THE SCHOOL OF THE TURBULENT SWIRLING FLOW AT THE FACULTY OF MECHANICAL ENGINEERING UNIVERSITY OF BELGRADE

by

Miroslav H. BENIŠEK, Milan R. LEČIĆ, Djordje S. ČANTRAK**, and Dejan B. ILIĆ

Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia

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This review paper provides data about research activities at the School of the turbulent swirling flow at the Faculty of Mechanical Engineering, University of Belgrade, conducted in the period 1941 up to date. An overview is provided of the main directions in this research area. First papers dealt with the turbulent swirling flow in hydraulic turbines to be continued by the experimental and analytical approaches on the axial fans pressure side. The complexity of 3-D, non-homogeneous, anisotropic turbulent velocity fields required complex experimental and theoretical approach, associated with the complex numerical procedures. Analytical approaches, complex statistical analyses and experimental methods and afterwards CFD employed in the research are presented in this paper. The 150 scientific papers, numerous diploma works, several master of science (magister) theses, six Ph. D. theses and two in progress, 40 researchers, national and international projects are the facts about the School. Scientific references are chronologically presented. Numerous abstracts from scientific conferences, presentations, projects with industry and lectures are not given here.

Key words: *swirl, turbulent flow, mathematical modeling, hot-wire anemometry, particle image velocimetry, laser Doppler anemometry, computational fluid dynamics*

Introduction

The turbulent swirling flow phenomenon has captured the attention of the researchers worldwide for more than eight decades. There is a good reason for it, because phenomenology itself is the challenge for scientists dealing with the fluid mechanics. On the other hand, such flows occur in many areas of engineering, meteorology, biology, physics, etc. The researches lead to better understanding of the phenomena and their practical applications. The term *turbulent swirling flow* incorporates all flows which, observed in the cylindrical coordinate system (r, φ, z), have the circumferential velocity component (tangential velocity in the direction of coordinate φ). A special class of the turbulent swirling flow is generated as the result of superposition of the axial and circumferential flow. The main characteristic of these flows is that the flow parameters vary from point to point in the whole region.

* Corresponding author, e-mail: djcantrak@mas.bg.ac.rs

Many researchers of the School of the turbulent swirling flow at the Faculty of Mechanical Engineering, University of Belgrade (FME UB) carried on and contributed to the research of the turbulent swirling flows [1-150]. Vušković (1912-2005) published his first paper [1] in 1941, where he studied the problem of generation and stability of the vortex core in turbomachines, specifically behind the hydraulic turbine runners. Vušković continued his research and afterwards published paper [2], and Vušković and Velenšek [4].

Obradović (1900-1982) [3] discussed vortex hydrodynamic stability with constant circulation in the cylindrical pipes.

Determination of the *dead water* diameter behind the axial fan without guide vanes was done by Protić (1922-2010) [5]. Also, he was the first to introduce the idea of investigating the turbulent swirling flow behind the axial fan in the pipe. Further investigations are conducted at the Chair for hydraulic machinery and energy systems and at the Chair for fluid mechanics FME UB.

Experimental investigations of the turbulent swirling flow in the long lined straight pipes behind the axial fan without guide vanes started at the FME UB in 1972, when experimental test rig was built and measurement equipment was designed by Benišek. First results from this test rig were published in [6, 7, 9, 13].

Čantrak S. [19] was the first to commence investigations of turbulence at the FME UB and implemented turbulence statistics in the turbulent swirling flow.

These investigations are ongoing getting deeper into the turbulent swirling flow phenomenology. The defended theses and published papers are part of this review and are listed in references. Chronologically are presented almost all scientific papers, a number of master of science (magister) theses and six Ph. D. theses that belong to the School. Two Ph. D. theses in this field are in progress. Numerous diploma works were defended at the Chair for hydraulic machinery and energy systems and at the Chair for fluid mechanics FME UB in this field. Forty researchers from Serbia, and from abroad as well, are members of this School. National and international projects, numerous abstracts from scientific conferences, presentations, projects for industry and lectures are not listed herein due to the scope of the paper.

Swirl flow integral parameters

The first period of investigation is characterized by the design of the test rig for experimental investigations of the turbulent swirling flow behind the axial fans - first design. It was built using adequate experimental apparatus – original probes, described in Benišek [6, 7, 13] and Benišek *et al.* [115] at the Laboratory for hydraulic machinery and fluid mechanics FME UB.

A number of axial and circumferential velocity profiles, as well as pressures for various Reynolds and swirl number values were measured behind the axial fan impeller along the straight pipe. Stable profile of the circumferential velocity was determined, as well as energy loss coefficients. In addition, there are theoretically determined distributions and variations of the circulation along the pipe. The procedure for determination of the turbulent stresses was defined. Also, an algebraic model was made for calculation of the pressure and velocity profiles along the pipe. Results of calculation are compared with the experimental ones in Benišek [6, 7, 9, 13, 18, 25, 28], Benišek *et al.* [15, 16, 34, 39, 50, 51, 53, 60, 70, 75, 76, 79, 80, 86, 88, 93, 94, 98, 99, 102, 115], Protić *et al.* [14, 20, 31, 38, 45, 77, 114], Čantrak S. [19, 21, 26, 33, 37, 48, 68, 81, 101], Čantrak S. *et al.* [24, 27, 30, 35, 36, 49, 54, 62, 63, 67, 78, 85, 87], Lečić [97], Lečić *et al.* [64, 104], Vukašinović [72], Vukašinović *et al.* [61, 69], Belošević *et al.* [82], Glavčić *et al.* [89, 96], and Stevanović *et al.* [105].

The turbulent swirling flow behind the hydraulic turbine runners in conical diffusers due to its influence on the turbine efficiency and vortex core instability presents a special challenge for researchers. Vušković was the first researcher from the School of the turbulent swirling flow at the FME UB to publish papers on this topic [1, 2, 4]. Protić built the test chamber and test rig for axial fans, where the measurements in the conical diffusers have been performed. Further experiments are conducted on this installation and results and analyses are presented in papers [4, 8, 10, 42-45, 50, 51, 65, 66, 84, 91, 102, 116, 137]. These papers present the designed and built test rig, measurements of the axial and circumferential velocities as well as the pressure profiles in the cross-sections along the conical diffuser for various Reynolds numbers and swirl flow parameters. Total energy losses along the conical diffuser are determined. An algebraic model for calculation of the flow and energy parameters for diffusers of various angles is defined. Results of calculation are compared with those experimentally obtained.

Turbulence statistics

Theoretical and experimental investigations of the turbulence characteristics of the turbulent swirl flow in the straight pipe and conical diffusers started in 1979 by Čantrak S. on the test rig built at Technical University Karlsruhe, Institute of Fluid Mechanics and Fluid Machinery, Karlsruhe, Germany [17, 19, 21, 22, 23]. Čantrak S. initiated turbulence research at the FME UB [24, 26, 27, 29, 30, 32, 33, 35-37, 41, 46-49, 52, 54, 56-59, 61-64, 67-69, 71-74, 78, 81, 83, 85, 87, 89, 90, 92, 94, 95, 96, 100, 101, 103, 124, 129, 132, 143, 144, 149]. Čantrak S. dealt with turbulence statistics in the turbulent swirling flows in the pipes and diffusers, as well as the intermittency problems and turbulence anisotropy. Higher order statistical moments were experimentally determined for the first time by the use of hot-wire anemometry (HWA) triple sensor probe and turbulence correlation theory. He discovered complex structures and non-local turbulent transfer and processes of non-gradient turbulent diffusion in the turbulent swirling flows in the pipes and diffusers. A bimodal structure of the turbulence transfer was revealed. A new turbulence algebraic model is presented in these researches. Vukašinović modelled the non-local turbulence transfer in the turbulent swirling flow in the straight pipe on the basis of Čantrak S.'s experimental results [61, 69, 72]. Correction of the generalized gradient model was performed. It was shown that turbulence model, defined in this way, points out an important role of the central moments of the third order in the processes of non-local turbulence transfer. Non-local turbulent transfer and non-gradient turbulent diffusion play a key role in the research of the turbulent swirl flow in diffusers.

It was shown that the regions of non-local turbulent transfer are correlated with the domains of the negative production of the kinetic turbulence energy and negative values of the turbulent transfer, and consequently components of the tensor of the turbulent viscosity. It was shown that, due to the swirl action, non-homogenous anisotropy turbulence occurred. Distributions of the anisotropy tensor components for the turbulent swirling flow in the diffuser are analyzed. It is shown that swirl has crucial influence on the turbulence anisotropy.

Lečić continued experimental researches in the field of the turbulent swirling flow in the pipes using the VP-2vs HWA original probes with high temporal and spatial resolutions, designed by Vukoslavčević [97, 109, 110, 113, 123, 138, 144, 149]. Their specific geometry provided measurements in the turbulent swirling flow boundary layer, extremely close to the wall, as well as measurements of the axial and radial correlations. All these measurements demanded new experimental equipment that was developed – a new wind tunnel, precise positioners, etc. [97, 123, 138, 144, 149]. The original wind tunnel enabled calibration of the hot-wire anemometers. Calibration and measurement data processing was performed on the basis of the original algorithm [97, 109, 113, 138]. Piezoresistant probe, designed by Jankov (1940-2002) [97, 104, 112], enabled a new approach in the calibration of the hot-wire anemometers [113]. This calibration provides higher accuracy of velocity field measurements. Fluctuations, statistical moments, probability density functions and autocorrelations are calculated on the basis of the measured instantaneous axial and circumferential velocity fields. Calculations and analyses were also performed in the frequency domain and adequate spectral characteristics of the turbulent swirling flow in the straight pipe have been determined [97, 138]. Original mechanisms for the probes positioning allowed for the measurements of the spatial velocity correlations. These are the first results of spatial velocity correlation measurements in the scientific literature [97, 149]. Wall turbulence, spatial and spatial-time velocity correlations were determined. Calculated autocorrelation functions provided time integral scales and time micro-scales. Adequate spatial scales were approximately determined. It was also shown that distribution of the kinetic turbulence energy in circumferential direction, by the convective part of the axial velocity fluctuations, was mainly performed in the axial direction.

In the vortex core

Čantrak Dj. introduced stereo particle image velocimetry (SPIV) in his research in 2007 [106, 108, 114, 118, 119, 121, 122, 125, 126, 127, 128, 132, 133, 139, 141, 146, 147, 150]. He investigated the structure of turbulent swirl flow generated by the axial fan impellers in the pipe. Mathematical interpretation of the structural analysis of turbulence was presented using the correlation-spectral theory of turbulence. Experimental and theoretical considerations provided adequate physical interpretation of complex interactions between the average and fluctuating velocity fields that characterized the processes of turbulent transfer. The phenomenon of the vortex core precession and the statistical characteristics of the turbulent swirl flow in the straight pipe behind the axial fans are studied. The effects of Reynolds and swirl number, *i. e.* the effects of rotation speed and blade angle on the turbulence structure and turbulent transfer mechanism were also investigated in this research. Experimentally determined autocorrelation functions and turbulence integral scales, as well as obtained spectral functions of circumferential velocity fluctuations supplied additional pieces of information on turbulent structure physics. Three axial fan impellers were used in these experiments. The influence of the fan types on the skewnees and flatness, and the generation of the vorticity field and vortex core precession movement, are determined. Besides SPIV, this research also introduced a high speed SPIV (HSS PIV), as well as laser Doppler anemometry (LDA) – one- and two-components. Numerous experiments were carried out in the modified existing test rig at the FME UB and in the entire newly built experimental test rig in Karlsruhe Institute of Technology, Institute of Fluid Machinery (KIT IFM). Turbulent stresses were determined on the basis of the HSS PIV measurements what enabled the formation of anisotropy invariant maps for various fan blade angles for the first time in the scientific literature [125, 141].

Ilić [137] upgraded the test rig for the measurements in the conical diffusers, with two new diffusers, and studied turbulent swirling flow in three various diffuser geometries for various Reynolds and swirl numbers. He performed measurements with original classical probes [6, 13, 115, 137] and conducted research using one- and two-component LDA systems [137].

Ćoćić introduced CFD in the research of the turbulent swirling flow in the School of the Turbulent Swirling Flow [107, 135, 136, 143, 145]. He used OpenFOAM, an open-source CFD software for all computations, and implemented Reynolds stress models suitable for computations of swirling flows into the OpenFOAM code. He tested the models on axisymmetric computations of swirling flows in the pipe previously theoretically and experimentally investigated by Čantrak S. [19, 21], where good agreement with experimental results was found. He also performed URANS and hybrid LES/RANS calculations of swirling flow in the pipe behind the axial fan. For these computations a high quality block-structured grid was generated, and taking into account the geometry of the fan, k-omega SST and SST-SAS models were used. These computations were verified using experimental results [125]. Additionally, using the same numerical grid, computations with LES and dynamic Smagorinsky model were also performed in SPARC, an in-house code from the KIT IFM. These hybrid LES/RANS and LES computations gave additional insight into the dynamics of the vortex rope which is formed in the pipe axis region.

Conclusions

The year 2016 marked the 75th anniversary of the School of Turbulent Swirling Flow at the Faculty of Mechanical Engineering, University of Belgrade.

During that period, many great breakthroughs were made in the field of the turbulent swirling flow phenomenon, theoretical, experimental and numerical methods were developed. Test rigs were built at the FME UB and KIT IFM. Original anemometry and pressure probes were developed and manufactured, optical anemometry measurement techniques such as laser Doppler anemometry and particle image velocimetry were introduced and new calibration procedures were developed.

Some of the most important scientific results of the turbulent swirling flow investigations in the School of the Turbulent Swirling Flow at the FME UB include the following.

– Determination of:
- the *dead water* diameter behind the axial fan without guide vanes,
- stable profile of the circumferential velocity in the pipe,
- energy loss coefficients in the pipe,
- the algebraic model for calculating the pressure and velocity profiles along the pipe,
- theoretically established distributions and variations of the circulation along the pipe,
- the procedure for identifying the turbulent stresses,
- total energy losses along the conical diffuser,
- the algebraic model for calculating the flow and energy parameters for diffusers of various angles,
- complex structures and non-local turbulent transfer and processes of non-gradient turbulent diffusion in turbulent swirling flows in the pipes and diffusers,
- of the spectral characteristics of the turbulent swirling flow in the straight pipe,
- a bimodal structure of the turbulence transfer,
- a new turbulence algebraic model, and
- correction of the generalized gradient model is done.

– Presentation of:
- important role of non-local turbulent transfer and non-gradient turbulent diffusion in the research of the turbulent swirl flow in diffusers,
- non-homogenous anisotropy turbulence occurrence due to the swirl action, and

- swirl's crucial influence on the turbulence anisotropy.

– Measurements of:

- the first spatial velocity correlation done in the scientific literature, and
- wall turbulence in the high pipe wall vicinity.

Higher order statistical moments were for the first time experimentally investigated by use of HWA triple sensor probe and turbulence correlation theory.

Mathematical interpretation of the structural analysis of turbulence was presented using the correlation-spectral theory of turbulence.

Experimental and theoretical considerations provide adequate physical interpretation of complex interactions between the average and fluctuating velocity fields that characterize the processes of turbulent transfer.

– Studies of:

- the phenomenon of the vortex core precession phenomenon by implementing original procedures,
- the effects of Reynolds and swirl number, *i. e.* the effects of rotation speed and blade angle on turbulence structure and turbulent transfer mechanism,
- influences of the axial fan impellers geometry on the turbulent vortex core and turbulence structure and statistics,
- different behavior of generated turbulence structures in the pipe behind the axial fans,
- the solid body vortex significant transformation downstream, in contrast to the Rankine vortex.

– In addition:

- invariant maps are determined using data obtained by high-speed stereo PIV measurements,
- Reynolds stress models suitable for computations of turbulent swirling flows are successfully implemented into the OpenFOAM code,
- URANS and hybrid LES/RANS calculations of swirling flow in the pipe behind axial fan were also performed and verified using experimental results, and
- computations with LES and dynamic Smagorinsky model are also performed.

The latest researches are in progress, such as the turbulent swirling flow in the jet behind the axial fan and compressible flow in a vortex tube.

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