usually designed based on two-dimensional flow approaches [1], [2]. Also two-dimensional flow concept is applied for the development of blades used for turbomachinery applications, although most recently, the flow is modeled in 3D space. The flow field, however is becoming three-dimensional in all real circumstances. The origin of three-dimensionality is due to the finite extension of the blades, wing sections or the space in which they are operating. This influences both the operational characteristics and the determination of their theoretical "two-dimensional" aerodynamic characteristics. In case of low angle-of-attack situations, the two-dimensional approach acts as a very good approximation but for higher performances when high lift is needed, the angle-of-attack is increasing and the two-dimensional has to be handled with skepticism. The airfoil of the present investigation is an RAF 6 type low Reynolds number airfoil which was designed mainly for airscrews of old military aircraft and later it was used frequently as the airfoil of fan blades. The airfoil has a flat pressure side and a specially designed suction side that operates with the presence of a short laminar separation bubble which is generated via quick transition in curvature just downstream the leading edge. This laminar separation bubble increases lift and induces boundary layer transition from laminar to turbulence for maintaining attached flow until the trailing edge. The flow field was visualized experimentally and discussed in [6].

5. CONCLUSIONS

The executed examinations described in this work have shown that the numerical simulation is a good device for the planning and investigation of ventilation systems. Parameters, such as comfort and safety can also be examined by means of it. These parameters have been improved using the results of the simulations. A 3D simulation has been used only for the investigation of the ventilation system, because the modelling of the complete system would have been too expensive from the point of view of the computational effort. Numerous details of the analysis could not be followed without the 3-dimensional numerical simulation of the ventilation.

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2D-PIV MEASUREMENTS IN A TWO-PHASE WIND TUNNEL NORMAL TO THE MAIN FLOW

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1. INTRODUCTION

Particle Image Velocimetry (PIV) is an optical method to measure velocity and related quantities in fluids. Fundamental principles of the PIV method can be found in [1]. Here, different operation modes like Laser-Speckle-Mode or Particle-Tracking-Mode are also discussed. The current status and development of PIV is summarized by Adrian in [2].

There are different error sources influencing the velocity obtained by PIV measurements [3]. The correction of the velocity vectors deduced from two-dimensional PIV images is often discussed. We concentrate here on the errors affecting low-level transverse velocity components. Let us consider a simple case, when the system consists of planar surfaces with good optical access. For such a case correction with linear transformations has already been solved (e.g. in [4]) and is available in commercial software. In the work of Grant et al. [4] it can be seen that the correction is easier when the optical axis of the camera is normal to the light sheet. These authors use intercept theorems to convert every coordinate. Therefore, they employ the distance between the lens centre and the CCD-chip. But in many applications the camera has a significant angle compared to the light sheet, so that the spatial position is falsified because of the perspective view. As a consequence, Reeves and Lawson [5] used cross-correlation and a quadratic distortion mapping function to correct perspective errors of their single-lens system. They found that the single-lens system has significant in-plane-errors, caused by perspective effects. In the case of stereoscopic PIV with more than one camera, such a correction is indispensable [6, 7]. Scarano has published a dedicated review article [8] concerning iterative methods for processing PIV images. He recognized that several methods only differ in their implementations but are fundamentally similar. Nogueira et al. [9] presented post processing steps that can enhance PIV performance. These steps contain the detection of erroneous vectors as well as correction and calculation of derived flow magnitudes. They focused on the first spatial derivative, component of flow divergence and vorticity.

In the present paper 2D-PIV measurements of the disperse phase of a two-phase air/droplet flow are described. Velocity components normal to the main flow direction are measured by PIV in a two-phase wind-tunnel. The velocity components of the main flow are one order of magnitude larger than those of the transverse direction. It will be shown that a post processing of the PIV measurement data is needed and possible to obtain proper results.

2. EXPERIMENTAL SETUP

The aim of the measurements discussed here is to get the velocity components lying in the plane normal to the main flow direction in a two-phase wind tunnel, available in our laboratory (Fig. 1, left). It is a fully computer-controlled, Göttingen-type wind tunnel. Operation with closed test-section enables the investigation of two-phase (air/liquid) mixtures in the test-section (Fig. 1, right), with the following dimensions: (H×W×L): 500×600×1500 mm.

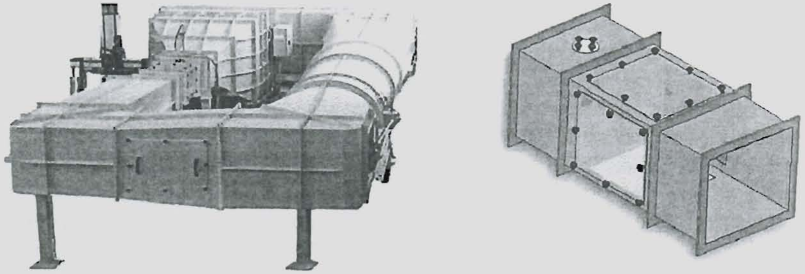

Fig. 1
Two-phase wind-tunnel (left) and
measurement section with optically transparent windows (right)

In the region of the measurement section, the walls of the closed test-section are optically transparent (450x500 mm) for standard laser wavelengths. Main flow velocity can be adjusted from 0.3 to over 50 m/s, with a precision of 0.03 m/s, limited by the electronic regulation. Turbulence intensity of the undisturbed air flow in the measurement section is below 0.5 %. The dispersed liquid phase can be injected with the help of a dedicated injection system. During the measurements discussed here, the flow velocity has been always set to 3 m/s. The flow is disturbed by the support of the water injection nozzle employed for spray injection, thus neither the velocity distribution in the main flow direction (*x*-direction) is homogeneous, nor can the *y*- and *z*-components of the flow velocity be neglected. Since most of the disturbances induced by the nozzle support are found in the upper half of the cross-section, measurements have been limited to the lower half of the measurement section.

To generate water droplets, a two-fluid atomizer has been used, with six orifices, each with a smallest cross-section of 1 mm. Mass flow rate ratio of water and air was

$$\frac{\dot{m}_w}{\dot{m}_a} = 2. \qquad (1)$$

The mean diameter (D_{10}) of the droplets was set around 12.5 μm. Preliminary velocity measurements have shown that the relative velocity of the droplets is minimal thanks to a favorable Stokes number [10]

$$\mathrm{Stk} = \frac{1}{18}\frac{\rho_d}{\rho}\left(\frac{d}{r_k}\right)^2 = 0.02 \qquad (2)$$

of the water droplets, where ρ_d and ρ are the density of the dispersed and continuous phases respectively, d is the droplet diameter and $r_K \sim 0.6$ mm is the Kolmogorov length scale of the turbulence.

Table 1
Components and properties of the PIV-system

Component / property	**Description**
Laser	Double-pulse Spectra Physics PIV-200
Laser energy @ wavelength	120 mJ @ 532 nm
Repetition rate	10 Hz
Beam transmission	High power Dantec light guiding arm with LaVision sheet optics (f=-20)
Camera	Double frame Dantec FlowSense 2M
Resolution	1600x1186 pixels @ 8 bit
Camera optics	1:2.8D 60mm AF Micro Nikkor
Wavelength filter	532 nm

The nozzle should be installed of course well before the measurement section, in order to reduce the influence of the injection system (wake of the cylindrical shape nozzle support). Position $x = 0$ (inlet of the measurement section) is 630 mm downstream of the nozzle. The selected nozzle has got a typical six-hole spray pattern because of the six orifices on the nozzle. The water is therefore injected in counter-flow direction. In this manner the droplets are more homogeneously distributed and the six-hole pattern is suppressed before the entrance of the measurement section.

The optically transparent windows make the non-intrusive PIV measurements possible. In this paper, we describe the specific procedure and post processing of the PIV measurements used to determine the transverse velocity component (perpendicular to the main flow direction). The water droplets themselves are used as PIV tracer particles. Accurate velocity measurements are difficult due to: 1) the relatively large angle between the camera axis and the normal of the measurement plane; 2) the low level of the transverse velocity compared to the main flow velocity. The angle α between camera axis and the normal of the laser sheet is 45° and is prescribed by the local configuration of the wind-tunnel. The light sheet is set perpendicular to the main flow direction. All PIV measurements have been carried out with the system described in Table 1. Calibration, evaluation and first results are presented in the next section.

3. CALIBRATION AND FIRST RESULTS

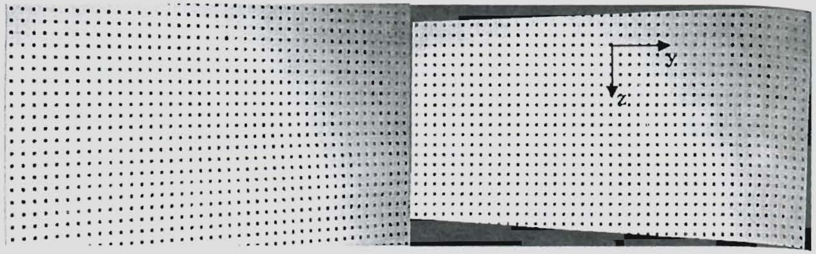

Fig. 2
Recorded calibration plate (left) and corrected camera image (right)

For the calibration, a large-area (450×250 mm) calibration plate with dot pattern (see Fig. 2 left) has been machined with a high precision and placed into the test section of the wind-tunnel. The diameter of the dots was 3 mm and the distance between the neighboring dots 11 mm. The origin was marked by a dot with a diameter of 4 mm. Positive and negative *y*- and *z*-directions were marked by four dots of 2 mm respectively in each direction. The plate has been aligned into the middle of plane *x*=0, so that its origin was 630 mm downstream of the nozzle, in 250 mm height and 300 mm from each side-wall. Calibration and dewarping of the camera image have been carried out by the Dantec Flow Manager software, where a direct linear transformation has been applied.

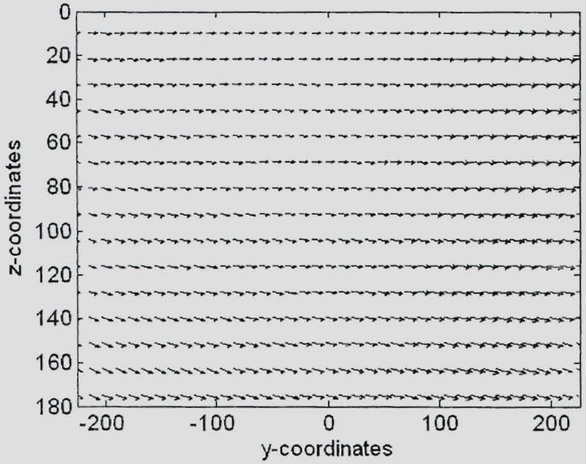

Fig. 3
Resulting vector map of the PIV-measurements;
average of 250 instantaneous vector fields

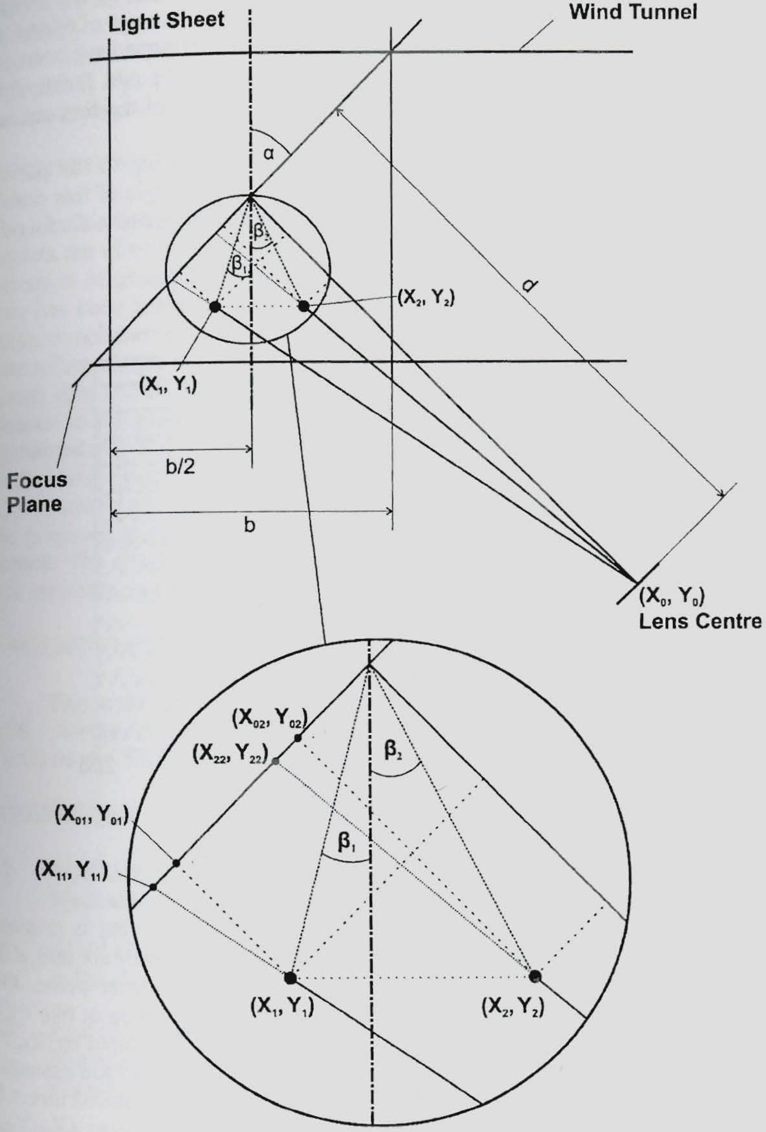

Fig. 4
Schematic drawing of the measurement setup

The recorded 4×250 double frame images have been first corrected (Fig. 2, right) with the Flow Manager software from Dantec Dynamics with the built-in dewarping tool. This correction should eliminate the error caused by the perspective view. Thereafter an adaptive correlation with an interrogation area of 64×64 and an overlap of 75% has been carried out. The resulting vector maps have been filtered by range validation of the vector components in a range of ±1 m/s. Finally 250 images of each set have been averaged and one of the results of the four sets can be seen in Fig. 3.

In Fig. 3 can be seen that all the vectors are showing to the positive *y*-direction, which does not correspond at all to reality. The origin of this problem, a proposed, simple correction procedure and the corresponding results are found next.

4. CORRECTION METHOD AND IMPROVED RESULTS

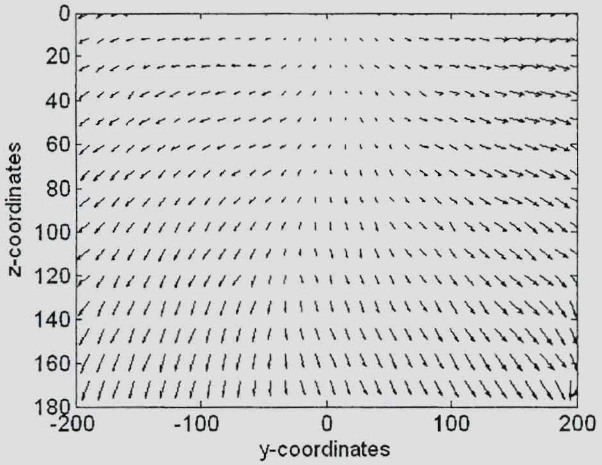

Fig. 5
Correction applied to the PIV vector map in Fig. 3

To understand the origin of this error, a schematic drawing is proposed in Fig. 4. $\alpha=45°$ is the angle between the sheet and the camera axis and d is the distance between the camera optics and the middle of the laser plane. On the bottom, the area of interest is magnified. A tracer particle location at two different time instants (corresponding to the 1st and 2nd PIV frame) is marked by X_1,Y_1 and X_2,Y_2 respectively. Though the marked tracer moves parallel with the channel axis, the resulting vector will have both, *x*- and *y*-components. The applied direct linear transformation corrects the perspective error, the distance between (X_{0i},Y_{0i}) and (X_{1i},Y_{1i}) respectively. The aim of the correction described here is to eliminate additionally the *y*-components in the example, as shown in Fig. 4. The proposed correction is to subtract the projection of the *x*-component of the velocity vector from (X_{01},Y_{01}) to (X_{02},Y_{02}) from the resulting velocity vectors. This means that complementary velocity information is needed for the main flow direction, which is available from Laser-Doppler Velocimetry (LDV) measurements. In a first step an elementary correction is applied by using the mean velocity values of LDV measurements in the main flow direction and the measured transversal velocities are corrected by a projection of the velocity component in the main flow direction. The corrected image can be seen in Fig. 5.

5. CONCLUSIONS

In this article, PIV measurements of water droplets have been presented. The droplets are directly used as tracer particles during the measurements. Despite the correction of perspective errors the first results did not correspond to reality. The error has been explained and a possible solution is proposed. This correction requires complementary measurements to get the velocity in the main flow direction. Here a first, simple correction is presented using only the mean axial flow velocity, though it is known that the velocity distribution in the main flow direction is not constant in the present case. Therefore, the results presented here should only be considered as a first step of the correction. Nevertheless, the resulting vector field is nearly symmetrical, as physically expected. The influence of the cylindrical nozzle support can be adequately observed in the upper region of the resulting vector field. The proposed correction will be validated in the future by comparison with another method. The obtained vertical components show already a very good coincidence with available measurements relying on Laser-Doppler Velocimetry.

6. ACKNOWLEDGEMENTS

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MODELLING OF FLOW AND DISPERSION IN A STREET CANYON WITH VEGETATION BY MEANS OF NUMERICAL SIMULATION

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ABSTRACT

In general, vegetation planting in urban areas brings about many benefits in air quality. This paper exclusively focuses on the effects of urban trees situated in a symmetric street canyon on the dispersion of passive pollutants exhausted by traffic. The calculations have been performed by the MISKAM code, which is mainly applied to the simulation of micro-scale dispersion processes. The investigated cases imply various vegetation densities at the oblique flow direction of 45° to the canyon axis. Qualitative and metric comparison of the results to wind tunnel measurements of Gromke and Ruck (2008) [7] show that MISKAM 6 predicts the effect of vegetation on the concentration field with a slight overestimation.

INTRODUCTION

The air quality in the urban area is mainly affected by the dispersion of traffic-induced pollutants, which is significantly influenced by the ambient buildings. Street sections flanked with buildings (street canyons) promote the accumulation of pollutants, since the air exchange is very restricted due to the isolation effect of the buildings to the airflow. In a wide range of approaching wind direction, the flow conditions inside the street canyon are governed by a dominant phenomenon, the canyon vortex. Numerous studies have fully dealt with the process of the pollutant dispersion and flow regime developed in a street canyon (see Vardoulakis et al., 2003 [12], Ahmad et al., 2005 [1]).

However, the urban vegetation is also regarded to a significant factor having effect on the airflow. The most extensive study on this topic is the wind tunnel experiment carried out by Gromke et al. (2008) [7], which comprises a street canyon of different aspect ratios. The vegetation was modelled by block-shaped canopies of different porosity, which are placed along the street axis forming an avenue-like planting. This experimental dataset (available also in the CODASC [3] online database) served as a basis of the numerical simulations, which have been performed using the MISKAM CFD code. A previous study for the wind perpendicular to the street axis was issued by Balczó et al. (2009) [2] concluding that the increase of the concentration level inside the street canyon due the vegetation was overestimated by 50% in MISKAM 5.02 simulations, although qualitative agreement was quite acceptable. The current paper focuses on the diagonal (45° to the street axis) wind direction as a general case, using the improved version 6 of the MISKAM model.