International Workshop on Application of CFD Technology in Innovative Nuclear Power Plant and Safety Analysis

Final Project Report

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With the fast development of computer hardware and computational techniques, Computational Fluid Dynamics (CFD) analysis becomes a potential advanced tool to assist nuclear engineers in screening and optimizing their designs for nuclear power systems, and in understanding the phenomena occurring in the reactor system during operational and accidental conditions. In order to satisfy the demand for multi-scale simulations in the reactor systems, scientists have devoted themselves to developing innovative computational methodology, such as coupling CFD simulation with neutronics calculation, subchannel and/or system analysis. To satisfy the requirements for reactor design and safety analysis tools, CFD technology itself has to evolve and CFD users have to learn more.

Aiming to provide a platform for young nuclear engineers and students to share their experience in CFD application in nuclear engineering, the AC21 International CFD Workshop for Young Nuclear Engineers (AC21 CFD4You workshop) co-organized by three AC21 universities (Shanghai Jiao Tong University, Nagoya University, and North Carolina State University) and one non-AC21 university (Xi'an Jiao Tong University) was held at Shanghai Jiao Tong University from September 22 to 24, 2014.

In order to promote the exchange of experiences in CFD application, the students and young engineers participating in the workshop were encouraged to perform one of the two CFD benchmark exercises released by the workshop technical committee in May 2014.

a) Rod bundle benchmark

The rod bundle simulation benchmark was proposed as one of the options for the 2014 CFD4You workshop participants. In the call for participation it was described as follows:

For advanced analysis of nuclear reactor thermal hydraulics, the correct prediction of resolved subchannel flow on CFD scale is crucial. The most challenging part of the subchannel flow is the prediction of the flow through the mixing vanes and spacer grids. The participants are invited to present their solutions to one (or more) of the following problems:

a) flow through a simple subchannel (without spacer grid or mixing vane) using PWR geometry

b) flow through a set of subchannels using porous model for the spacer grids / mixing vanes (in this case the mixing vanes / spacer grids are not meshed, but a closure model is applied to represent a pressure drop in the flow due to their presence)
c) flow through fully resolved spacer grids in a subchannel

The participants are welcome to choose the fidelity of the CFD approach:

1) Reynolds-Averaged Navier-Stokes (RaNS)
2) Large Eddy Simulation (LES)
3) Direct Numerical Simulation (DNS)

The CFD results should include:

- Contour / stream-line representation of the resolved flows in axial direction (similar to Fig. 5 in Reference 1 and Fig. 7 in Reference 2).
- Velocity profiles at different locations compared to the experimental data
- Lateral velocity changes due to mixing vanes (if applicable for your chosen case).

Benchmark data source:

1 Xiong, J.B., et al. “Laser Doppler measurement and CFD validation in 3 × 3 bundle”, Nuclear Engineering and Design, **270**, 396–403, 2014. (CAD geometry file is available)

2 Conner, M.E., Hassan, Y.A., Dominguez-Ontiveros E.E. “Hydraulic benchmark data for PWR mixing vane grid”, Nuclear Engineering and Design, **264**, 97-102, 2013.

The organizers received 6 benchmark results from the following participants:

1. Chao Lin, Shanghai Institute Of Applied Physics, Chinese Academy Of Sciences
2. Yin Cao, Shanghai Institute Of Applied Physics, Chinese Academy Of Sciences
3. Zhao Chen, School of Nuclear Science and Technology (SNST), University of Science and Technology of China (USTC)
4. Rui Zhang, Tenglong Cong, Wenxi Tian, Guanghui Su, Suizheng Qiu, School of Nuclear Science and Technology, Xi’an Jiaotong University
5. Sen chen, Wenxi Tian,Zhang rui,Suizheng Qiu, Guanghui Su, School of Nuclear Science and Technology, Xi’an Jiaotong University
6. Wang Xiaoyan, Wenxi Tian, School of Nuclear Science and Technology, Xi’an Jiaotong University

b) Flow through an elbow

The second benchmark problem is an elbow flow, which is widely adopted in energy power plants. There were 6 participants (4 from China, 2 from Japan) for this problem. When computing this flow field, there are three important points to be considered. These are (1) high-Reynolds number (order of 10^5), (2) unsteady separation occurrence, and (3) initial flow condition effect. The results are compared with the experimental data by Ono et al. We requested the participants to report the following results:

(a) Contour / stream-line representation of the resolved flows.
(b) Velocity profiles at different locations compared to the experimental data
(c) Estimated error of the simulations compared to the experimental data

Benchmark data source:

[1] Ono, A., Kimura, N., Kamide, H., Tobita, A. “Influence of elbow curvature on flow

structure at elbow outlet under high Reynolds number condition", Nuclear Engineering and Design, 241, 4409-4419, 2011.

Four groups used the RANS (Reynolds Averaged Navire-Stokes) model to simulate the flow field. Among the models, the most convenient is a standard k-e model. But it can only be applied to the stationary homogeneous isotropic flow field. In the elbow the flow is non-stationary and non-homogeneous. Thus, the researchers should take this point into account. You cannot discuss the unsteady separation nor the secondary flow in the cross section. The RSM model has the ability to predict the non-homogeneous flow.

In order to discuss non-stationary flow, we must use DNS (Direct Numerical Simulation) or LES (Large Eddy Simulation). Both require the fine mesh configuration. Depending on the computer's ability, we have to decide how large a computational domain is possible. Three groups used LES. They discussed the unsteady flow separation and secondary flow. This approach is appropriate. The benchmark experiment is a high Re condition. In an elbow the flow field strongly depends on Re number. The separation and secondary flow patterns vary in a complex manner as Re increases. We need finer meshes for higher Re numbers. The appropriate mesh sizes are required for accurate computation. So, the important question is: how can we predict unsteady phenomena using LES? It is a really challenging theme. One group tried to answer this question, but it was not perfect. In a real plant, the flow Re is large; thus we still continue the discussion of what we can know from numerical simulations.

Another feature in an elbow flow field is the dependence of curvature ratio. Long elbow and short elbow are widely used in engineering applications. The former has a curvature ratio of 1.5, while the latter is 1.0. The benchmark experiment provides the results of both curvatures. The separations occur frequently in short elbow but are intermittent in long elbow. Accordingly, the secondary flow patterns vary and the flow field becomes different between them. There were no discussions regarding this point. All groups computed one curvature ratio and discuss their results. We expected the participants to compare both flow fields and to learn how the flow changes depending on the curvature ratio.

The mean velocity profiles computed by each participant are plotted in Fig.1. Among the RANS calculations, the results are slightly different from benchmark results. This may be a limit of the RANS method, which cannot adopt the unsteady flow motions. For the LES results, there is little difference. No one discusses in detail the initial condition. In the benchmark experiment, the flow is fully developed but the straight pipe region is only 10 times the pipe diameter; this may influence the flow field. If some participants had changed the initial flow conditions, the discussions may have been fruitful. In Fig.2, the flow in a cross section is plotted. The secondary flow seems to be well captured by LES. It occurs in clockwise and counter clockwise directions, and reaches around the pipe center. It would have been better if the separation frequency was discussed and compared with the experiment.

All participants used commercial codes for the computation. Although they are convenient to use, we have to be careful in comprehending the computed results, because the commercial codes sometimes stabilize the numerical instability; in such cases, the results change depending on what codes you adopted. In order to understand the code effect, the benchmark workshop is very important, especially for young researchers.

Please see the attached appendices for the examples of the participants' efforts for the benchmark problems. After the oral and poster presentations at the workshop, an independent committee evaluated the quality of the participants' work. The following participants were recognized for their efforts:

1. The best oral presentation was awarded to Mr. Yang Yu from Shanghai Jiao Tong University and Mr. Kai Wang from Xi'an Jiao Tong University.
2. The best poster presentation was awarded to Mr. Yuki Katai from Nagoya University, Ms. Rui Zhang from Xi'an Jiao Tong University, Mr. Zhao Chen and Mr. Shuzhou Li from the University of Science and Technology of China.

The workshop, which was held from September 21 to 23, 2014, attracted more than 30 participants from 11 institutes in 3 countries (China, Japan and the U.S.). During the workshop three invited lectures were given by leading professors in their fields, including Professor Seiichi Koshizuka from the University of Tokyo, Professor Hong Luo from North Carolina State University and Professor Yanhua Yang from Shanghai Jiao Tong University. The lectures provided the participants with a chance to learn about the cutting-edge front of CFD technology development and application. During the workshop two oral benchmark sessions and two poster benchmark sessions were organized. During these sessions the participants presented and compared their CFD application methodologies for the same problem, and had intensive and insightful discussions on the progress on CFD application in nuclear engineering. The two best oral presenters and three poster presenters in the benchmark sessions were awarded for their excellent performance.

At the end of the workshop, a technical tour to the factory of the Shanghai Nuclear Power Equipment Company was organized. The participants were impressed by the huge components of the nuclear reactor system, and increased their knowledge of the issues that they are working on. The workshop helped the professors from four universities establish initial connections, and was very helpful for them to start new collaborations in their research or student exchange programs.

Appendix A: Sample Benchmark results for rod bundle

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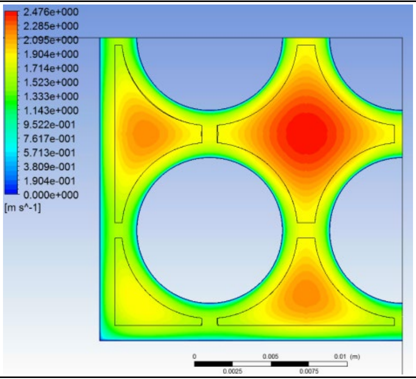
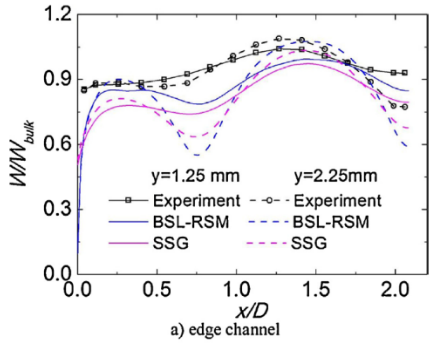
<tr><td>1</td><td>
</td><td>
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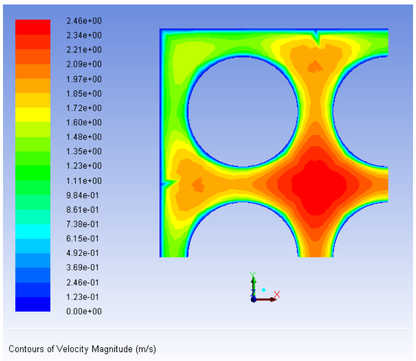
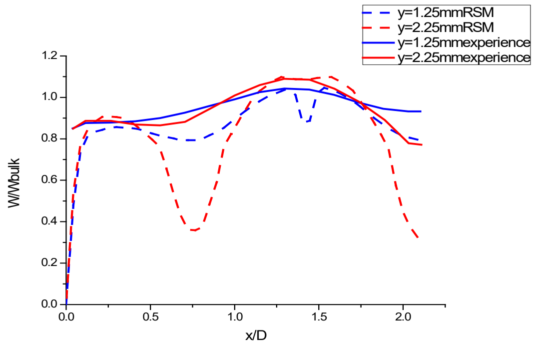
<tr><td>2</td><td>
</td><td>
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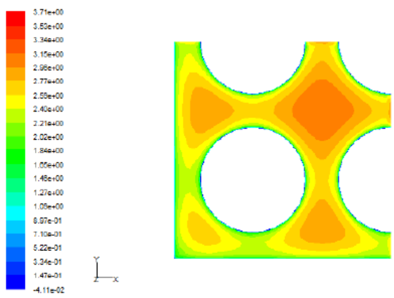
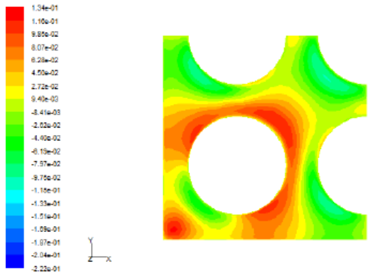
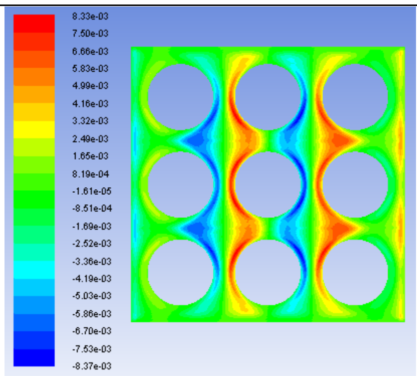
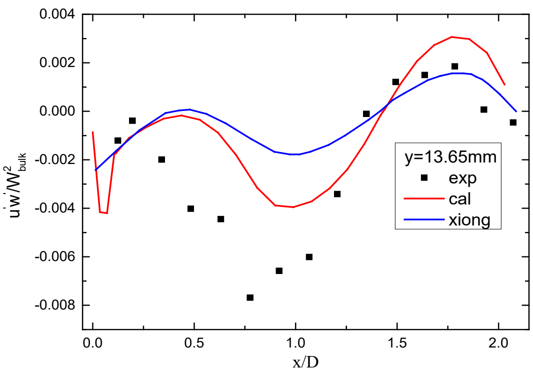
<tr><td>3</td><td></td><td></td></tr>
<tr><td>4</td><td>
</td><td>
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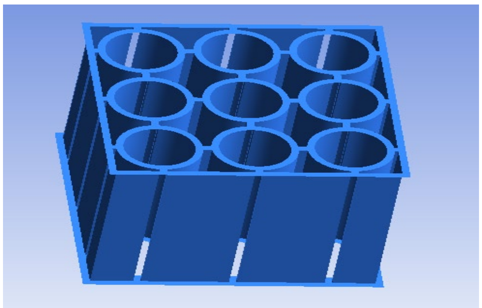
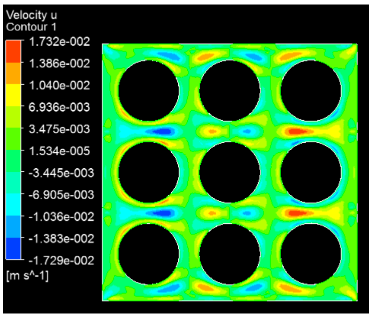
<tr><td>5</td><td></td><td>
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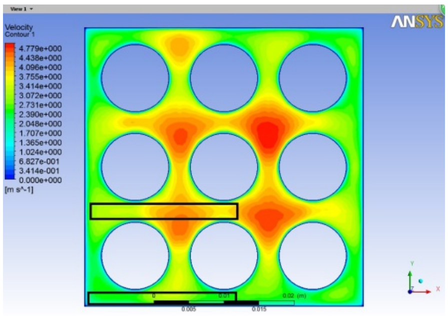
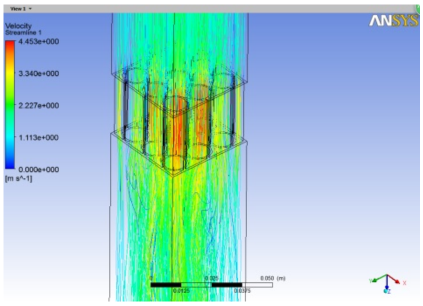
6	 Velocity Contour 1 4.779e+000 4.438e+000 4.096e+000 3.755e+000 3.414e+000 3.072e+000 2.731e+000 2.390e+000 2.048e+000 1.707e+000 1.365e+000 1.024e+000 6.827e-001 3.414e-001 0.000e+000 [m s^-1] ANSYS	 Velocity Streamline 1 4.453e+000 3.340e+000 2.227e+000 1.113e+000 0.000e+000 [m s^-1] ANSYS

Appendix B: Sample Benchmark results for elbow

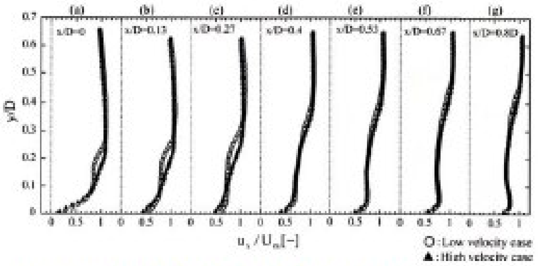


Fig 1a. Benchmark data by Ono et al[1].

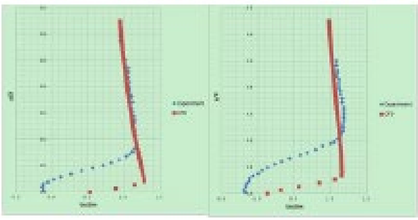


Fig1c. results by Chen XI

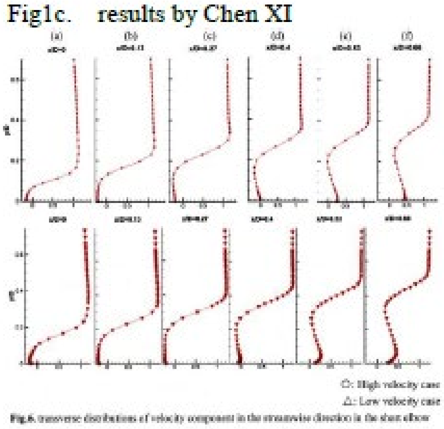


Fig1e. results by S. Li and P. Zhao

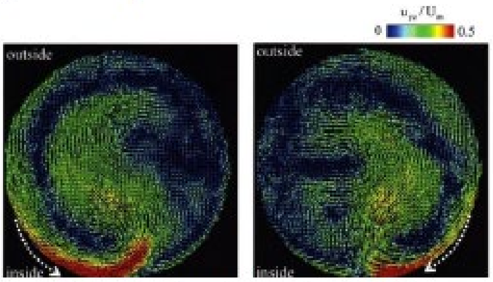


Fig 2a. Benchmark data by Ono et al[1].

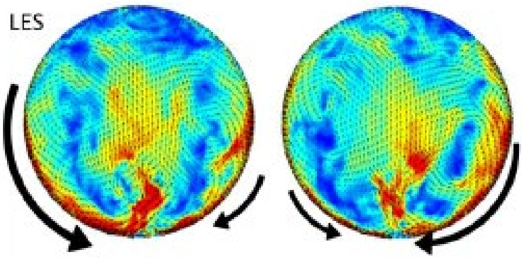


Fig2c. results by T. Tsuneyoshi

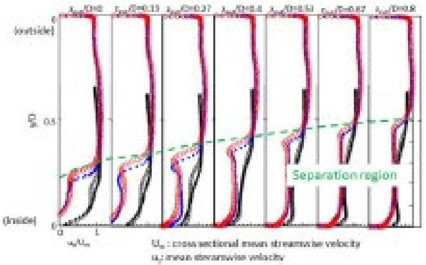


Fig1b. results by Y. Katai

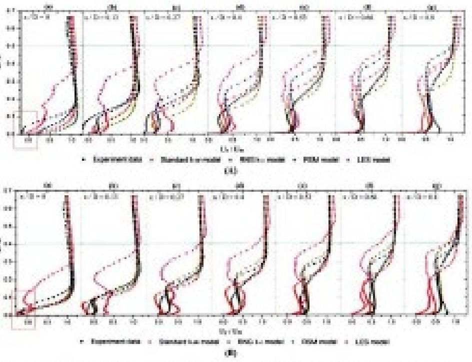


Fig. 5 Time-averaged transverse distributions of velocity components in the streamwise direction; (A) 1.71 million grids; (B) 3.35 million grids

Fig1d. results by D. Gong

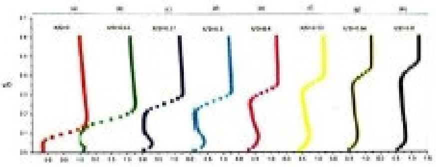


Fig.5 The transverse distribution of velocity component in the streamwise direcion in the short-elbow

Fig1f. results by K. Wang and W. Tian

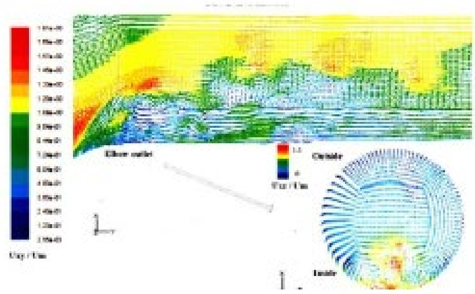


Fig 2b. results by D. Gong.

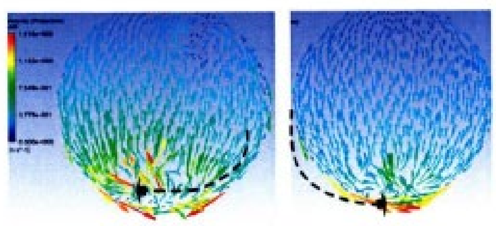


Fig.6 Time-series velocity in the cross-section of the tube

Fig 2d. results by K. Wang and W. Tian.

Appendix C

AC21 International CFD Workshop for Young Nuclear Engineers

AC21 CFD4You Workshop
Final Program

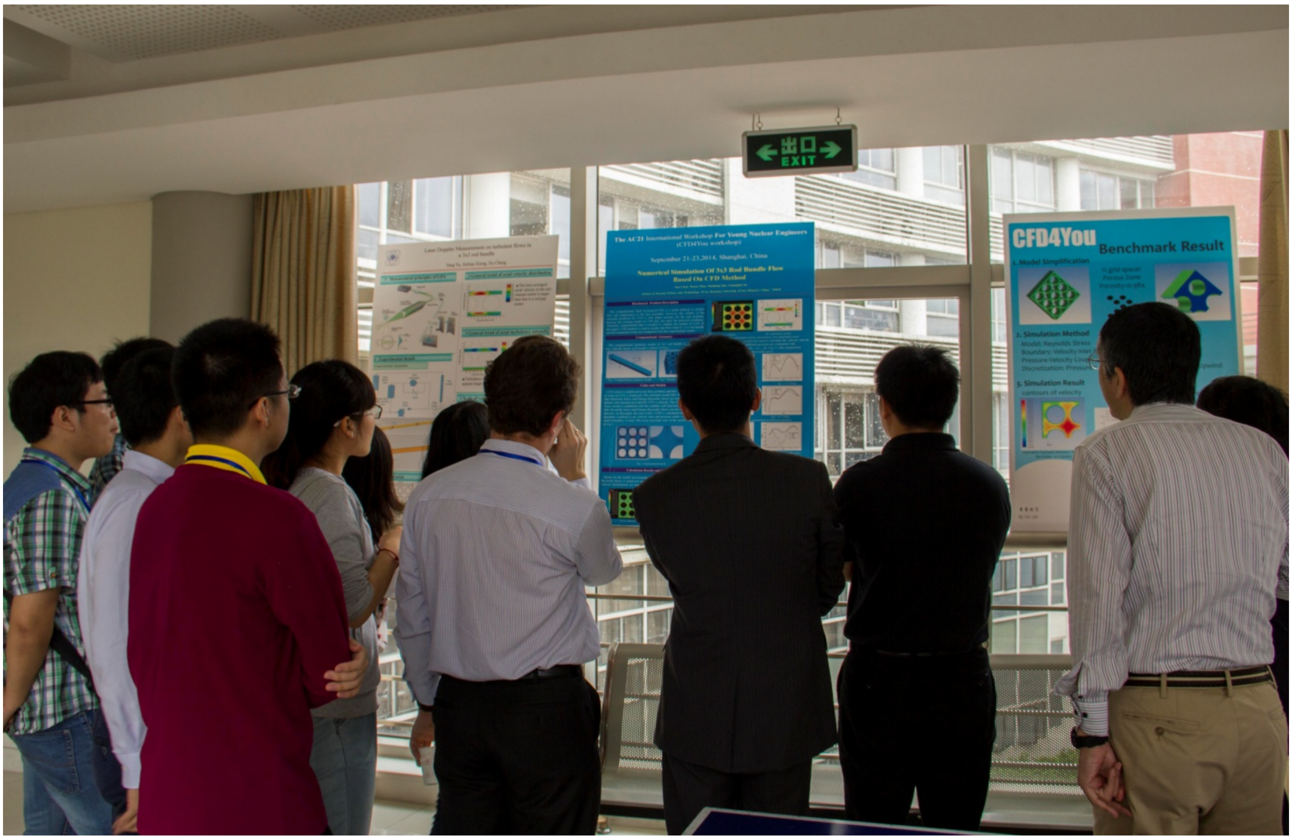
Co-organized by

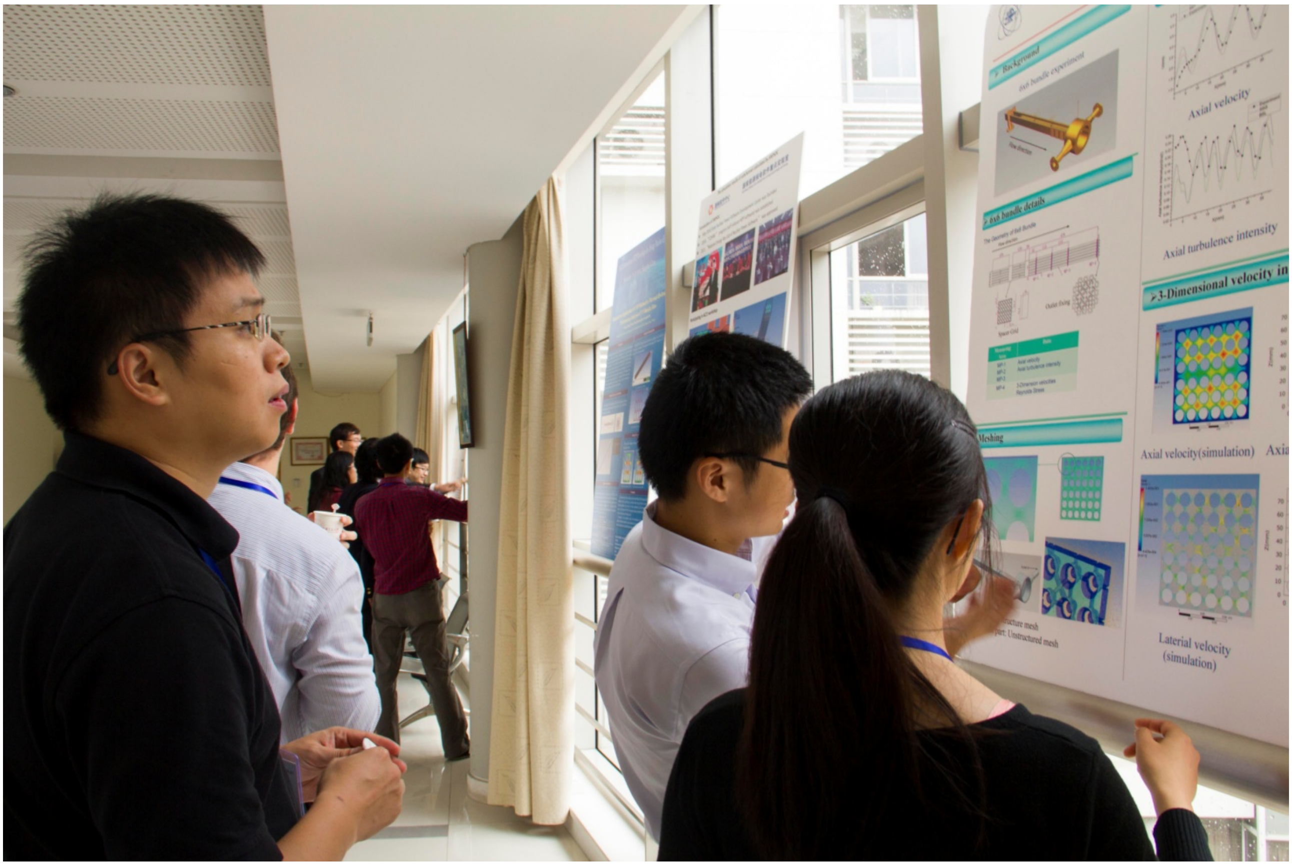
September 21, 2014	**Academic Exchange Center of SJTU**	
15:00-18:00	**Registration**	
18:00-20:00	**Reception dinner**	
September 22, 2014	**Room F310 Mechanical Building of SJTU**	
08:30-08:40	**Welcome Remarks**	
08:40-08:50	**Self-introduction by delegates**	
08:50-09:00	**Group photo**	
09:00-10:30	**Advanced simulation methods (1)**	**Chair: Prof. Yanhua Yang (SJTU)**
09:00-09:40	**Invited lecture**: Advanced simulation and visualization with particle method	*Prof. Seiichi Koshizuka (Univ. of Tokyo)*
09:40-10:10	Advanced methods in reactor thermal hydraulics	*Dr. Igor Bolotnov (NCSU)*
10:10-10:30	Melting simulation with the MPS method	*Ms. Hongyan Wang (SJTU)*
10:30-10:50	**Coffee Break**	
10:50-12:10	**Advanced simulation methods (2)**	**Chair: Prof. Seiichi Koshizuka (Univ. of Tokyo)**
10:50-11:30	**Invited lecture**: Development and application of a reconstructed discontinuous Galerkin method for computational fluid dynamics on arbitrary grids	*Prof. Hong Luo (NCSU)*
11:30-11:50	Numerical analysis of melt behavior at each stage of fuel coolant interaction	*Mr. Mingjun Zhong (SJTU)*
11:50-12:10	Grid Resolution Dependence in LES and Effects of Reynolds Number at Elbow in Circular Pipe Flow	*Mr. Tatsuya Tsuneyoshi (Nagoya Univ.)*

12:10-14:00 Lunch break (Campus Cafe)		
14:00-15:40 CFD application in Nuclear Engineering (1)		**Chair: Prof. Hong Luo (NCSU)**
14:00-14:40	**Invited lecture**: Challenges and Perspectives of CFD Application in Nuclear Engineering	*Prof. Yanhua Yang (SJTU)*
14:40-15:10	CFD Application in Nuclear Reactor Design in NPIC	*Ms. Songwei Li (NPIC)*
15:10-15:40	CFD Application in Reactor Internals Design	*Mr. Wei Zhang (SNERDI)*
15:40-16:00 Coffee Break		
16:00-17:00 CFD application in Nuclear Engineering (2)		**Chair: Prof. Yoshiyuki Tsuji (Nagoya Univ.)**
16:00-16:30	Validation of CFD calculation for rod bundle flow with LDV measurement data	*Dr. Jinbiao Xiong (SJTU)*
16:30-17:00	CFD application in predicting the two-phase flow in a steam generator	*Prof. Wenxi Tian (XJTU)*
17:00-18:00 Lab tour		
18:30-21:00 Welcome Banquet (Liuyuan Restaurant)		
September 23, 2014, Room F310 Mechanical Building of SJTU		
09:00-09:50 Benchmark Calculation for Rod Bundle		**Chair: Prof. Wenxi Tian (XJTU)**
09:00-09:10	Description of rod bundle benchmark	*Dr. Jinbiao Xiong (SJTU)*
09:10-09:20	CFD simulated results for CFD4YOU benchmark problems	*Mr. Zhao Chen (USTC)*
09:20-09:30	CFD simulation of turbulent flow in a 6x6 rod bundle	*Mr. Yang Yu (SJTU)*
09:30-09:40	Evaluation of flow characteristics on 3×3 bundle flow channel based on CFD method	*Ms. Rui Zhang (XJTU)*
09:40-09:50	Subchannels benchmark results	*Mr. Daqiang Yan (SNPSDC)*
09:50-10:20 Coffee Break & Poster Session for Rod Bundle Benchmark		
10:20-11:20 Benchmark Calculation for T-junction		**Chair: Dr. Igor Bolotnov (NCSU)**
10:20-10:30	Description of T-junction benchmark	*Prof. Yoshiyuki Tsuji (Nagoya Univ.)*
10:30-10:40	Comparison between RANS and LES with Experimental Measurements at Elbow in Circular Pipe Flow	*Mr. Yuki Katai (Nagoya Univ.)*
10:40-10:50	CFD simulation on flow through short elbow under Reynold number with RANS turbulence model	*Mr. Xi Chen (NPIC)*
10:50-11:00	CFD Simulations on flow structure at elbow outlet under high Reynolds number condition	*Mr. Kai Wang (XJTU)*
11:00-11:10	Benchmark report ---flow through an elbow	*Mr. Daxin Gong (THU)*
11:10-11:20	CFD simulated results for AC21 CFD4YOU benchmark problem (ii)	*Mr. Shuzhou Li (USTC)*

11:20-11:50	**Coffee Break & Poster Session for T-junction Benchmark**
11:50-12:00	**Award for Best Benchmark Posters and Presentations and Closing remarks**
12:00-13:00	**Lunch break (Campus Cafe)**
13:00-17:00	**Technical tour to Shanghai Nuclear Power Equipment Company** **Bus waits nearby the Campus Cafe.**

Appendix D: Photos during the workshop


出口
EXIT
The AC21 International Workshop For Young Nuclear Engineers
(CFD4You workshop)
September 21-23,2014, Shanghai, China
Numerical Simulation Of 3x3 Rod Bundle Flow Based On CFD Method
CFD4You
Benchmark Result
1. Model Simplification
2. Simulation Method
3. Simulation Result


Background
Axial velocity
Axial turbulence intensity
3-Dimensional velocity in
Meshing
Axial velocity(simulation)
Lateral velocity
(simulation)


MEMORY
Award Certificate
presented to
for