RESULTS OF CALCULATIONS OF THE IAEA BENCHMARK EXERCISE ON STEADY-STATE FLOW OF SUPERCRITICAL WATER IN A HEATED PIPE

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Abstract

The paper reports on a benchmarking activity carried on within the frame of the IAEA CRP on "Heat Transfer Behaviour and Thermo-hydraulics Codes Testing for SCWRs". The paper contains the description of the Benchmark Exercise No.1 "Steady state Flow in a Heated Pipe" (hosted by OKB "GIDROPRESS"), the computational results of 10 participants getting by 11 codes, and preliminary conclusions.

1. Introduction

The task of development and verification of thermal-hydraulics codes is one of the most urgent tasks to prepare designing supercritical water cooled reactors (SCWRs). The information on temperatures of fuel rod claddings and elements of reactor structure with operational states and accident conditions is critical when choosing existing or developing new constructional materials, it may considerably influence time-frame and feasibility of SCWR projects.

The principal difficulty of the application of subchannel and system thermal-hydraulics codes is the absence of the recommended and tested correlations for heat transfer coefficient and friction factor within the whole range of operating parameters and for rods bundle geometry. At present the most complete summary of the available experimental data and correlations is presented in [1].

The application of CFD codes has also some difficulties (for example, refer to [2]) related to the selection of turbulence model and nodalization of the test section. A dramatic variation of thermal-physical properties in the vicinity of pseudo-critical temperature is the reason for the difficulties. As the assessments have shown [3], at heat flux 1 MW/m^2 the water temperature changes by 20°C (from 395°C to 375°C) at 7 μm distance from the wall on the radius. Nearby pseudo-critical temperature normal velocity component occurs because of strong fluid extension, under such conditions the flow is similar to that with coolant blowing through the permeable wall [3]. Another difficulty of the application of CFD codes is "re-simplification" of the initial system of equations [3].

Within the IAEA Coordinated Research Project "Heat Transfer Behaviour and Thermo-hydraulics Codes Testing for SCWRs", it was proposed to take the first step and to realize the testing of thermal-hydraulics codes that exist or are developed by CRP participants. Generally, the testing was realized to compare the results of different codes and computational methods for the purpose to reveal possible considerable mistakes and shortcomings and to estimate possible range of computational results. The specifications of two benchmarks were prepared:

- Benchmark Exercise No.1 “Steady state Flow in a Heated Pipe” (hosted by OKB “GIDROPRESS”);
- Benchmark Exercise No.2 “Benchmark on Stability” (hosted by the University of Pisa).

Since the conditions of previous experiments were used when preparing computational tasks for Benchmark Exercise No.1, additionally the comparison of computational results with experimental data was performed.

This paper summarizes the description of the Benchmark Exercise No.1, the computational results of 10 participants obtained by 11 codes, and preliminary conclusions.

2. Description of the computational Benchmark Exercise No.1

The benchmark problem in this proposal consists of a simple steady-state flow of supercritical water in a heated pipe. Two cases are proposed for which experimental data exist:

- Case 1: Upward flow in a heated pipe;
- Case 2: Upward and downward flow in a heated pipe of a larger diameter.

2.1. Case 1: Upward flow in a heated pipe

The data for this case consist of heat transfer measurements (wall temperature) in a vertical circular pipe with uniform heating and are reported in [4]. The geometric parameters and boundary conditions of the task are presented in Table 1.

Table 1 Geometric and Test Parameters for the Case 1 and 2.

Parameter	Case 1 [4]	Case 2 [5]		
		Variant 1		Variant 2
		Up	Down	Up and Down
Pipe inside diameter, mm	10	25.4		
Heated length, m	4	2		
Unheated bottom length, m	-	0.63		
Unheated top length, m	-	0.16		
Mass flux, kg/m^{2}s	1500	820	892	380
Inlet temperature, ºC	352	250		200
Outlet pressure, MPa	24	25		
Heat flux, kW/m²	884	400		

2.2. Case 2: Upward and downward flow in a heated pipe

This will be a "blind" exercise in which the same modeling approaches that is chosen in Case 1 will be applied without any modification or tweaking. This exercise uses test data [5] where deteriorated heat transfer is observed only in the upward direction and should provide a good challenge for the modeling approach that was chosen for Case 1. The geometric parameters and boundary conditions of the task are presented also in Table 1.

3. Participants and codes

Ten participants took part in the computation of Benchmark Exercise No.1:

AECL	–	Atomic Energy of Canada Limited, Canada;
BARC	–	Bhabha Atomic Research Centre, India;
CIAE	–	China Institute of Atomic Energy, China;
GP	–	OKB "GIDROPRESS", Russia;
JRC	–	European Commission DG Joint Research Centre, the Netherlands;
KAERI	–	Korea Atomic Energy Research Institute, Republic of Korea;
MP	–	cooperation of the University of Pisa and McMaster University;
SJTU	–	Shanghai Jiao Tong University, China;
UMAP	–	cooperation of the University of Manchester, the University of Aberdeen and the University of Pisa;
VTT	–	VTT Technical Research Centre of Finland, Finland.

The above abbreviations of test problem participants are used subsequently to identify the calculation results.

Table 2 gives a list of researchers who took part in the exercise and the name of 11 computer codes used for calculations. Turbulence models used for CFD analysis are presented in Table 3. The turbulence models abbreviations from Table 3 are used subsequently to identify the subvariants of participants' calculation results.

Table 2 Participants and codes

Participants	Name of personal participants	Codes	
AECL	T. Beuthe, B. Hanna	CATHENA	Subchannel and system codes
GP	P.V. Yagov, A.N. Churkin	TEMPA-SC	
JRC	L. Ammirabile	COBRA-EN	
MP	F. Fiori, D. R. Novog, A. Petruzzi	TRACE5.0	
		RELAP5/Mod3.3	
VTT	J. Kurki, M. Hänninen	APROS	
BARC	A.M. Vaidya, P.K. Vijayan, N.K. Maheshwari	NAFA	CFD codes
CIAE	Z. Minfu, Y. Chen	ANSYS CFX	
KAERI	B.-H. Cho	Fluent	
SJTU	H. Gu, X. Cheng	Fluent	
		SIMPLE2D	
UMAP	W. Ambrosini	SWIRL	

Table 3 Turbulence models used for CFD analysis

Institute	Code	Turbulence Model (Abbreviation)
BARC	NAFA	Standard k-ε (SKE)
CIAE	CFX	Shear-Stress-Transport K-ω (SST)
KAERI	Fluent	ReNormalization Group k-ε (RNG); Reynolds Stress Model (RSM); Standard K-ω (SKW); SST; V^2-f (V2F); Low Re models: ABD, AKN, CHS, LB, LS, YS[1]
SJTU	Fluent, SIMPLE2D	SKE; RNG; SKW; SST; RSM; Low Re models: ABD, AKN, CH, CHC, JL, YS
UMAP	SWIRL	Low Re models: AKN, LS, YS

4. Results of calculations and discussions

Figures 1 – 5 show computational results of wall temperature for the subchannel and system codes (S&S codes). Figures 6 – 15 show computational results of wall temperature for the CFD codes.

[1] Abbreviations of the low Re models: AKN – Abe-Kondoh-Nagano; ABD – Abid; CH – Chien; CHC – Chang-Hsieh-Chen; JL – Jones-Launder; LB – Lam-Bremhorst; LS – Launder-Sharma; YS – Yang-Shih.

Some participants performed several variants of calculations for each exercise. All results can't be given in this paper because of volume limitation.

In Figures 1 – 5 symbols (1) and (4) for GP results mean different heat-transfer correlations: (1) – Kirillov ets. [6]; (4) – Krasnoshchekov and Protopopov [7]. Symbols (R) and (T) for MP results mean different codes: (R) – RELAP5/Mod3.3; (T) – TRACE5.0.

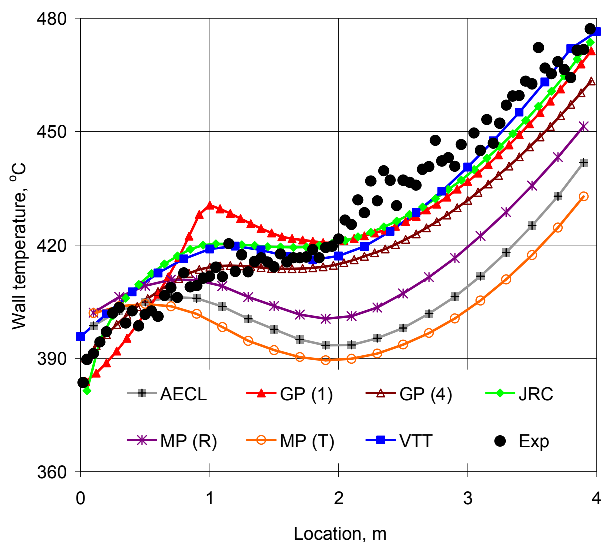

Figure 1 Case 1. S&S codes

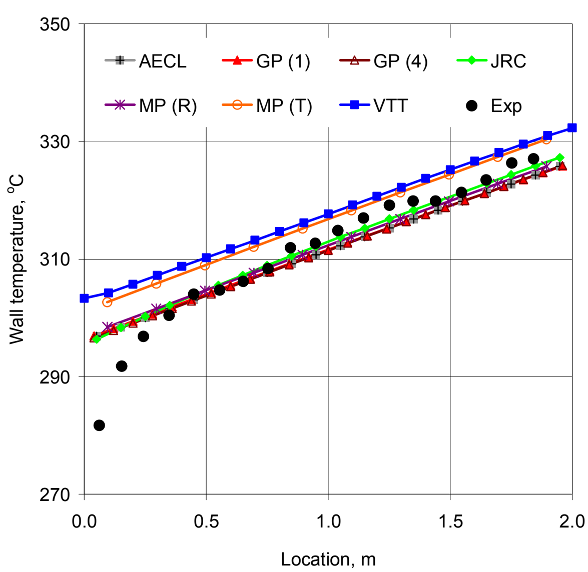

Figure 2 Case 2. Variant 1. Upflow. S&S codes

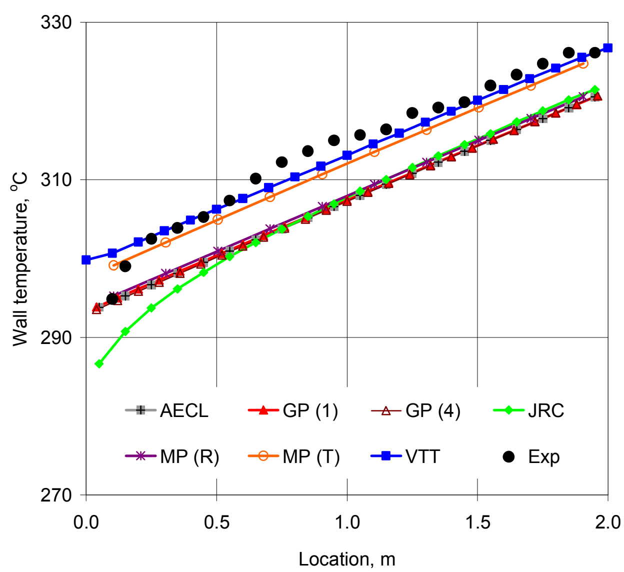

Figure 3 Case 2. Variant 1. Downflow. S&S codes

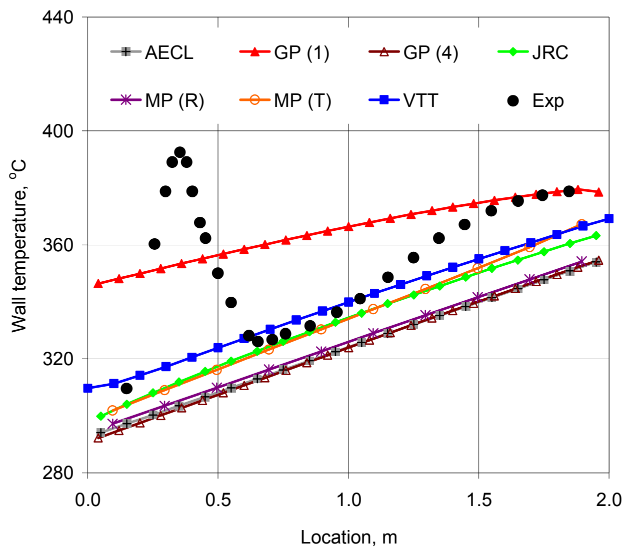

Figure 4 Case 2. Variant 2. Upflow. S&S codes

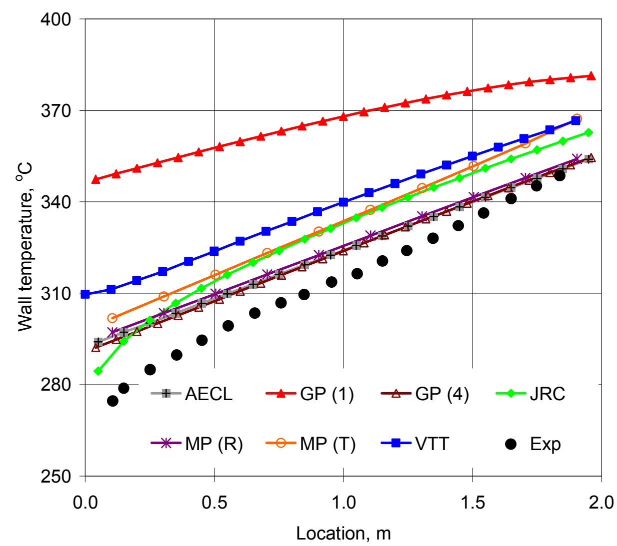

Figure 5 Case 2. Variant 2. Downflow. S&S codes

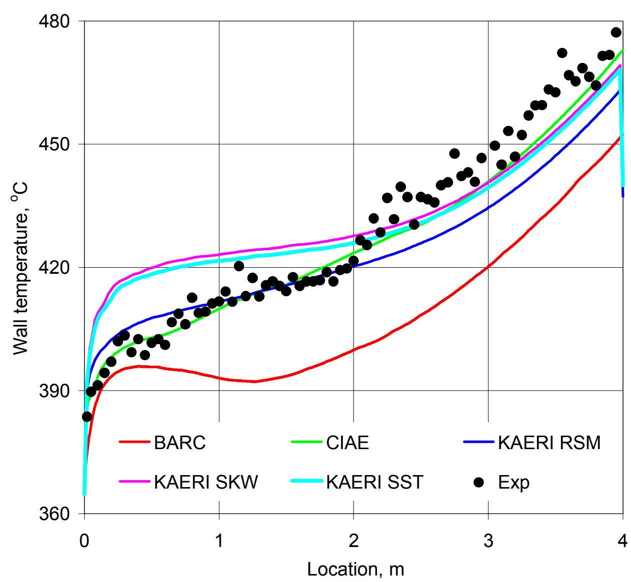

Figure 6 Case 1. CFD codes (Part 1).

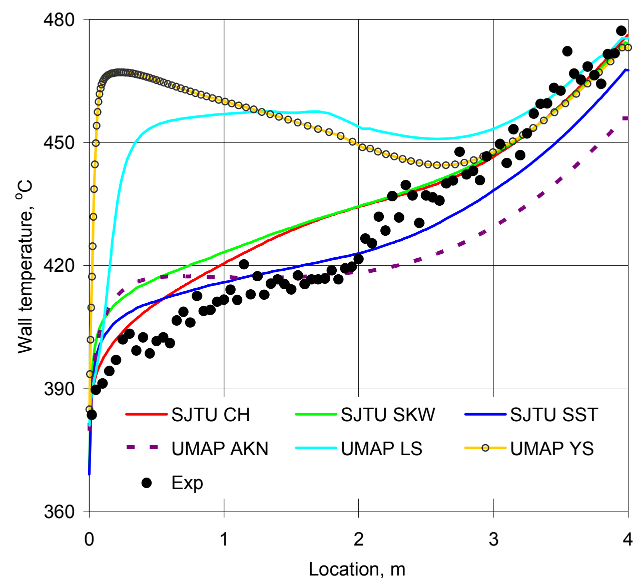

Figure 7 Case 1. CFD codes (Part 2).

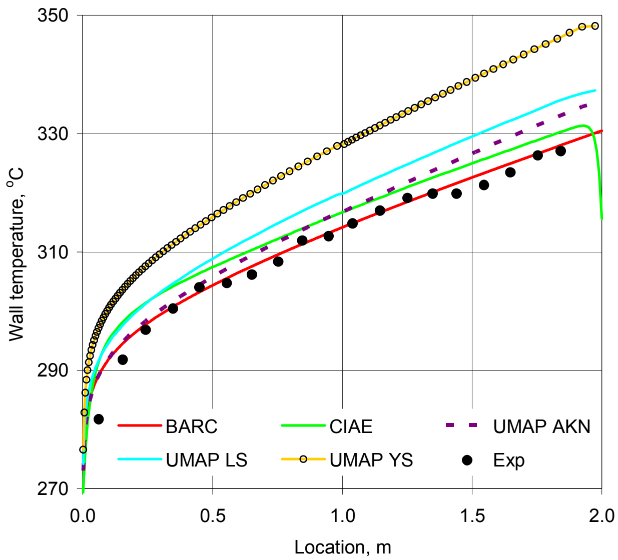

Figure 8 Case 2. Variant 1. Upflow. CFD codes (Part 1)

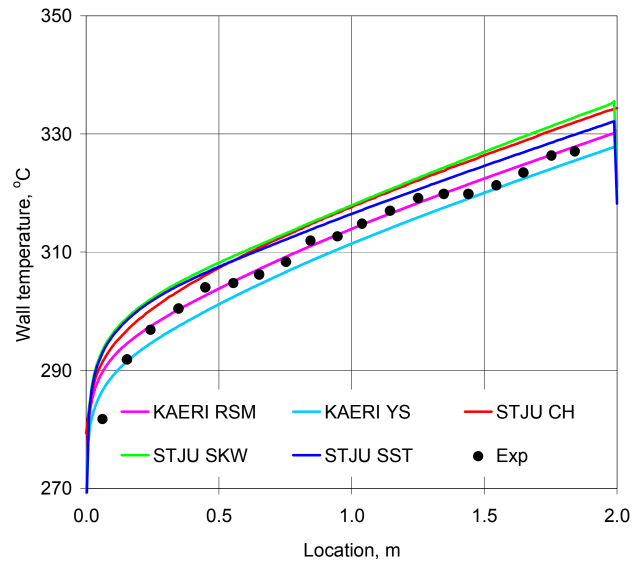

Figure 9 Case 2. Variant 1. Upflow. CFD codes (Part 2)

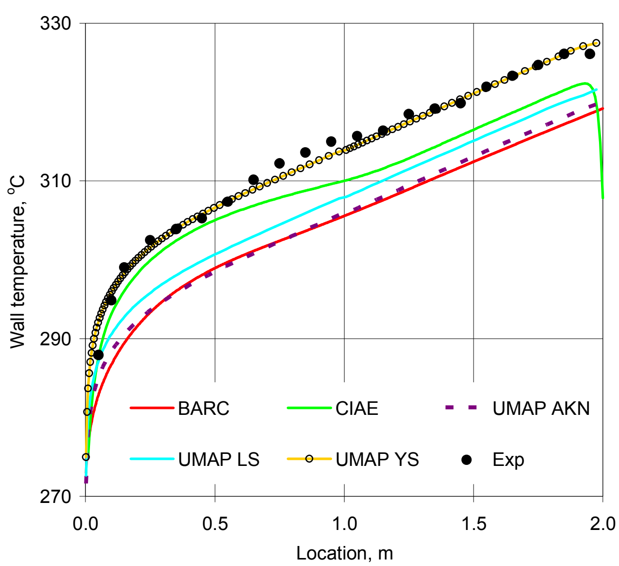

Figure 10 Case 2. Variant 1. Downflow. CFD codes (Part 1)

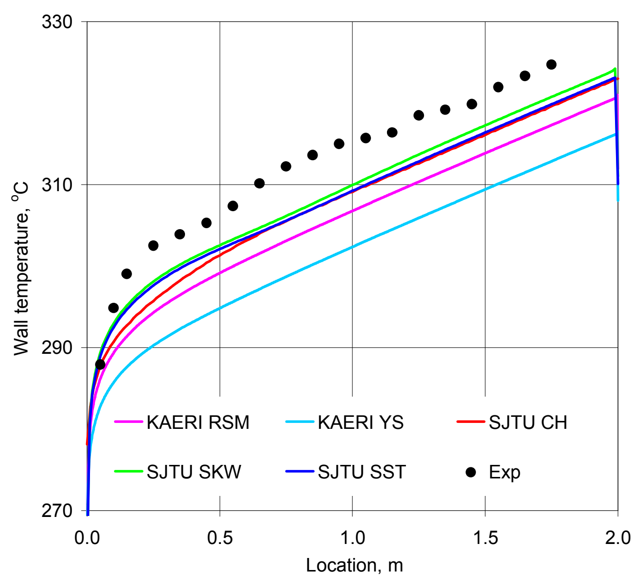

Figure 11 Case 2. Variant 1. Downflow. CFD codes (Part 2)

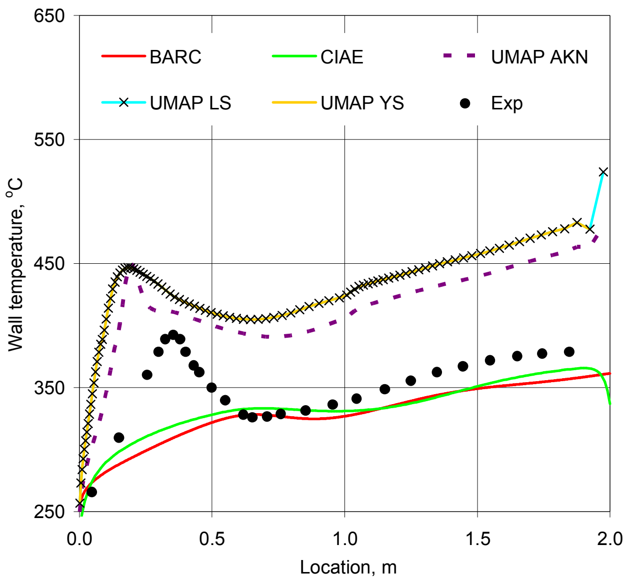

Figure 12 Case 2. Variant 2. Upflow. CFD codes (Part 1)

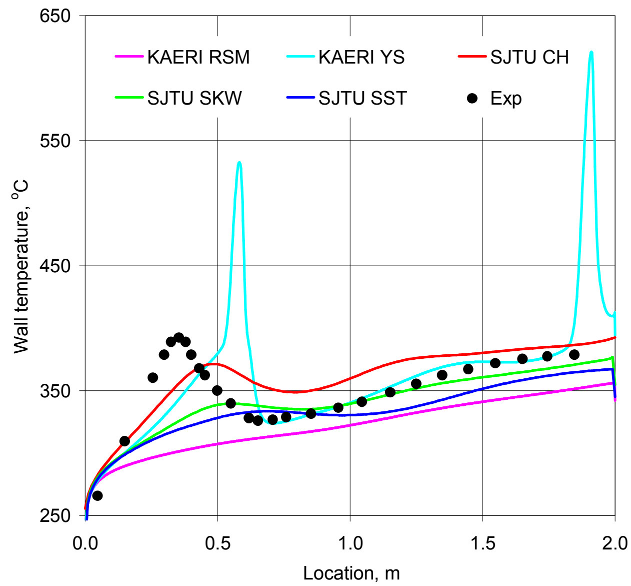

Figure 13 Case 2. Variant 2. Upflow. CFD codes (Part 2)

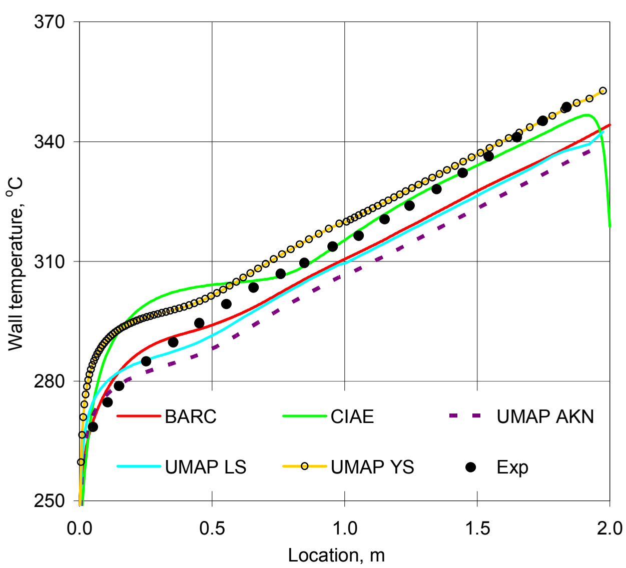

Figure 14 Case 2. Variant 2. Downflow. CFD codes (Part 1)

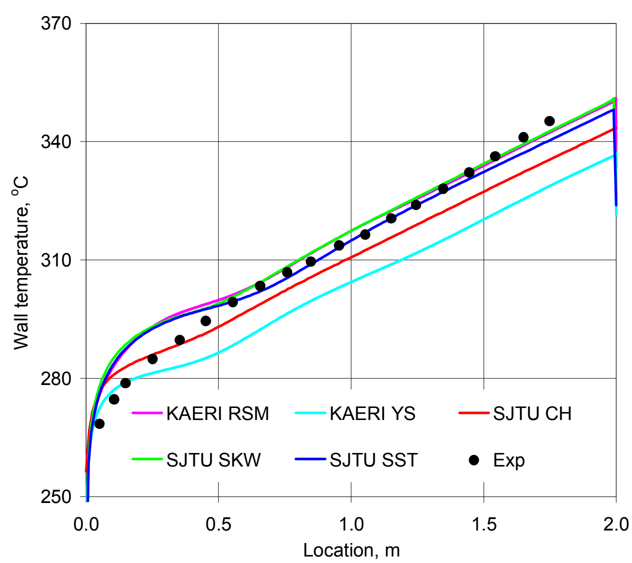

Figure 15 Case 2. Variant 2. Downflow. CFD codes (Part 2)

Only graphs of experiment and estimated values of temperature for inner surface of heated pipes are given in this paper. Other parameters such as temperature, density, water enthalpy, heat transfer coefficient and pressure drop along pipe were compared in Benchmark Exercise No.1. At present the analysis of obtained results is carried out. The analysis of experiments with new methods that Prof. J.D. Jackson (University of Manchester, UK) has developed is being carried out as well.

The participants' calculations made by subchannel and system codes showed very close values of integral parameters: balk water temperature, enthalpy and density. Only MP results of the enthalpy of water differ from the results of other participants. The mathematical model and computer code should be analyzed to determine the reasons for the differences.

Noticeable differences are observed in local parameters that are defined by correlations: pressure drop and heat transfer coefficient. It emphasizes again the necessity of formulating heat transfer and wall friction standard correlations for supercritical fluids.

For CFD codes, turbulence models SST, SKW and CH were found to perform better than other models as shown in Figures 6 – 15.

5. Conclusion

The paper presents calculation results of the Benchmark Exercise No.1 "Steady state Flow in a Heated Pipe" and their preliminary analysis. This Benchmark was prepared within the framework of the IAEA Coordinated Research Project "Heat Transfer Behaviour and Thermo-hydraulics Codes Testing for SCWRs" to test thermal-hydraulic codes.

It is preliminarily concluded that there are correlations and turbulence models that predict heat transfer coefficient and wall temperature of round pipe quite well, for supposed conditions of SCWR nominal operation. Revision of computational methods and programs is necessary for conditions where acceleration and buoyancy effects influence considerably.

Computation codes testing in pressure drop experiments on pipe is required, as Benchmark Exercise No.1 showed a considerable discrepancy of computation results. In addition it is necessary to perform experiments in bundles of fuel rods and to test codes for these geometries.

More detailed description of obtained results, cause analysis of discrepancies and recommendations on codes improvements will be given in the report of Coordinated Research Project "Heat Transfer Behaviour and Thermo-hydraulics Codes Testing for SCWRs".

6. Acknowledgment

The authors of this paper express their gratitude to all participants of Benchmark Exercise No.1, the list of whom is given in Table 2, for kindly presented calculation results and participation in discussions.

The authors are also thankful to Dr. R.B. Duffey (AECL), Dr. H. Khartabil (IAEA), Dr. N. Aksan and Dr. L. Leung (AECL) for participation in exercise performance and help in organizing Benchmark Exercise No.1. Deep gratitude to Prof. J.D. Jackson for given experiment data [5] and valued consultations.

7. References

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