# VALIDATION OF THE CATHENA FUEL CHANNEL MODEL FOR THE POST BLOWDOWN ANALYSIS FOR THE CS28-1 EXPERIMENT, I - STEADY STATE

Bo W. Rhee, H.S. Kang, H.T. Kim, B-J Min, J.H. Park
Korea Atomic Energy Research Institute,
*P.O. Box 105, Yuseong, Daejeon Korea, 305-600*
*Tel:* +82-42-868-2986,, *Fax:* +82-42-868-8256 ,

*Email:* bwrhee@kaeri.re.kr, jhpark@kaeri.re.kr

**Abstract**

To form a licensing basis for the new methodology of the fuel channel safety analysis code system for CANDU-6, a CATHENA model for the post-blowdown fuel channel analysis has been developed, and tested for a high temperature thermal-chemical experiment CS28-1.
As the major concerns of the post-blowdown fuel channel analysis are with the current CANDU-6 design characteristics how much of the decay heat can be discharged to the moderator via a radiation and a convective heat transfer at the expected accident conditions, and how much zirconium sheath would be oxidized to generate $H_2$ gas at what fuel temperatures, this study has focused on understanding these phenomena, their interrelations, and a way to maintain good accuracy in the fuel temperature prediction throughout the post-blowdown phase of a LBLOCA. Considering that an accurate prediction of the initial steady state of the experiment is important to better prediction, it was attempted to find what factors significantly contributes the prediction accuracy. As a result, the use of the constant emissivity of 0.80 for the entire transient for FES, and the non-participating medium treatment of the $CO_2$ gas annuls in CATHENA radiation model and the inability of CATHENA modeling of the possible natural convective heat transfer between the hot PT outer wall and the cold CT inner wall are identified as these factors. However the radiation model of CATHENA between FESs and PT is found to be accurate in the order of TC measurement accuracy reported Based on the prediction comparison of the current CATHENA model and the experiment data, the steady state model seems adequate as a starting point of the following high temperature thermal-chemical experiment of a metal-water reaction.

## I. Introduction

In a CANDU reactor the fuel and coolant are separated from the heavy-water moderator by two concentric horizontal fuel channels. Owing to this physical separation, even during a large break LOCA without a ECC injection, the decay heat from the fuel can be discharged to the cool huge volume of a moderator once the fuel temperature rises to such a degree not too high to jeopardize the structural integrity of the fuel bundle and channel, but high enough to dissipate the decay heat via a radiation heat transfer. So it has been a great concern as to whether the fuel channel integrity can be maintained even if there is no effective ECC injection from a long term core cooling viewpoint. As the fuel and fuel channel can be disintegrated not only by melting, but also metal-water reaction such as zirconium-steam, it is very important to thoroughly understand high-temperature fuel-channel behavior and to know the effectiveness of the moderator as a heat sink to demonstrate the safety of current and future PHW reactors during postulated accident.

This may be best achieved by understanding the involved phenomena not only by employing the appropriate mathematical models to describe them, but also by performing an intensive numerical simulation backed up by various separate effect tests results. These models can then be coupled into an integrated circuit code to predict a fuel-channel behavior under accident conditions. Computer codes such as CHAN-II, CATHENA and FACTAR are regarded as capable of predicting the thermal-chemical response of CANDU fuel channels when the internal coolant is superheated steam. These codes, however, must be validated against experimental data whenever possible. Data for a validation of the codes comes from various experiments involving the complex interactions of the temperature, material properties, heat transfer and reaction kinetics on fuel-channel components subjected to a severe temperature transient. One of these experiments used for a validation of the post-blowdown fuel channel analysis model of CATHENA is so called CS28-1, which is the first 28-element bundle high temperature experiment.

In Korea, since the completion of the Wolsong 2,3,4 licensing, there have been few appreciable activities on the CANDU safety except that for a CANFLEX-NU demonstration irradiation at Wolsong-1 in 2004. Therefore properly maintaining the safety analysis system such as the related computer codes, input deck, the computer hardware and staffs has been the task of the CANDU safety analysis group. Meanwhile a significant effort has been poured to establishing a self-sustaining CANDU safety analysis system while filling the technology gap for those areas which were the responsibilities of AECL during the Wolsong 2,3,4 projects, one of which is the moderator circulation and subcooling analysis. Another effort was to replace the old analysis codes with more recently developed and realistic codes and methodology, one of which is to replace the CHAN-II code with CATHENA for the post-blowdown fuel channel analysis. To this end an advanced model for the post-blowdown fuel channel analysis for CANDU-6 has been developed based on the interim version of the CATHENA fuel channel model for the post-blowdown analysis which was frozen since the completion of the Wolsong 2,3,4 licensing, and is being considered to replace the current CHAN-II model in the near future after a proper testing and validation. This paper describes one of these efforts to validate this advanced fuel channel model of CATHENA for the post-blowdown fuel channel analysis. As there is only a few high temperature thermal-chemical CANDU fuel channel experiments subject to a metal-water exothermic reaction resulting in a fuel sheath and possible bundle disintegration which are applicable to 37-element fuel case, it was decided to develop a 3-D post-blowdown fuel channel analysis model by using the CFD model based on the commercial codes such as CFX or FLUENT and to validate it against the existing 28-element high temperature thermal-chemical CANDU fuel channel experiment such as CS28-1, 2, 3. Then the same technique and methodology can be applied to develop one for a 37-element fuel channel case for a CANDU-6 application. Eventually this model after proper validation will be used to generate a benchmark problem of 37-element fuel case, which can then be used to validate the CATHENA post-blowdown model for CANDU-6. Therefore to this aim a 3-D CFD model based on the CFX code is being developed and a validation of this model against CS28-1[9] will be performed. This paper describes one of the recent studies to validate the CATHENA post-blowdown fuel channel model for the CS28-1 experiment. The motivation of this work is the authors belief that the theoretical and technical know-how involved in developing and validating post-blowdown fuel channel models for 28-element and 37-element fuel channels would be essentially the same. So once the one for a 28-element channel is successful, it can be also applied to 37-element case without much difficulty.

As a first step to carry out this research, the authors reviewed the previous works[1-9] for validating the CHAN-II and CATHENA codes against 1-, 7- and 28-element experiments. I was found that there was room to be improved in these works, especially the matching of the computer code models' prediction of the initial steady state. It is the authors opinion that the loose prediction of the transient fuel and fuel channel behavior by the CHAN-II code or especially the CATHENA code are partly due to the failure to match the steady state condition more accurately at the outset, and then use it as the initial condition for the rest of the transient. Therefore it is treated separately in this paper and how the authors managed to match the initial steady state fuel and fuel channel condition rigorously and thus succeed to better predict the rest of the whole transient of the CS28-1 experiment is given in detail.

## II. Test Conditions, the Measured Temperatures of the Steady State of Experiment CS28-1.

In this steady state, a radiation and convective heat transfer problem, two heat transfer mechanisms contribute and compete with each other to determine the FES fuel temperature for the given boundary conditions, which are the pool water temperature, the temperature, pressure and flow rate of the inlet steam and the incoming CO2 flow into the annulus as well as the heat input of the individual FES heater.

1. Experimental Set Up and Operating Conditions are as follows;

1) This is the high temperature thermal-chemical experiment with the largest number of fuel elements carried out by AECL
2) All the FES (Fuel Element Simulator) of a length of 1.8m is held in place and divided into 6 axial regions separated by 5 Zirconium spacer grid plates.
3) In the annulus between the inside pressure tube and the outside calandria tube $CO_2$ gas of 10 g/s is flowing.
4) For cooling the calandria tube it is submerged in the water pool of a temperature of 40 $\pm$5 $^{o}$C
5) The superheated steam at 700$^{o}$C flows into the short inlet plenum through the small sized inlet piping located at the top of the calandria tube entrance at a rate of 10.2 g/s.
6) The heater power is 10kW, and the power ratio of the inner, middle, and outer ring fuel is 0.78; 0.88 ; 1.10 respectively and one of the heater R-1, red shaded one in the inner ring, has failed.
7) The T/C was installed at two locations of each FES, one at the inner and the other at the outer to measure the difference inside and outside due to a radiation heater transfer as shown in Fig.1 of the bundle cross section.
8) The pressure tube temperature was measured at 8 locations which were evenly spaced as shown by black dots on the right outside the pressure tube in Fig.1.
9) The calandria tube temperature was measured at two locations, one at the bottom and the other at the top as shown as by black dots on the right outside of the calandria tube.

10) The moderator temperature was measured at two locations, one at the pool bottom, and the other at the top of the pool water. Both thermocouples indicate that the pool water heat up rate lies between 0.0035$^o$C/s and 0.0040$^o$C/s.

The basic heat transfer mechanisms in the fuel channel are the radiation heat transfer between the FES heaters and the pressure tube, and the convective heat transfer between the FES heaters and the steam coolant. The relative contribution of each mechanism to the total heat transfer will be determined by the relative thermal resistances of each mechanism at various axial positions of the test bundle. The basic heat transfer mechanisms between the pressure tube and the calandria tube are again a radiation heat transfer between the pressure tube and the calandria tube, and a convective heat transfer between the pressure tube and the $CO_2$ gas flow, and a calandria tube and $CO_2$ gas flow, and a conduction heat transfer between the pressure tube and the calandria tube via a garter spring. The heat transfer between the calandria tube and the pool water would be a natural convective heat transfer by the pool water. The method as to how each of these heat transfer mechanisms are modeled and handled is described in the following section of the CATHENA model description. In this case, the reference temperature to which all the other temperatures are computed would be the temperatures of the pool water and, the inlet steam coolant provided the effect of the $CO_2$ convective heat transfer be negligible. Thus accurate temperature prediction of the calandria tube, the pressure tube, the FES heater and the steam coolant against the experimentally measured values are very important to validate the appropriateness of the corresponding models of the CATHENA code.

The measured parameters of the major solid components and the test section inlet are:

1) Calandria Tube Temperature., Pressure Tube Temperature.
2) FES (Fuel Element Simulator) Temperature.
3) Steam Temperature, Pressure, Flow Rate and the Electric Power to the FES Heaters.

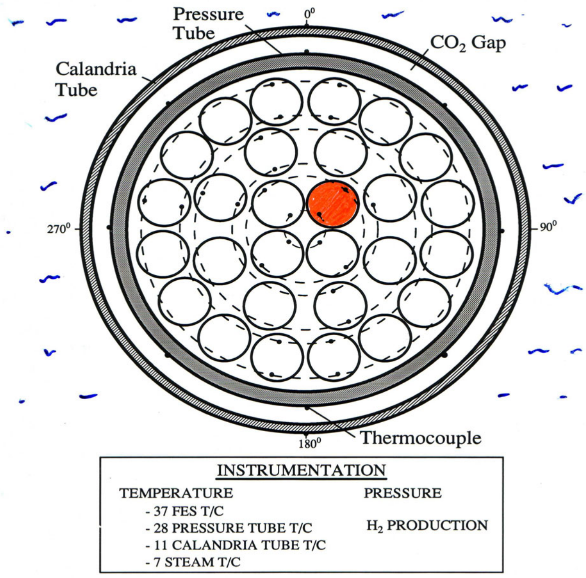


Fig. 1. Cross Section of the CS28-1 Test Bundle and Thermocouple Locations.[11]

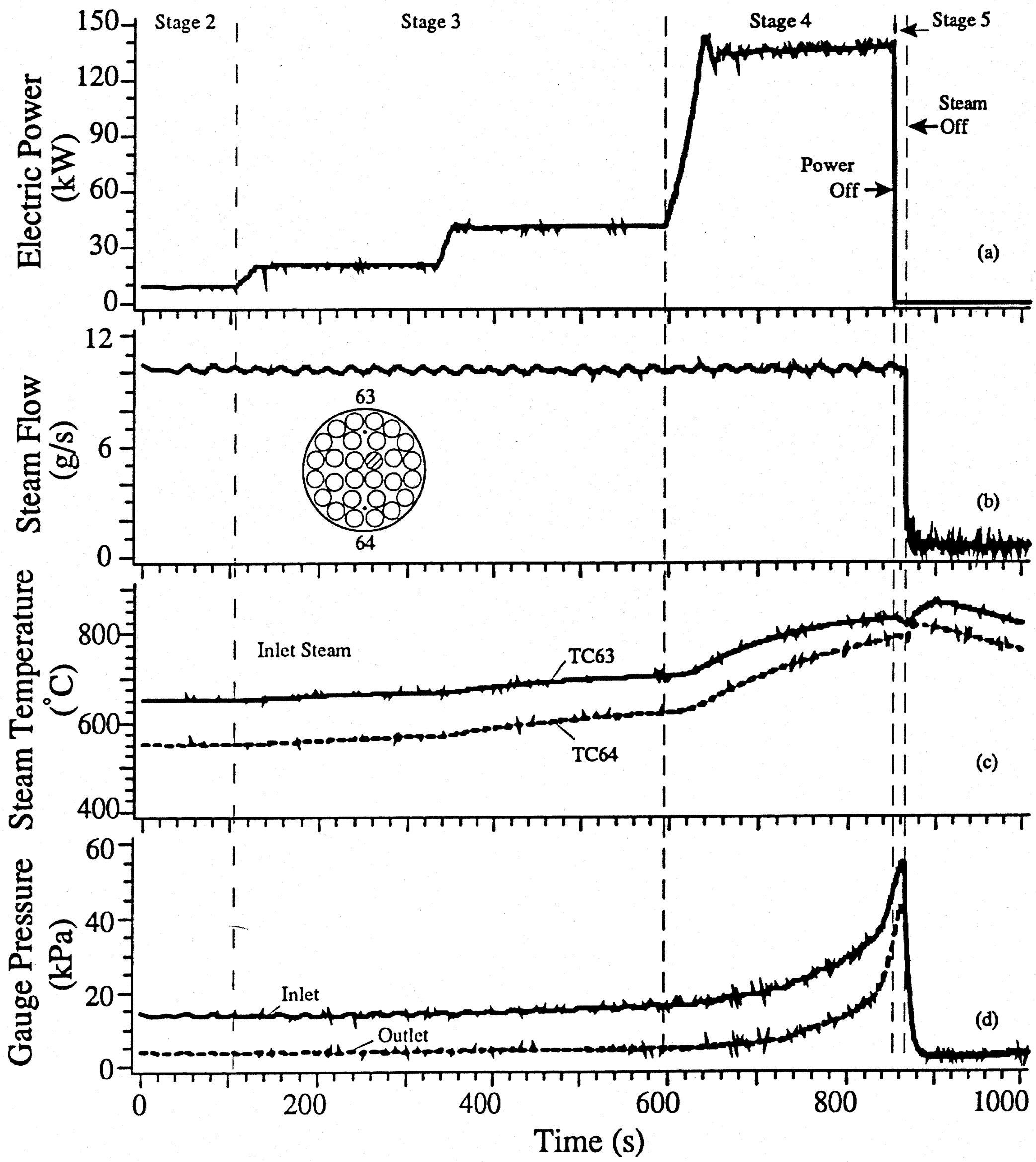


Fig.2. Electric Power to the Heater, and the Inlet Steam Flow Conditions.[9]

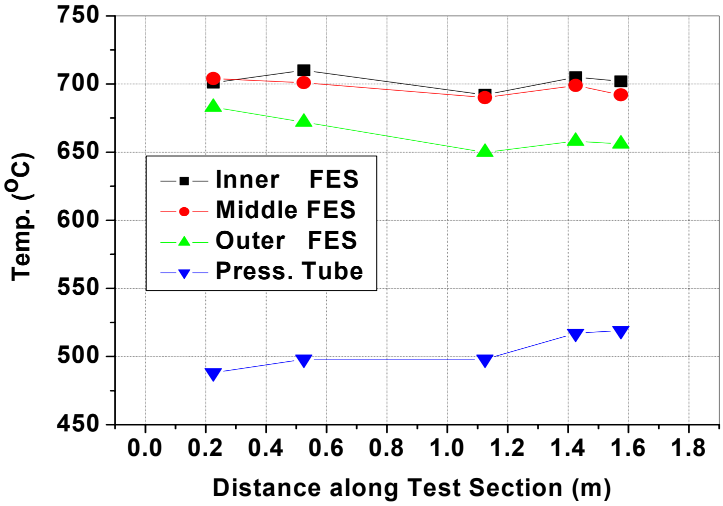


Fig. 3. Inner, Middle and Outer Ring FES and the PT temperatures along the axial Direction [11]

## III. Heat Transfer Model Description of the CATHENA Post-Blowdown Analysis

1. Solid Structure Model
   1) Fuel Element Simulator

      Graphite heater, oxide layer, gap, zircaloy sheath and a $ZrO_2$ oxide layer on the outside surface of the sheath are modeled as is, and the $ZrO_2$ layer is included to model the zirconium-steam reaction. Each FES is circumferentially divided into two sectors to represent the surfaces facing inward and outward. The size of these two sectors is chosen to approximately match the surfaces facing each coolant subchannel. Axially the total length of the FES is divided into 12 segments, two per each axial section divided by a spacer grid. A circumferential conduction is neglected. The urbanic-Heidrick correlation is used to model the metal-water reaction. The thickness of the oxide layer and the volume of the hydrogen produced are considered.
   2) Pressure Tube, Calandria Tube

   No circumferential and axial conduction are assumed. The pool water simulating the moderator is coupled to the calandria tube as a thermalhydraulic boundary condition. Zircaloy is used for the pressure tube material, and a heat generation from the zirconium-steam reaction is modeled on the inside surface of the pressure tube, by using the initial oxide layer thickness of $10^{-6}$ m. Pressure tube and calandria tube are divided circumferentially into 10 sectors. The annulus gap between the pressure tube and the calandria tube is modeled as an insulated space with a prescribed boundary condition.

2. Annulus Shaped Subchannel Model

Each fuel bundle consists of 28 fuel elements arranged in 3 rings (4,8 and 16 pins in the inner, middle and outer fuel rings respectively). The FES are equispaced along the concentric pitch circles. This ring type bundle structure can cause a density-stratified flow when steam is heated up under a low flow condition. To consider it, a coolant channel is divided into three subchannels as shown in Fig.4. The flow rate in each subchannel depends on the subchannel cross-sectional area and the relative flow resistance among the subchannels. Therefore depending on the flow condition, and the steam properties, a convective heat transfer can be calculated between the steam and the solid components. (fuel pin and/or pressure tube). Where there is a spacer grid plate, a complete coolant mixing is enforced by modeling a small pipe component at each spacer grid location.

3. Radiation Heat Transfer Model

The radiation model calculates the heat exchange due to a thermal radiation among the solid component models; between the FES facing each other, between the FES and the pressure tube, and also between the pressure tube and the calandria tube. The view factor matrix is generated separately by using the utility program MATRIX. An emissivity of 0.8 (based on $ZrO_2$) is used for the fuel sheaths and the inside surface of the pressure tube and the inside surface of the calandria tube. A detailed view factor matrix between the pressure tube and each of the 28 FES is generated first, and then converted to the contracted view factor matrix file which is consistent with the solid component models.

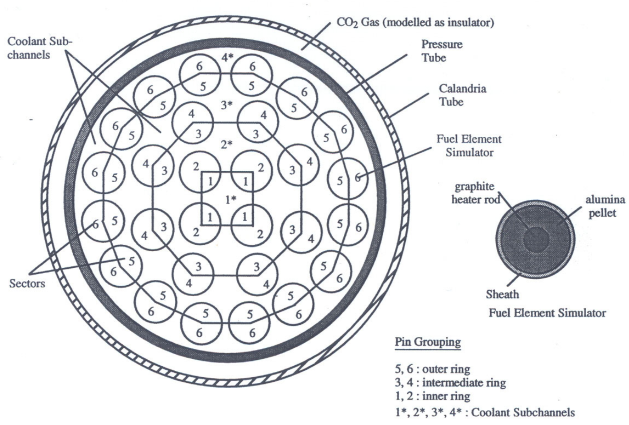


Fig. 4. Solid Structure Model and Subchannel Model for CS28-1 Experiment

As there remains a significant discrepancy between the measured pressure tube temperatures and those predicted by CATHENA after accounting for all these radiation and convective heat transfer of $CO_2$, it was decided as necessary to introduce a multiplying correction factor to the $CO_2$, convection heat transfer coefficient necessary to match the measured pressure tube temperature, which is conjectured to account for the enhanced conduction effect of the garter spring between the pressure tube and the calandria tube.

## IV. CATHENA Fuel Channel Analysis and Results.

The measured inner ring temperature remains essentially constant along the length of the test section as shown in Fig.3 whereas that predicted as shown in Fig.5 shows a slight decrease along the axial distance. This indicates that the heat transfer rate is uniform along the length of the inner FES elements. Generally because of their closer proximity to the pressure tube, the middle ring FES elements are cooler than the inner ring FES elements. Because of this, the middle ring FES element temperatures are expected to exhibit similar trends to those of the inner ring FES elements, as shown in Figure 6. Outer ring FES element temperatures are strongly affected by the presence of the nearby pressure tube. Since the pressure tube temperatures tend to be significantly lower than the FES temperatures, the heat removal rate from the outer ring of the FES elements is limited by the temperature of the adjacent circumferential segment of the pressure tube. The comparison of the outer ring FES temperatures shown in Fig.3 and Fig.7 indicates that there is an axial temperature gradient for the first half length of the test section with the highest temperature occurring near the steam inlet. This indicates that the hot inlet steam is being cooled at the entrance to the test section and that the “cooling length” is roughly half the length of the test section. The CATHENA prediction in Fig.7, though the slope change is not that clearly recognizable, shows a similar trend. Considering that the accuracy of the temperature measurement is ±2%, which corresponds to ±19.5°C for the temperature of 700°C, and the accuracies for the other boundary condition parameters, the prediction of the CATHENA model of this work can be deemed to be acceptable.

As for the justification of the adjustment of the convective heat transfer coefficient across the $CO_2$ gap to match the measured pressure tube temperature, the authors could not explain whatsoever the reason why the pressure tube temperature should be so low in spite of accounting for all the radiation heat transfers as well as the convective heat transfers of the $CO_2$ gas flow enhanced by the secondary type natural circulation flow between the hot pressure tube and the cold calandria tube[13,14]. A few possible explanations for this high heat transfer rate across the $CO_2$ gap are; (1)the enhanced conduction by the garter spring, (2)the enhanced cooling effect of the $CO_2$ flow caused by the intrusion of the welded spot of the T/C embedded into the pressure tube outside[10], (3)Deposition of thermal radiation from PT in the high absorptive medium of $CO_2$.gas, thus heating the $CO_2$ gas more than CATHENA radiation model can account for, and then cooled by natural convection at the cold CT inside wall.

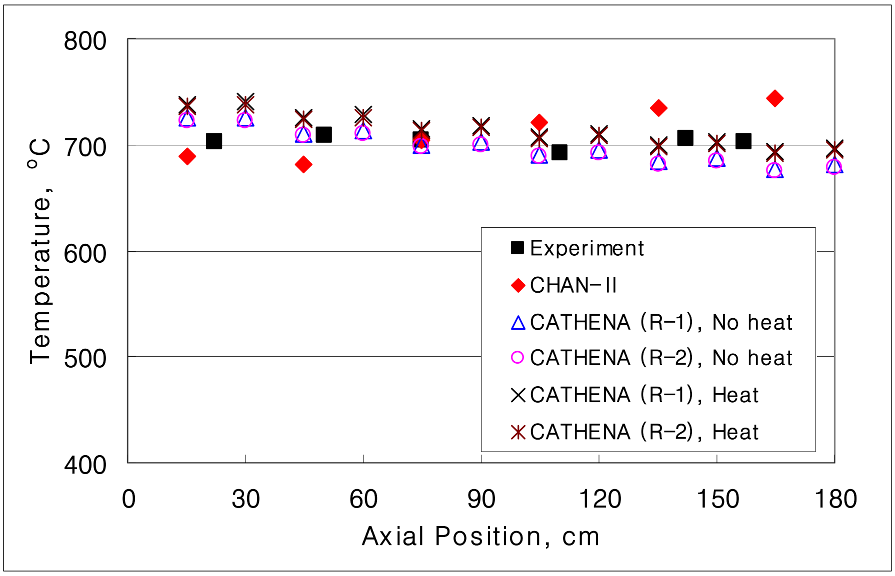


Fig. 5 Inner Ring FES temp. along the axial direction

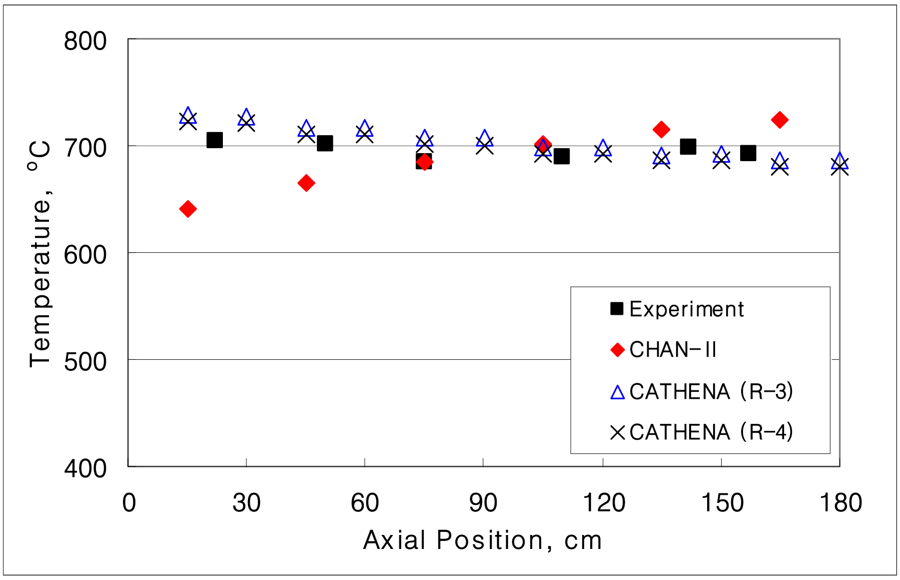


Fig. 6. Middle Ring FES temperature along the axial direction

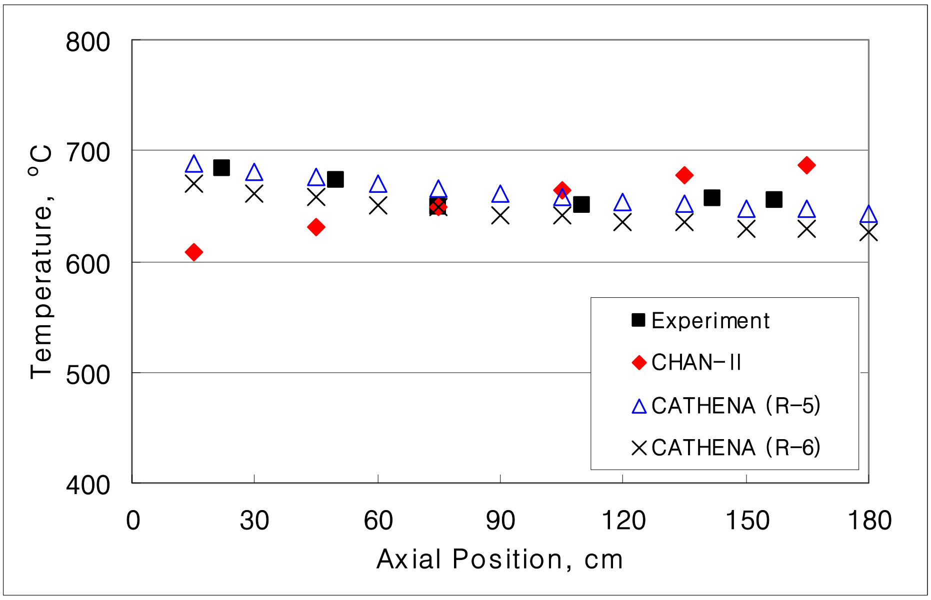


Fig. 7. Outer Ring FES temperature along the axial direction

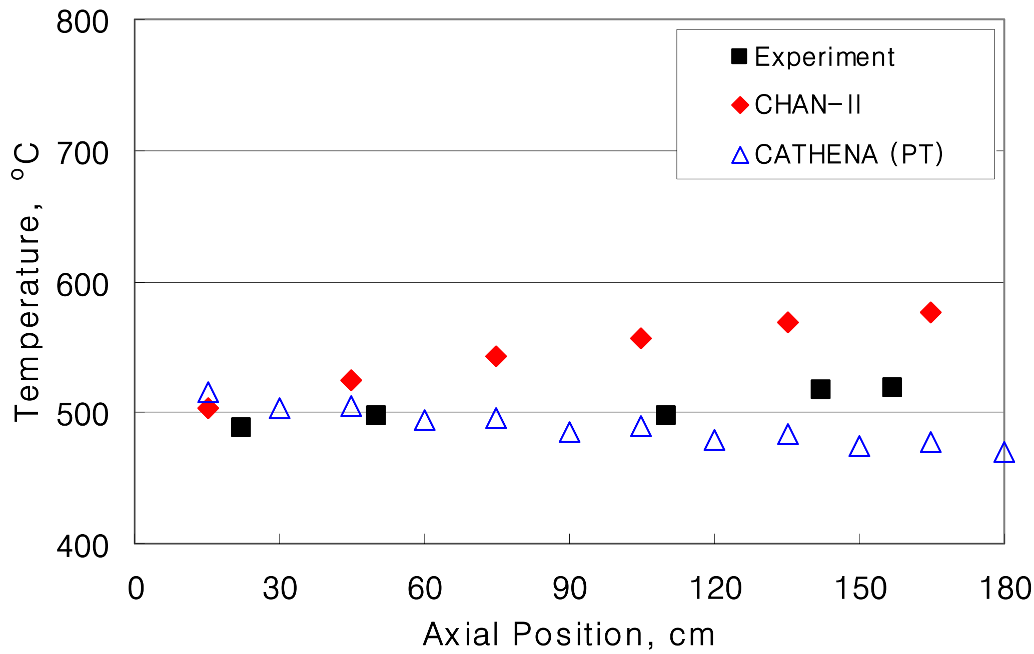


Fig. 8. Pressure Tube temperature along the axial direction

## V. Conclusion

Once the pressure tube temperature is predicted correctly by the CATHENA radiation model between PT and CT through some adjustment, all the remaining temperatures of the inner ring, middle ring and outer ring temperatures can also be predicted quite satisfactorily, say to within an accuracy range of $\pm 20 \sim 25^{o}C$, which is comparable to the reported accuracy of the temperature measurement is ±2%[9]. In CATHENA the pressure tube temperature can be matched to the measured ones by applying a correction multiplier to the $CO_2$ conductivity as there is no way to account for enhanced convective heat transfer between PT and CT along with using radiation heat transfer model. Once this can be done, the FES temperatures can be pretty easily matched, which proves the robustness of the radiation model, at least between FES and PT.

The slightly decreasing trend of the pressure tube temperature prediction along the axial direction seems to affect all the other FES temperatures so that they show similar trends unlike the flattened trend of the measured temperatures. From a closer observation of the results, it was found that this slope is sensitive to the magnitude of the radiation heat transfer rate, and it can be adjusted by varying the emissivity of the PT and CT tubes.

Through this study, several possible reasons or factors could be identified that may significantly affect the accurate prediction of the initial steady state of the experiment, which in turn is very important to the accurate temperature prediction of the whole transient. Also the relationship between the emissivities of the FES, PT and CT and the axial slope of these temperatures could be better understood.

## ACKNOWLEDGMENTS

This work has been carried out under the Nuclear Research and Development program of Korea Ministry of Science and Technology. The authors also thanks to Dr. D.B. Sanderson and T. Nitheanandan of AECL for their great help for valuable information on the CS28-1 experiment.

## References

[1] M.Risk, et al, "Assessment of the Code CHAN3 for the Prediction of the Thermal Response of a CANDU Fuel Channel During a Loss-of-Coolant Accident With Impaired Emergency Cooling Against Experimental Results", Proc. 8th Annual Conference of Canadian Nuclear Society, St.Jone, NB, Canada, June 1987.

[2] M.H. Bayoumi, et al, "Verification of CHAN-Ⅱ(MOD6) Against Experiments", 10th Annual Conference of Canadian Nuclear Society, Ottawa, Ontario, Canada, June 4-7, 1987.

[3] N.H. Bayoumi, A.P. Muzumadar, F.B.P. Tran and K.E. Locke, "CHAN-Ⅱ(MOD6) - Further Verification Against Seven Element Experiments",Proc.11th annual Congerence of Canadian Nuclear Society, Toronto, ON, June 1990.

[4] D.B. Sanderson, K.A. Haugen, R.G. Moyer and H.E. Rosinger, "Out-of-Pile Fuel Channel Experiments for Severe Accident Conditions", Proc. ANS International Topical Meeting on Safety of Thermal Reactors, Portland, Pregon, July 1991.

[5] Q. Lei, D.B. Sanderson, M.J. Brown and H.E. Rosinger, "Comparison of CHAN-Ⅱ_WL Predictions with Measurements Made During Seven-Element High Temperature Thermal Chemical Experiments", 12th Annual Conference of Canadian Nuclear Societh, Saskatoon, SK, Canada, 1991.

[6] J.P. Mallory, M.A. Wright and H. Hyunh, "Validation of CATHENA at High Temperature Conditions Using CHAN Thermal-Chemical Experimental Resules", 12th Annual Conference of Canadian Nuclear Societh, Saskatoon, SK, Canada, 1991.

[7] D.B. Sanderson, Q.M. Lei, J.P. Mallory and M.Bayoumi, "A Blind Simulation Study of an Out-of-Pile High-Temperature Fuel Channel Experiment", 16th Annual Nuclear Simulation Symposium, St..John, NB, Canada, 1991.

[8] M.H. Bayoumi and W.C. Muir, "Post-Test Simulation and Analysis of the Second Full Scale CHAN 28-Element Experiment (Validation of CHAN-Ⅱ (MOD6) against Experiments)", 16th Annual Conference of Canadian Nuclear Society, Saskatoon, SK, Canada, 4-7 Jun 1995.

[9] Q.M. Lei, D.B. Sanderson, K.A.Haugen and H.E. Rosinger, "Post-Test Analysis of the 28-Element High-Temperature Thermal-Chemical Experiment CS28-1",4th International Conference on Simulation Methods in Nuclear Engineering, Montreal Canada, June 2-4, 1993.

[10] CHAN 28-Element Fuel-Channel Thermal-Chemical Experiments, T. Nitheanandan, May 2005, JRDC Meeting between KAERI and AECL.

[11] Validation of CHAN-IIA MOD2.0 Against the CHAN CS28-1 High Temperature Experiment, TTR-493, D.B. Bowslaugh, October 1993, AECL CANDU.

[12] Notkuhlung eines 37-stabbundels durch Warmestralung, Van W. Hufschmidt, E. Burck, H. Hoffmann, pp 307-311, Reactor Technique and Technology, Atomkernenergie [ATKE] Bd.19[1972] Lfg.4.

[13] CFD Analysis for the Natural Convection in the Annulus Gap under Post-Blowdown, Hyung Seok Kang, Bo W. Rhee, B-J Min, Presented at KNS Fall Conference, Busan, 2005.

[14] An experimental and theoretical study of natural convection in the annulus between horizontal concentric cylinders, T.H. Kuehn and R. J. Goldstein, pp 695-719, J. Fluid Mech. (1976), vol.74, part 4.