REVIEW OF THE RESEARCH ON THE TURBULENCE IN THE LABORATORY FOR THERMAL ENGINEERING AND ENERGY

by

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Paper gives a review of the most important results of turbulence research achieved by the Laboratory for Thermal Engineering and Energy at the Vinca Insitute of Nuclear Sciences. Paper presents detailed overview of the history of the scientific research provided in the laboratory, from the beginning in the mid-60s to today, pointing out the main reasons initiating the investigations in this field. After the first period, which was mainly devoted to the research of the structure of the turbulence, since the beginning of the 80s, research is mainly oriented to the flows at high temperatures including chemical reactions and to the development and improvement of differential mathematical models as a modern and very efficient tool in the technological development. This research significantly contributed to the development of pulverized coal burners, plasma-chemical reactors, and optimization of pulverized coal fired boilers operating parameters and prediction of the greenhouse gases emissions. Most recent period includes experimental and numerical studies of the coherent structures in turbulent fluid jets, mathematical modeling of various turbulent thermal flow processes including two-phase turbulent flow in the multiphase heat exchangers and mathematical modeling of the atmospheric boundary layer.

Key words: *turbulent flow, high temperature flow, fundamental research, two-phase gas-particles flows, mathematical modeling, applied research, technology development*

Introduction

Turbulent flows have been very interesting and one of the most important subjects for researchers in the laboratory since its foundation. In the area of turbulence, researchers from the Laboratory for Thermal Engineering and Energy at the Vinca Insitute of Nuclear Sciences (Laboratory) were the initiators of many studies done for the first time in former Yugoslavia. High quality achievements in the field of research of turbulence, especially the results of the academician Prof. Zoran Zaric, established the Laboratory for Thermal Engineering and Energy as one of the world's most significant research centers for turbulent flows research. This enhanced opportunity for very fruitful cooperation with many world

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famous research centers in the field of turbulence: Imperial College London, Akademiya nauk SSSR Sibirskoe Otdelenie – Institut Teplofiziki Novosibirsk, University of Michigan, University of Southern California, Stanford University, University of Karlsruhe, and University of Erlangen. Laboratory for Thermal Engineering and Energy was for many years the only scientific organization in former Yugoslavia which dealt with research of turbulent flows. World's trends and research topics related to the turbulence were always among the laboratories top interests. It started at the beginning with statistical analysis of the measurements with the hot wire anemometer, methods of identifying coherent structures, vortical flows, modeling of dispersion of the warm water flows from nuclear and conventional thermal power plant to the rivers and the problems of environmental heat pollution, contact and optical measuring methods for measuring in high temperature flows, the study of turbulent flow with particles, with chemical reactions and combustion, low temperature plasma flow and development of mathematical models for calculation of complex turbulent flows, and recently, experimental and numerical studies of the coherent structures in turbulent fluid jets, external and self-sustained modification of turbulent structures, impinging heat transfer from a turbulent jets, optimization of pulverized coal fired boilers operating parameters and prediction of the greenhouse gases emissions, mathematical modeling of various turbulent thermal flow processes including two-phase turbulent flow in the multiphase heat exchangers and mathematical modeling of the atmospheric boundary layer.

First period – fundamental knowledge in the field of the turbulent flow

Solving at the beginning practical problems of heat transfer intensification from fuel elements in a gas cooled nuclear reactors, researchers in the Laboratory from very beginning understood that the intensification of heat transfer is based on a deep knowledge of the turbulent flow. At the initiative of Prof. Zaric are investigated the characteristics of fuel element with polyzonal-spiral finning in a gas-cooled nuclear reactors, the influence of variable pressure gradient and the influence of surface roughness on the intensity of the convective heat transfer, with a very practical purpose, to determine the necessary experimental correlations for fuel elements calculations [1, 2].

Shutting down of Yugoslav nuclear program on the federal level was lost the practical aim of the turbulence research, but fundamental research on the structure of turbulence was continued. Starting point was premise that fundamental knowledge in the field of the turbulence is necessary as initial, fundamental research to be able to solve problems of fluid structure and heat transfer in any industrial devices and systems.

Research on the influence of longitudinal pressure gradient on convective heat transfer by late Prof. Zaric was the basis for his later, highly significant research on structure and the nature of turbulent flows. The Laboratory, under the leadership of Prof. Zaric, first time in Yugoslavia began measurement of the characteristics of turbulence with a hot wire anemometer. His investigations of structure of turbulence near the wall have received international awards. Prof. Zaric was one of the first researchers in the world that is widely applied digital computers in the analysis and processing of results from measurements of the turbulent characteristics with a hot wire anemometer [3, 4].

A significant contribution to the development of measurement in turbulent flows is given by determination of the influence of the cold wall on the hot wire anemometry measurements [5]. Prof. Zaric was first scientists to describe the shape of the probability distribution function of the velocity and temperature fluctuations induced by cyclic rapid entrainment of surrounding fluids and slow rejection of the fluid from the surface of the wall as a result of presence of coherent structures in near wall region.

Method proposed by Prof. Zaric for the detection of coherent structure TERA (Turbulent Energy Recognition Algorithm) has received worldwide recognition as the only method that has been successfully verified by the results of independent experiments with visualization of coherent structures in near the wall region [6, 7]. Joint work with initiator of the idea of coherent structures in turbulent flows, Prof. R. E. Falco, is considered as "the classical investigation" of structure of turbulence [8, 9]. For this study Prof. Zoran Zaric got the October Award of Belgrade in 1972, and was elected as a corresponding member of Serbian Academy of Sciences and Arts (SASA) in 1978.

The study of heat transfer from fuel element with polyzonal-spiral finning in a gas-cooled nuclear reactors and rough surfaces has grown into a multi-year research of the turbulent flows in the cavities, and research on turbulent flow past a group of cylinders in different configurations and different flow conditions. This research was first pointed out that in the transverse flow past two cylinders, on a critical distance, is forming stationary closed vortex region in a space between cylinders [10, 11]. The results of years of research of flow patterns with cylinders in a cross-flow are listed in the review paper [12].

As a very important area of work in this period should be emphasized modeling of dispersion of the warm water flows from nuclear and conventional thermal power plant to the rivers, lakes and seas and modeling of plume spreading from thermal power plants cooling towers. This activity is a significant from various points of view. For the first time in our country are developed and implemented modern differential mathematical models to describe the turbulent flow, which induced the beginning of intensive work in the Laboratory on modeling of turbulent flows. At the same time this is our country the first serious consideration of environmental pollution from thermal power plants that explored completely new field at that time – limited heat capacity of the atmosphere and water. For engineering practice is a significant introduction of modern mathematical modeling in design and in the process of selection of optimal location of nuclear and conventional power plants.

Using accumulated fundamental knowledge in the field of the turbulent flows, Prof. Zaric and his associates (A. Vehauc, Lj. Zivojinovic, N. Ninic) developed a series of mathematical models and applied them to analyze the location and design of cooling system for nuclear and conventional power plants: Krsko Vir, Prevlaka, TENT in Obrenovac [13, 14]. This group also developed calculation model of heat capacity of rivers and applied to the Sava River basin [15].

In the period of ten years (1965-1975) studies of turbulent flows are left without significant funding during the shutdowns of nuclear energy program in former Yugoslavia. In this period the only study that were not interrupted was study on structure of turbulence by academician Prof. Zoran Zaric which was financed by SASA and abruptly stopped in 1985 with his early death.

Initiation of research cooperation with the Yugoslav National Army (JNA) in a field of high-temperature flows provided the opportunity in 1976 to rehabilitate the research of turbulent flows. Extensive work on the development of new technologies (coal dust burners, spray dryers and technology based on the use of low temperature plasma) was increasingly demanded fundamental knowledge and research of turbulent flows. At the same time widen cooperation with industry enabled to use funds from industrial dedicated research to restart the research of turbulent flows.

After many years of unsuccessful attempts to secure funding of fundamental scientific research in the area of turbulence, finally, on a proposal Prof. Simeon Oka in 1985 in the Science program financing of the Republic of Serbia were included the task of research of turbulent flows in process engineering and energy, as a subproject within the project of fluid mechanics applications. This was the first time that turbulence research is recognized and funding was approved for fundamental research for technology development needs. The study of turbulent flows again received a "citizenship" status and since then fundamental investigations of turbulent flows have a stable funding from the government funds for science.

Second period – Targeted experimental fundamental research for technology development

During the first period of research of turbulent flows from 1962 to 1975 can be observed two orientations in studies: application oriented character (impact of roughness, vortex field, the impact of the pressure gradient, cylinder in a cross flow, heat pollution of the environment) and fundamental investigation of structure of turbulence. Under the strong influence of academician Zaric, and thanks to its world known results in this period was prevailing fundamental research. Applied research was suspended in the early seventies. In the period from 1976 to today prevailing targeted fundamental and applied research in the field of turbulent flows. In this period in the research group are included a new generation of researchers (J. Jovanovic, D. Milojevic, M. Matovic, P. Stefanovic, G. Zivkovic, and S. Nemoda). In the late eighties, with the arrival of M. Sijercic from famous Sarajevo school of mathematical modeling, the research group for mathematical modeling of the process has been extended to new topics.

In the early eighties, the Laboratory started work on the development of high-temperature processes and technologies – pulverized coal combustion, low temperature thermal plasma flows, development of plasma-chemical reactors, protection and insulation for thermally loaded surfaces and development of high speed swirl gas burners. In the newly created environment with more stable funding from the fundamental scientific research funds, JNA and industry, extensive research of turbulent flows gain new orientations. The research interests were oriented to the fundamental and applied research of turbulent flows in complex high temperature flows with the presence of particles and chemical reactions in order to create a basis for the development of new technologies and the development of modern engineering methods for the calculation and optimization of the processes.

The main directions of research were: development of specific methods for accurate measuring in the high temperature flows, the development of the experimental base for research in the high temperature flow and combustion, experimental research in order to obtain of the input data for mathematical models and verification of the model, and as the final goal development of differential mathematical models for calculation of complex turbulent flow.

A significant influence on the orientation of research and the results achieved had international cooperation with the University of Erlangen, Germany, and the Institut teplofiziki in Novosibirsk, Russia.

Measurement methods have been developed for turbulent flows of very challenging parameters: velocity of 200 m/s or more, temperature up to 6000 K, the presence of solid particles, high turbulence intensity, for unsteady and pulsating flows – mobile Pitot tube [23, 24], mobile thermocouple [25, 26], the probe for measuring of the flow enthalpy [27, 28] and probes to measure heat flux.

Measuring method of Laser Doppler Anemometry (LDA) is completely implemented [29] and methods of statistical analysis in hot wire anemometry are improved [16, 20].

In the Laboratory was built a significant experimental base for experimental research in high temperature processes: (1) two low temperature plasma generators with thermal power 150-200 kW and 5 kW, outlet temperature 3000-6000 K, and implemented methods of calculation and design plasma generators [30]; (2) as a source of lower gas temperature was built installation with an acetylene torch [31,32] with temperature up to 3000 K, the swirl gas burner and installation to explore the free jet flow and turbulent swirl flow at room temperature.

Experimental research was focused on the following complex turbulent flows research subjects in order to investigate the structure of turbulent cold flows and flame, influence of the combustion on the turbulent flow field, and to provide data for verification of the mathematical models:

– the statistical nature of turbulent flows,
– the structure of the flow field of free isothermal jet and acetylene flame,
– combustion in swirl hi-speed burners for gaseous fuels, and
– two-phase flow of gas and solid particles and processes in turbulent swirl burners for combustion of pulverized coal.

The statistical nature of turbulent flows

Fundamental research of turbulence structure under the leadership of academician Zoran Zaric continued, with thesis of J. Jovanovic [16] and the latest works by Z. Zaric [8, 9, 17]. Papers of J. Jovanovic on the relationship of higher moments of turbulence, the structure of turbulence near the wall, the modeling of turbulent energy dissipation were of the world's highest level and have been published in [18-22]. Continuing independent studies of the structure of turbulence, J. Jovanovic focused his research to the detection of non-Gaussian fluid behavior represented with fluctuation of velocity found in anisotropic, inhomogeneous turbulent flows. These studies, as well as attempts to improve existing models of turbulence [16] are part of the effort to adapt turbulence models based on Reynolds's assumptions to the specific nature of turbulent flow at high temperatures, the chemical reactions and high gradients, which leads to significant anisotropy of turbulent fluctuations.

The same objective had research [66, 67] that showed possibility to mathematically describe the probability density function of velocity fluctuations near the wall, i.e. in extreme anisotropy and non-Gaussian behavior. Mathematical description of the probability density function using a general distribution function (known as hyperbolic distributions) allow the description and calculation of turbulent fluctuations near the wall in an universal way. The introduction of this general distribution function match long lasting trials of researchers to describe the turbulent fluctuations with differential equation for the change of probability density functions, thereby giving up Reynolds's approach. Results of detailed experimental studies [16, 67] have shown that there is a strong connection between higher statistical moments of turbulent fluctuations in the boundary layer flow. Measurements in free turbulent jet also confirmed the existence of these relationships [36]. For further development in modeling of turbulent flows was very important that the theory confirmed that the probability distribution function of the so-called Gram-Charier series get a free link between the statistical moments of turbulence and results of the experiments [18, 19, 68]. Due to the lack of modern measuring methods in the Laboratory, these studies were performed mainly abroad, especially after leaving of J. Jovanovic to the University of Erlangen in 1990.

The structure of the flow field of acetylene flame and free isothermal jet

Research on structure of turbulent acetylene flame revealed the specific structure of turbulent fields with intensive laminarization of fluid flow downstream of the flame front, which is formed due to existence of specific area in which the mixing with the ambient air is very poor [33, 34]. Figure 1 shows the change in mean velocity and turbulence intensity measured in the axis of acetylene flame by V. Bakic. It is clearly showed that turbulent flow regime changes passing through the front of flame, flow become accelerated and a high level of turbulence exists in the front of the flame followed by subsequent slowdown and laminarization of the flow into the zone of constant velocity.

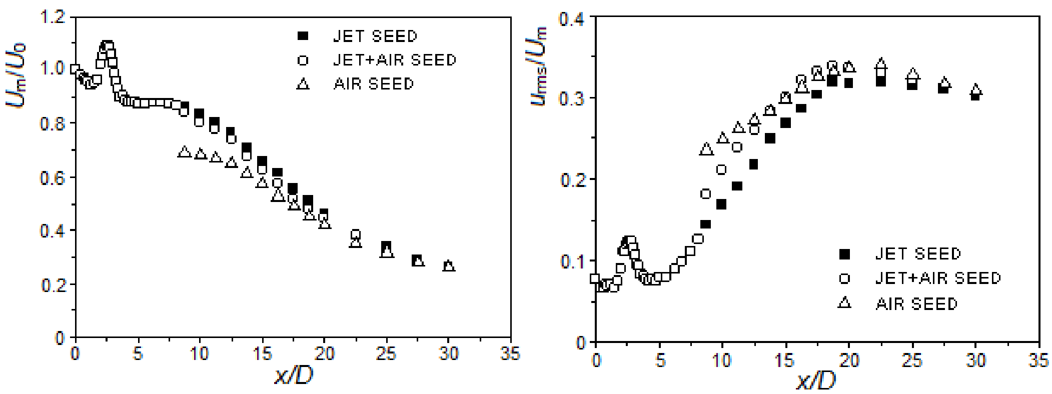


Figure 1. Change in mean velocity and turbulence intensity in the axis of acetylene flame

To study this phenomenon was developed a specific method of signal conditional sampling, and applied special method for averaging of turbulent fluid flow characteristics according to the origin – products of combustion and the ambient air [34, 35].

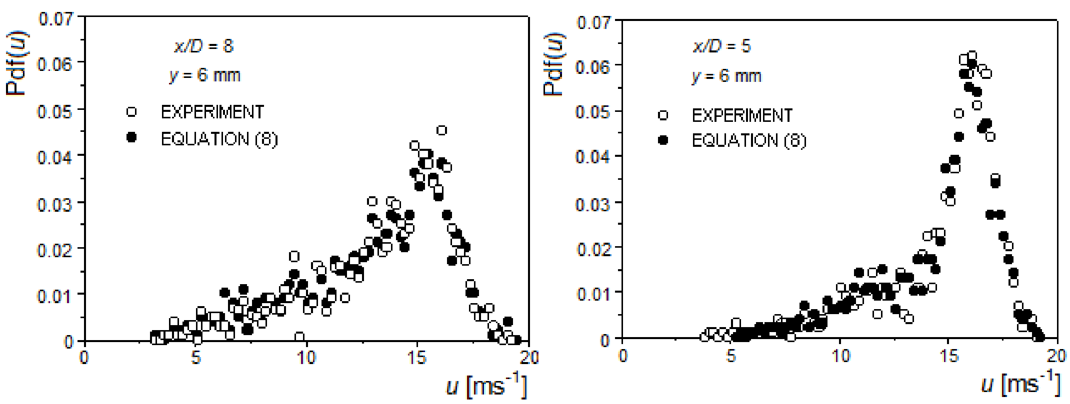


Figure 2. Probability distribution of velocity fluctuation in the direction of the axis of flame in two transversal cross-sections

Figure 2 shows the probability distribution of the velocity fluctuation in the direction of the flame axis at point in the cross-section which is close to the position of the flame front (measurement by V. Bakic). Measurements are provided with adding the tracers into the mainstream and into the surrounding air and results are compared to calculated values obtained by stacking the results obtained by measuring fluctuation which originate only from the basic flow and the fluctuations that come from the surrounding air. Good agreement of the results shows validity of the conditional sampling method that is applied in the calculations. Two maximums in a probability distribution function, which can be observed on the left picture, show that fluid flow comes to the measuring point from the base flow and from the ambient air intermittently.

In isothermal jets are confirmed the higher-order momentum correlations [36], discovered earlier in the boundary layers in the works of J. Jovanovic [18, 19]. For comparison with the results of mathematical modeling was investigated velocity and turbulence field in the two-phase flow of gas with solid particles using LDA [37, 38], and using a hot wire anemometer was determined velocity and turbulence intensity field is confined coaxial jet configuration [39, 40].

Combustion in swirl hi-speed burners for gaseous fuels

On the cold model of swirl burner velocity and turbulence intensity field were measured using LDA, temperature and concentration fields and heat flux on the walls of the burner were measured by contact methods [41-43]. Measurements were compared with the mathematical model of S. Nemoda.

Two-phase flow of gas and solid particles and processes in turbulent swirl burners for combustion of pulverized coal

Two phase isothermal flow with particles was investigated using the LDA [37, 44-46]. On the experimental study of the process of forming silicon nitride in a plasma chemical reactor [47-49], and the study of combustion in burners developed for pulverized coal [50, 51] (fig. 3), will be further discussed in the review of research in the field of plasma chemistry and thermal engineering.

Second period – Mathematical modeling of two-phase turbulent flows and high temperatures turbulent flows

In mathematical modeling of complex turbulent flows with particles at high temperatures as the basis was used well-known k-ε model of turbulence. To describe the complex processes in two-phase flow and the plasma have been developed some of the original models.

The most important models for a future developments were: stochastic-deterministic model for the solid particles motion in a turbulent fluid gas phase flow developed by D. Milojevic [37], model of melting and evaporation of particles in the plasma reactor by P. Stefanovic [47-49], model of turbulent flow in ionized plasma [49, 52], and the two-phase flow model by G. Zivkovic, which takes into account collisions among particles and particle collisions with walls [53-55], model of the flow over the surface with ablation [56, 57], the coupling of process in a surface material and gas phase during the surface ablation [58] and the new concept of dissipative combustion in turbulent flow by S. Nemoda [43]. The developed models for the calculation of turbulent flows are used to develop a plasma reactor, the previous optimization of flow field and thermal parameters of the burners, selection of thermal insulating materials, organizing the process of gasification and combustion of coal in a gasifiers and furnaces.

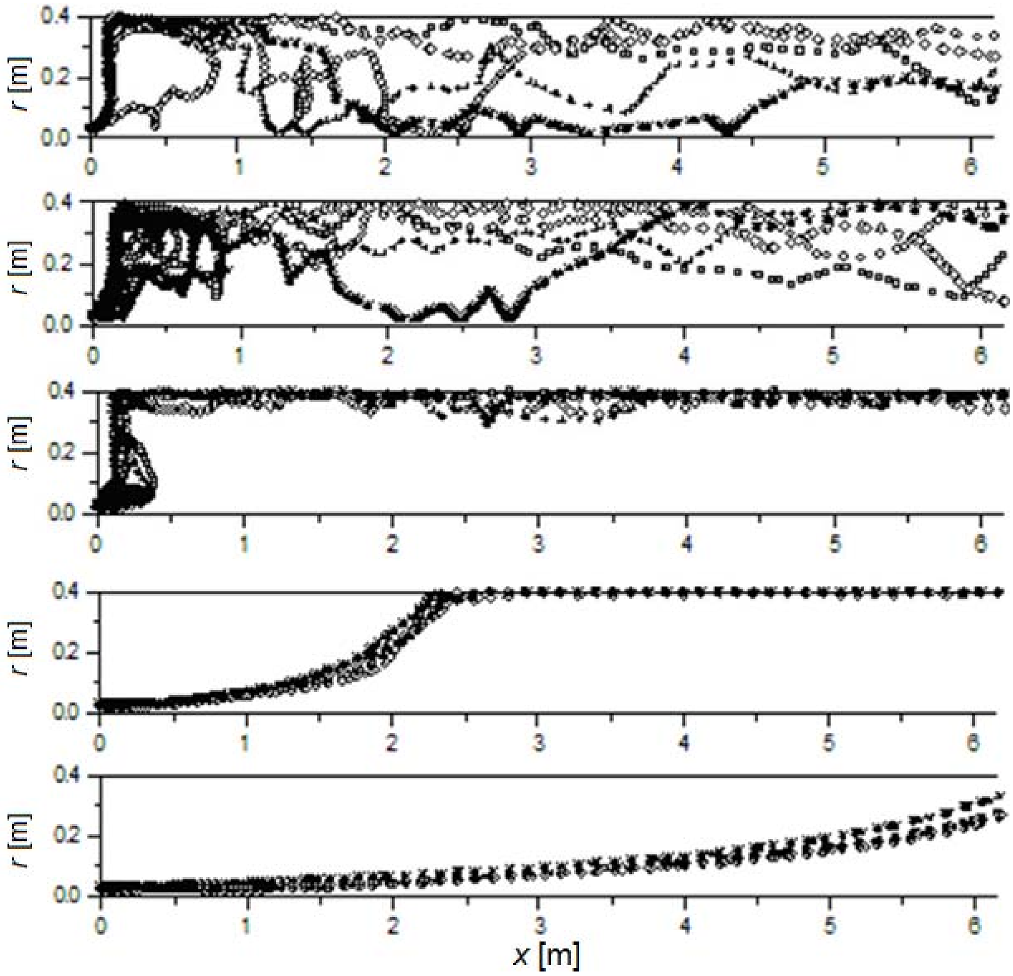


Figure 3. Measured pulverized coal particles trajectories after the swirl burner [50]; particle size is increasing from top to the bottom of the presented images

Motion of solid particles in a turbulent flow field and modeling of the flow with particles [37, 38, 44]

D. Milojevic has developed an original Lagrange stochastic deterministic (LSD) model of the particles motion in a turbulent field. The model is stochastic because the "current" velocity field is generated based on the known value of the kinetic energy of turbulence and turbulent macro scale, using random numbers. Particles motion during the interaction with turbulent eddies is deterministic since it is described by Lagrange's equations of motion. Developed model was used as the basis for all later models of complex flow with particles and chemical reactions that will be discussed in this review. Modeling the flow with particle and fluid interactions can be provided in two ways, so called Euler and Lagrange approach. Lagrange approach applied in the LSD model [37] is closer to the physical reality, while Euler approach is simpler [69]. The models differ in the modeling of particles diffusion, and therefore was carried their comparison [70]. Detailed analysis showed that both approaches have their place, Lagrange in the modeling flow combustion, and Euler approach when quick results is needed without spending a long time calculations.

The influence of collisions between particles and the particles with the walls [53-55]

Continued development of two-phase flow mathematical model was aimed at describing the influence of particle collisions and the roughness of the channel walls. The roughness of the wall and non sphericity of the particles was simulated by changing the local angle of inclination of the wall by stochastic process. Collisions between particles are also modeled by a stochastic approach, so as to each particle, at each time step is calculated the probability of collision and accordingly modified particle velocity. Due to the complexity of flow with particles in horizontal channels and pipeline elbows are modeled the following processes: (1) the deposition of particles in horizontal pipes, (2) inertial forces at the elbows and branches, (3) turbulent dispersion, (4) the buoyancy forces induced by rotation of particles and collisions with the wall, (5) collisions of particles with a rough wall, and (6) collisions between particles. The complexity of the flow geometry and movement of particles required a three-dimensional numerical scheme, a three-dimensional model of particle collisions and the wall, and the three-dimensional model of the wall roughness.

Turbulent flow of low temperature plasma with particles [47-49]

For the purpose of modeling of processes in plasma reactors for the production of ultra-disperse powders, model of the two-phase gas-particles flow had to be extended to a model that includes heat and mass transfer between fluid and the particles. The dissociation and ionization processes are hereby incorporated in the model [59, 60] while the thermodynamic equilibrium of the Si-N, Si-C-H and Si-O-C-H systems was discussed in [49, 61]. Especially important is the analysis of the influence of particles evaporation on the momentum, heat and mass transfer [48] and analysis of thermodynamic conditions of the process of plasma synthesis [49].

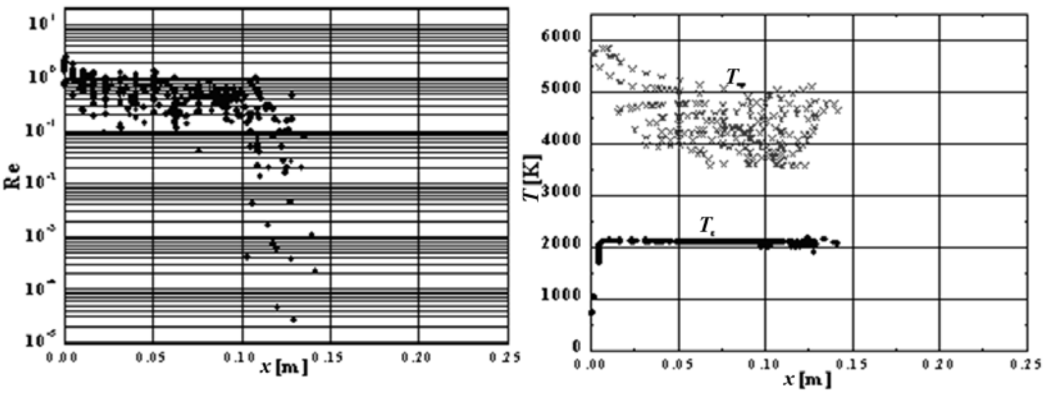


Figure 4. Left – Silicon particles Reynolds number depending on the axial position of particles in the plasma chemical reactor; right – temperature of silicon particles T_s and the plasma T_∞ as a function of the axial position of particles in the plasma chemical reactor

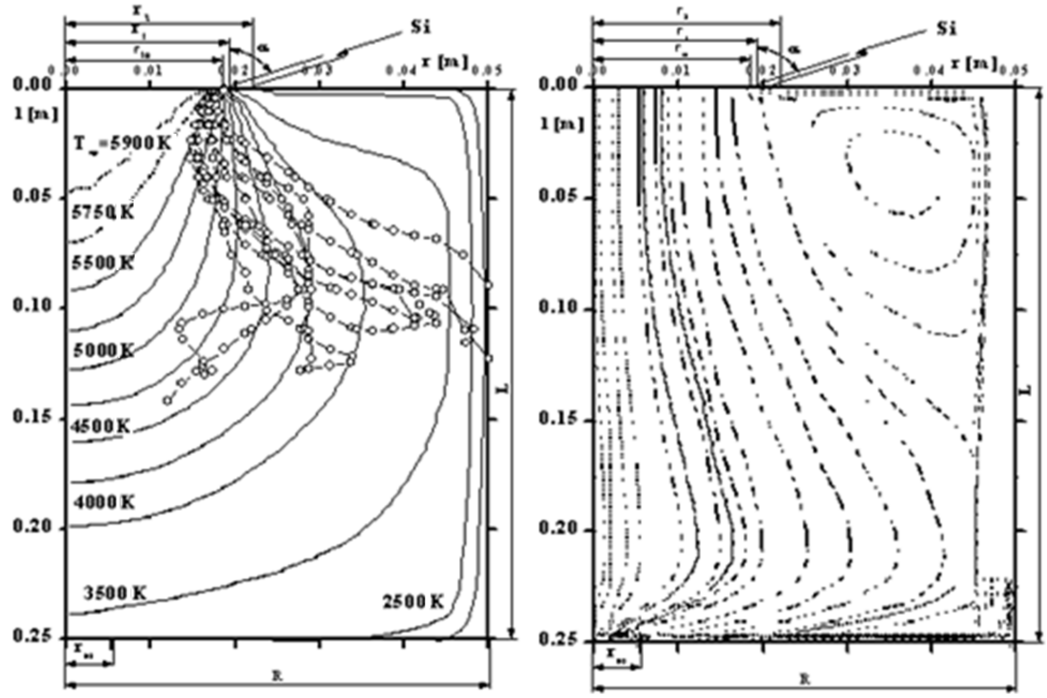


Figure 5. Axial section of the reactor with computed curves of constant (a) plasma temperature with some Si particle trajectories and (b) stream function; reactor parameters: $r_1 = r_{in}$= 18.75 mm, r_2 = 21.25 mm, R = 50 mm, L = 250 mm, r_{ex} = 4 mm, T_w = 1500 K, $T_{w;bottom}$ = 1700 K; nitrogen flow – m_{in} = 2.07 g/s, T_{in} = 6000 K; Si powder – m = 0.127 g/s, d_{po}=0.050 mm, α = 60°

In figs. 4 and 5 are shown the results of calculation of fluid flow field, the heat transfer and trajectories of particles in a plasma chemical reactor based on the model of P. Stefanovic.

Modeling of high temperature gas flow at the surface with the wall ablation [56, 57]

Ablative materials, producing large amounts of gaseous products, create intense cross flow in the basic gas flow and substantially change its character. Large cross-flow gas quantity, large gradients of temperature, concentration and velocity near the wall, intense chemical reactions in the gas near the surface, are very difficult for modeling. For the purpose of this complex flow modeling standard k-ε turbulence model is adapted for the detailed calculation in the near wall region characterized by gradients of temperature, concentration and velocity, and small local Reynolds's numbers. In the model are also included chemical reactions in the ablative and primary gas flow. The problem of boundary conditions on the ablated wall (wall temperature and gas velocity perpendicular to the wall) is solved in the paper [58] by coupling of the fluid flow model with a model of thermal processes in the material of the wall.

Modeling of processes in gas burners and combustion chambers [43, 62, 63]

For calculation and development of burners and combustion chambers model was developed, based on k-ε turbulence model which consists of three parts: (a) calculation of swirl turbulent flow in a free jet with the convective heat transfer to the walls, (b) model of chemical reactions (combustion) and (c) the model of heat transfer by radiation. The burning rate is related to the speed of turbulent mixing of fuel and oxygen at the level of the finest structures of the turbulent fields, i.e. the smallest eddies (Kolmogorov scale).

Modeling of processes of high temperature gasification and coal combustion

Based on the model developed for the classical gasification of coal [69, 70] was developed model for high temperature gasification of pulverized coal in low temperature plasma (3000-5000 K) and in the presence of water vapor [71]. Modeled was the turbulent fluid flow in axisymmetric chamber. On the basis of these models was developed model of pulverized coal combustion in swirl burners [51, 72].

Modeling of processes in the acetylene flame in swirl combustion chambers and diffusers

Using models developed for gas combustion and calculation of swirl flows were analyzed characteristics of simple turbulent flows and compared with the results of several experiments. Flow in the acetylene flame is successfully modeled in the papers [73, 74, 77-79], the flow in the diffuser in the papers [75, 76], and flow in swirl combustion chamber is analyzed in the papers [43, 76].

As a result of this research was developed three-dimensional mathematical model of the process in the furnace boiler for combustion of pulverized coal [82].

More details on the results of research in the field of turbulence in this period are given in the review articles [80, 81].

Third period – recent scientific achievements in the field of turbulent research and modeling

Third period of the research is characterized by the absence of funding in this area of research from any source of scientific funds. Turbulence as the research interest of the researchers in the laboratory can be found in many financed projects as suitable link to fundamental research in the development of new technologies and new devices. Experimental studies on the characteristics of the turbulence are performed only during exchange of researchers with foreign institutions, including in particular: Kyoto University, Kyoto, Japan, and the Academy of Sciences of the Czech Republic, Institute of Chemical Process Fundamentals, Prague, Czech Republic, for joint research within the international European Union research framework programs. Research work in this period opened possibility to use modern experimental techniques and modern experimental equipment that were available in foreign research centers, but, disadvantage was that only few researches participated in international projects without possibility to continue to work in the same field after returning back to the Vinca Institute of Nuclear Sciences, Laboratory for Thermal Engineering and Energy.

Mathematical modeling of the turbulence processes continues to be an essential element of research efforts in the Laboratory that is extended from use of "home-made" software to the use of commercial software packages for which are provided proper academic licenses. Among the software packages that are used for mathematical modeling can be listed: Phoenics by CHAM, ANSYS, FLUENT, CFX by ANSYS, and Fire by AVL. Scientific efforts and contributions were in developing, implementing and validation of new models into existing commercial codes that more accurately describe the processes of scientific interest.

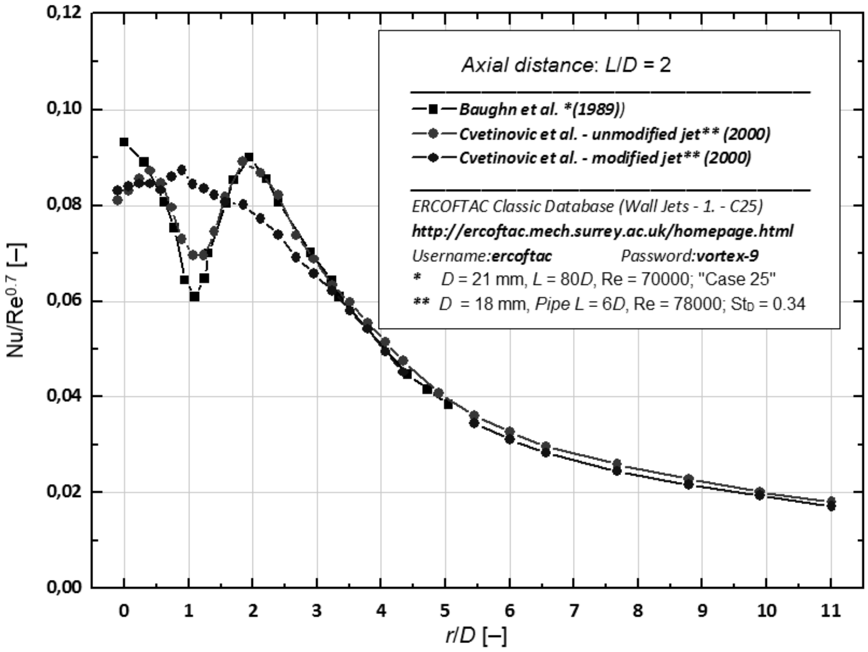
Experimental investigation and mathematical modeling of modified turbulent axisymmetric free and impinging jet

Submerged, round, unconfined turbulent axisymmetric jet issuing from nozzles with different geometries in steady surrounding atmosphere impinging to the flat heated plate positioned normally to the jet axis was the subject of this research.

The aim of experimental investigations, mathematical modeling and numerical simulations was to widely investigate properties and the vortex structures, that are assumed to have great importance in the heat transfer process, of the modified turbulent axisymmetric jet by acoustic modulations and, additionally, to study the possibility of their control. The considered mean of vortex structures control is a modulation of the nozzle exit velocity using external source of low-amplitude oscillations and self-sustained oscillations generated in the operation of the specially designed nozzles.

Experimental investigation was provided through cooperation with two international educational scientific institutions: Heat Transfer Laboratory, Mechanical Engineering, Faculty of Engineering, Kyoto University, Kyoto, Japan, where was provided experimental investigation of turbulent axisymmetric jet modification by self-sustained oscillation and Research Centre of Behaviour of Multiphase Systems under Super-Ambient Conditions, Institute of Chemical Process Fundamentals, Academy of Sciences of the Czech Republic, Prague, Czech Republic, where investigations of turbulent axisymmetric jet modification by external excitations were provided. Mathematical modeling and numerical simulation of the phenomenon of interest is provided at the Vinca Institute of Nuclear Sciences, Laboratory for Thermal Engineering and Energy.

Very extensive set of experimentally collected data from various kinds of experimental techniques used in the wide range of experimental working conditions was used for establishment of the relevant experimental data base that was compared with widely accepted experimental results presented in fig. 6 [83-85].



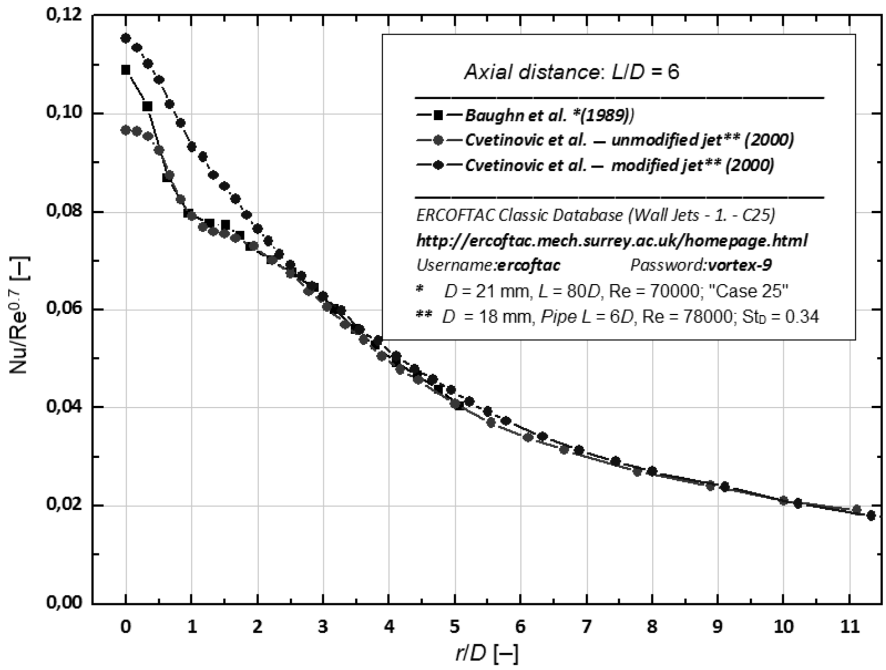
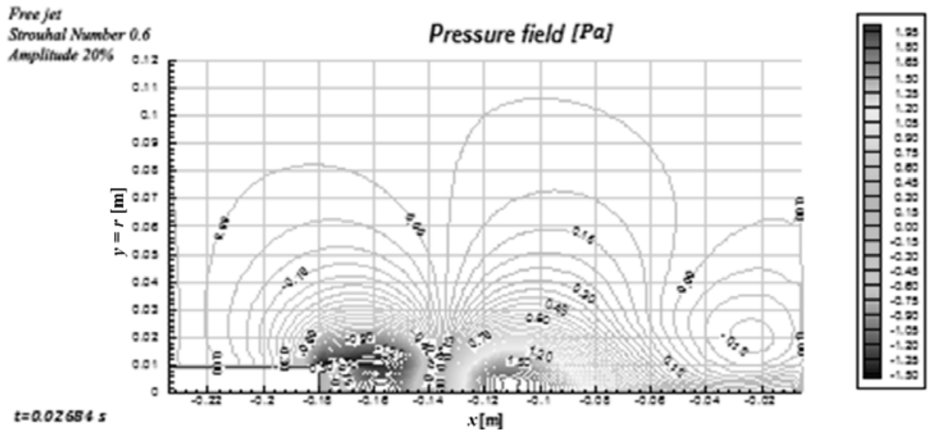


Figure 6. Comparison of the results with the results Baughn *et al.*, 1989, generally accepted as the reference for the heat transfer from the jet to the impinging surface – *L*/*D* = 2 and 6
(for color image see journal website)

After detailed analysis and post processing of the data, it could be possible to extract relevant conclusions about turbulent axisymmetric jet modified by acoustic oscillations properties and its influence on the process of the heat transfer from modified jet to the flat heated surface positioned normally to the jet propagation. Significant scientific contribution in broadening of the investigation of this specific phenomenon is given [86-90].

Mathematical modeling and numerical simulation of the phenomena which has compared different turbulent models has led to the recommendations for the models usage and optimization in flow setups that include heat transfer from the jet to the flat heated surface. Very interested were results of unsteady simulations, fig. 7, which clearly showed influence of applied sound modulation Strouhal number on the turbulent flow structures in a jet.



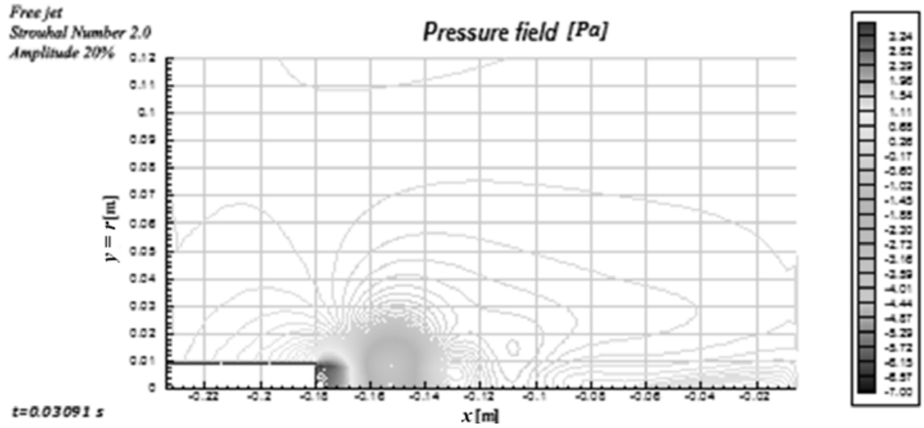


Figure 7. Change of the averaged pressure at one frozen time step Re = 10000, St_d = 0.6 and 2, amplitude of velocity fluctuation 20% *(for color image see journal website)*

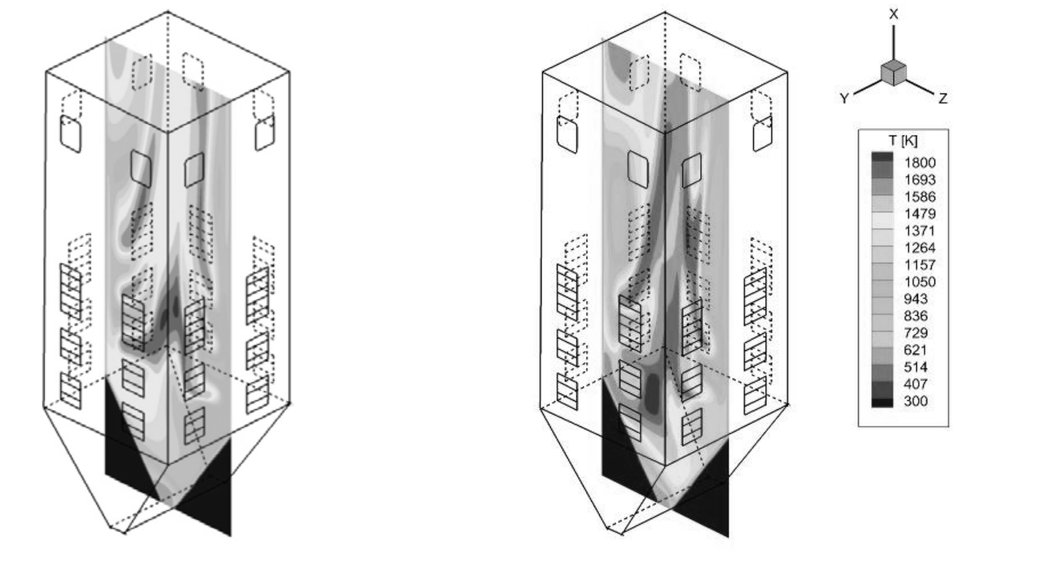
An important conclusion was derived from this research, from the standpoint of practical application of the research results in industry and technology development, that it was possible to further optimize technological processes that use fluid jets. In details were described and systematized all the most important parameters influencing the process of heat transfer from the jet to the surface, which gives the possibility for optimization of the processes. It also demonstrated the ability to control eddy structure by sound modulations applied to the turbulent jet as an attractive possibility to use in the technological processes.

Modeling of processes in the furnace boiler for combustion of pulverized coal

In order to predict turbulent two-phase reactive flow in pulverized coal-fired boiler furnaces at stationary conditions, a 3-D differential mathematical model and computer code were developed in-house, validated against available measurements and described in [91-93]. The comprehensive model offers such a composition of modeling approaches so as to balance computational efficiency with submodels sophistication. Two-phase flow is treated by Eulerian-Lagrangian approach. Submodels of NO_x formation/destruction and Ca-based sorbent reactions in furnace sorbent injection process were developed and coupled with the combustion code [94-96]. The 3-D model for simulation of furnace processes provides velocity, temperature, heat flux and gas mixture components concentration fields in full-scale furnace geometry, as well as furnace exit gas temperature (FEGT), NO_x and SO_2 emissions. Numerical experiments enable examining the influence of a number of input parameters and combustion modifications on the operation situations, pulverized coal flame, fig. 8, and NO_x emission, fig. 9, as well as investigating the possibility of SO_2 reduction by means of pulverized Ca-based sorbent injection into the furnace. An easy-to-use interface facilitates variation of operation parameters, introducing input data and convergence monitoring, so that the developed software can be used also by engineering staff dealing with the process analysis in boiler units.

Modeling of turbulence processes in the boiling and the boiling crisis

The critical heat flux (CHF) occurs in boiling process when generated vapor covers a certain area of the heated surface, which leads to the abrupt rise of the heated surface temperature. Prediction of the CHF is very important for safety and efficiency of thermal equipment, such as steam generators or heat exchangers due to a potential damage of a heated surface or a severe deterioration of the heat transfer at heat exchanger's surfaces. Due to its complexity and the importance for thermal safety, the turbulence of the boiling process and the boiling crisis has been attracting researchers for a long time.



(a) **(b)**

Figure 8. Control of the flame vertical position in the furnace by the fuel distribution over the burner tiers; (a) 56% and (b) 90% of coal through the lower stage burners (FEGT= 1093 °C and 996 °C, NO_x emission = 468.0 mg/Nm^3 and 344.6 mg/Nm^3, respectively) [94]
(for color image see journal website)

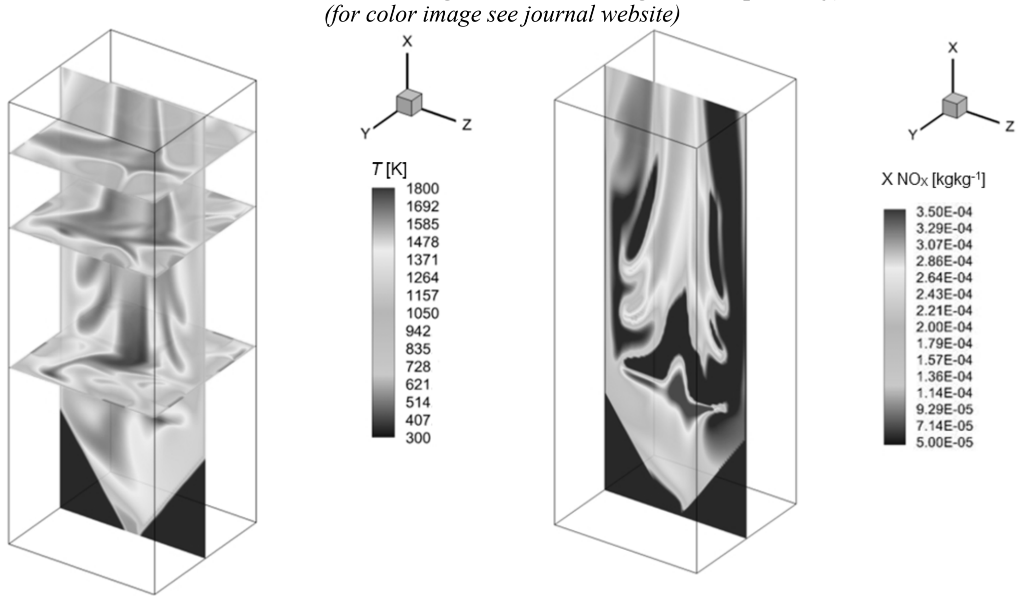


Figure 9. Gas temperature and NO_x concentration fields in the case-study pulverized coal-fired furnace [94] *(for color image see journal website)*

Experimental research on pool boiling was conducted by Afgan [97], while determination of the heat transfer coefficient and heat flux during the evaporation process was performed experimentally by Lazic [98]. This ensures safety of the plant and the maximum use of boiling phenomena as a way for intensive heat exchange. Spasojevic [99] studied the determination of minimal heat flux on the evaporation surface and variation of the pressure field and their influence on the stability of the working parameters. Stefanovic [100] analyzed the temperature fluctuation in two phase flow, while Jovic [101] established the character of oscillatory instability induced by inertial and dissipative effects.

Pezo and Stevanovic [102] performed numerical experiments with the two-phase mixture in pool boiling. Transient two-fluid model was used for description of mixture and transient heat conduction was used for heated wall. Dynamics of vapor generation on the heated wall is modeled through the density of nucleation sites and the bubble residence time on the wall.

Modeling of non-conventional liquid fuels combustion in a bubbling fluidized bed

A comprehensive CFD numerical model for simulation of unconventional liquid fuel combustion in a fluidized reactor is proposed. The unconventional fuel is a combustible industrial liquid waste with significant water content. The model is based on the two-fluid Euler-Euler (EE) bubbling fluidized bed (BFB) modeling incorporating the kinetic theory of granular flow (KTGF) to gas and solid phase flow prediction. The model of the complex processes in fluidized combustion chamber incorporates, besides gas and particular phase velocity fields' prediction, also the energy equations for gas and solid phase and the transport equations of chemical species conservation with the source terms due to the conversion of chemical components. The interaction between the liquid phase and the gas, as well as solid phase, has been separately modeled. Within the proposed fluidized combustor modeling the third phase has also been included in the process, which corresponds to a liquid fuel that is fed into the BFB.

For solving the system transport equations of the proposed EE model for liquid fuel combustion in BFB the software package FLUENT 14.0 was used. Thereby, for the models of drag forces, liquid fuel devolatilization and water evaporation, particular subroutines have been in-house developed.

The numerical procedure consists of two steps. In the first step of the calculation, the transformation of the fixed granular bed to fully developed bubble fluidization for desired hydrodynamic conditions is performed. In the second step calculation proceeds with the obtained gas and solid phase velocity and void fraction fields, but the boundary conditions are changed by introducing the inlet fuel flow, and the equations of chemical species with the source terms due to chemical reactions were activated [103, 104].

Modeling of atmospheric boundary layer

The popularity of the k-ε turbulence model in engineering applications raises the question of whether it could be used for micro and mezzo scales modeling in the atmospheric boundary layer. Applying the standard k-ε turbulence model, used in engineering applications to atmospheric flows, yields unrealistic results. Mostly, it is unable to reproduce the right level of turbulence in the weak shear layer away from the ground, where the turbulent viscosity is over predicted. Some modifications of standard k-ε turbulence model have been proposed, almost modifying the set of model's coefficients based on experimental evidence of open terrain. The performance of proposed new set of model's coefficients has been tested on Askervein case study [105].

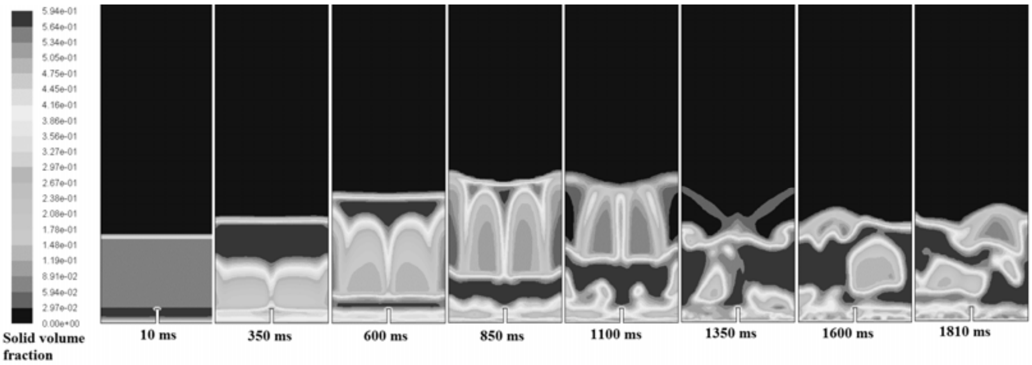


Figure 10. Development of the solid volume fraction distribution within the fluidized reactor before the combustion is started *(for color image see journal website)*

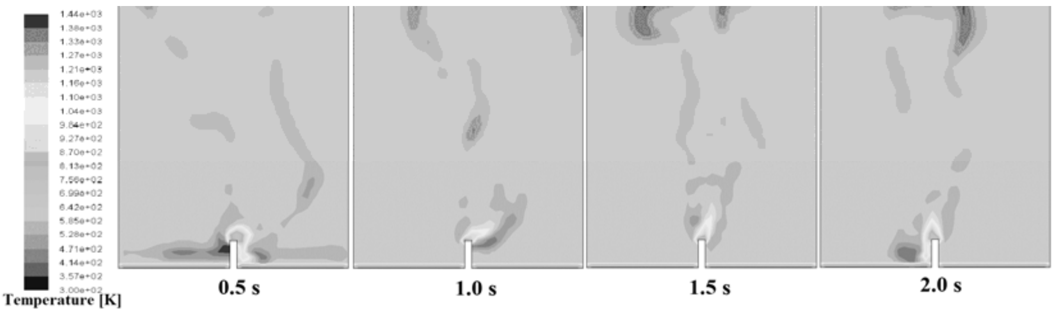


Figure 11. The change in time of the quasi-stationary temperature field in the fluidized combustion chamber *(for color image see journal website)*

Modeling of complex buoyancy-driven flows

In the thin enclosures

Thermal buoyancy-driven turbulent flow is interesting from a fundamental point of view, because the production of turbulence by shear and thermal buoyancy takes place in the same direction. This flow is also interesting from an applied point of view because it is representative for many practical heat transfer applications, such as double skin facades. Application of the second-moment closure, even in its simplest form, to the solution of thermal buoyancy-driven flows represents still a formidable task. This is not so much because of a large of differential equations involved, but more because of still too high uncertainties in modeling various terms in the equations that obscure real physics. It should be kept in mind that in buoyant convection, irrespective of how large the bulk Rayleigh number may be, the molecular effects will remain important in a significant portion of the flow domain, requiring the implementation of low-Reynolds number modifications. This makes the use of standard wall function inapplicable and requires the integration straight up to the wall, which in turns calls for a very fine numerical mesh. There is, therefore, much to be gained if the differential model can be truncated to an algebraic form in which transport equations will be solved only for major scalar quantities, primarily k-ε-θ^2. Therefore, the application of simpler models (at most at the algebraic level) should be served as a convenient alternative for handling complex industrial situations. These prospects have motivated the new work, aimed at verifying the current practice in modeling of the transport equations for the turbulent heat-flux and temperature-variance and at exploring the limits of simpler turbulence models at the algebraic level. Developed k-ε-θ^2 model has been tested and verified by experimental data and published by Stevanovic [106].

In the indoor naturally ventilated environment

Some weakness of adopted k-ε turbulence model for low Re and high Ra numbers in the case of natural – convection of indoor fluid flow have been occurred in the equation budget of dissipation rate when the empirical coefficient $C_{\varepsilon 3}$ has a constant value. The value of $C_{\varepsilon 3}$ is still controversial. Values of $C_{\varepsilon 3}$ which varied from 0 to $C_{\varepsilon 1}$ have been proposed by one researchers group, though two other groups use $C_{\varepsilon 3}$ = 0.8 and 1.44. Actually, the value of $C_{\varepsilon 3}$ depends on the flow situation. It should be close to zero for stably-stratified flow, and to 1.0 for unstably-stratified flows. In order to take into account both flow situations simultaneously, it is proposed that $C_{\varepsilon 3}$ not to be constant at the whole fluid domain, rather than calculating $C_{\varepsilon 3}$ by the formula $C_{\varepsilon 3} = \tanh(U_{||} / U_{\perp})$. The velocity components $U_{||}$ and $U_{\perp}$ are parallel and perpendicular to the gravitational vector, respectively. The proposed function arranges that $C_{\varepsilon 3}$ is unity when the main flow direction is aligned with gravity and zero when the main flow direction is perpendicular to gravity. The proposed model was tested on the thermal natural convection in the classroom [107].

Conclusions

Laboratory for Thermal Engineering and Energy in terms of researchers, measurement equipment and experimental bases was one of the most important scientific institutions in former Yugoslavia (at present in Serbia) that have well established and carefully organized research of turbulent flows. Contribution to the turbulence exploration has remarkably changed during last fifty years always struggling with a lack of finances for such fundamental scientific research.

The modern development of technology and efficient design and engineering calculation, evaluation and validation of devices operating in complex flow and complex thermodynamic conditions can be achieved only if the spatial velocity, temperature and concentration fields of gases; layout, size and concentration of particles and drops; temperature distribution and heat flux to the walls are known or possible to calculate. Answers to such difficult questions can only be obtained by harmonized organization of fundamental, targeted fundamental and applied research activities. The development of modern technology has clearly demonstrated that without a complete chain of organized research is not possible to achieve desired results. The importance of targeting fundamental and applied research of turbulent flows today is obvious. The differences in the scientific level of fundamental research and engineering approach are increasingly diminishing. Scientific research methods very quickly become an essential engineering tool. Best example of this is wide application of differential turbulence models for the calculation and optimization of processes in numerous, very important devices and technologies. For the development of many technologies of great importance is the development of reliable mathematical models for the calculation of turbulent flows. Increasing process efficiency, reducing emissions of harmful compounds and establishing of the basis for automatic process control can only be achieved using modern turbulence model, as a reliable tool for calculation of turbulent flows. Development of mathematical models were directed towards the research with the aim to complete the development of methods for turbulent flows calculation that lead to the user friendly engineering tools: (a) permanent need for mathematical models verification continuously enhancing further development of optical and contact measurement methods and detailed measurements of local flow characteristics, (b) study the specific structure of turbulence at high temperatures, (c) further development of mathematical models by applying models of turbulent stresses for complex anisotropic flows, (d) the development of three-dimensional computational codes, (e) introduction of "multi grid" method for the formation of the numerical computational meshes, and (f) the development of turbulent combustion models based on parameters fluctuations probability density function.

The research teams that provide planned and targeted research of turbulent flows represent a secure basis for the further development of the contemporary research of the turbulence.

During last fifty years in the Vinca Institute of Nuclear Sciences, Laboratory for Thermal Engineering and Energy were successfully finished 15 master theses and 18 doctoral dissertations by associates from Laboratory and young university scholars from Belgrade, Kragujevac, Nis, Novi Sad, Bitola, Skopje, Sarajevo, *etc.*, many of which continue research in the field of turbulence research and mathematical modeling at many domestic and foreign universities.

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