A VALIDATION OF THE CATHENA FUEL CHANNEL MODEL FOR A POST BLOWDOWN ANALYSIS AGAINST A HIGH TEMPERATURE THMPERATURE THERMAL-CHEMICAL EXPERIMENT CS28-2

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Abstract

To form a licensing bases for the new methodology of a fuel channel safety analysis code system for CANDU-6[1], an improved CATHENA[2] model for a post-blowdown fuel channel analysis of an aged fuel channel with a crept pressure tube has been developed, and tested for a high temperature thermal-chemical experiment CS28-2. Pursuant to the objective the current study has focused on understanding the involved phenomena such as the radiation and convection heat transfer and high temperature metal-water reaction of the 28-element cluster type fuel bundle in a crept pressure tube, their interrelations, and how the treatment of the pseudo-subchannels in the 1-D thermalhydraulic code can affect a prediction with an attempt to properly account for the important physics of the involved phenomena, and how well it relates to the experimental results. The transient simulation results for the Fuel Element Simulators (FES) of three fuel rings and a pressure tube were quite encouraging provided some adjustment of the fuel channel annulus gas thermal conductance is used. However this raises a question on how the authors can justify using the adjusted thermal conductance for the CO_2 gas gap. Various possible arguments for justifying the obtained results based on an adjusted gap thermal resistance were proposed and discussed. In spite of these difficulties, through this study, it was found that the radiation heat transfer model of CATHENA among the FES of three rings and the pressure tube as well as the exothermic metal-water reaction model based on the Urbanic-Heidrick correlation are quite accurate and sound even for the offset cluster fuel bundle of an aged fuel channel.

1. Introduction

In a CANDU reactor, the fuel and coolant are contained in a fuel channel separated from the heavy-water moderator of a large volume by two layers of concentric horizontal zirconium tubes, called the pressure tube and calandria tube. Owing to this physical separation, even during a postulated large break Loss of Coolant Accident (LOCA) without Emergency Core Cooling (ECC) injection, the decay heat from the fuel should be discharged to the huge cool volume of a moderator with the fuel temperature kept low so as not to jeopardize the structural integrity of the fuel bundle and channel, but high enough to dissipate the decay heat via a

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[1] CANadian Deuterium and Uranium
[2] Canadian Algorithm for THErmalhydraulic Network Analysis

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 point of view [1]. As the fuel and fuel channel can be disintegrated not only by melting, but also by a metal-water reaction such as a zirconium-steam reaction, it is very important to thoroughly understand the high-temperature thermal-chemical fuel channel behavior and to know the effectiveness of the moderator as a heat sink to demonstrate the safety of the current and future Pressurized Heavy Water Reactors (PHWRs) during a postulated accident.

During the post-blowdown phase of a postulated large break LOCA with an impaired ECC event in CANDU reactors, either saturated or superheated steam is assumed to be the only coolant available in the fuel channel for a conservative analysis of the accident. In this condition the dominant path for removing the decay heat is considered to be a radiation heat transfer from the fuel elements to the huge moderator across the pressure tube and calandria tube [2]. As too high a temperature of the fuel may initiate an auto-catalytic exothermic zirconium-steam metal water reaction and, if progresses to a worse situation, a breakdown of the mechanical integrity of the fuel sheath may cause a collapse of the fuel bundle in the fuel channel. Thus the confirmation of an adequate cooling capability of this heat transfer mechanism has been of great concern to the CANDU-6 safety analysis.

For the past several years Korea Atomic Energy Research Institute (KAERI) has carried out research on developing a new CANDU fuel channel safety analysis code system [3] where the CHAN-IIA code [4] is to be replaced by CATHENA[5], for the post-blowdown phase analysis of the CANDU-6 fuel channel under a postulated large break LOCA without an ECC event. For a validation of the CATHENA fuel channel model of this new safety analysis code system several analyses are under way, and two of them are the validation against high-temperature thermal-chemical experiments called CS28-1[6] and CS28-2[7]. As quite comprehensive experimental data is available, these tests have been intensively studied and simulated by using the CATHENA code as well as the 3D CFD code, CFX, equipped with various popular radiation models[8]-[12]. However as there are 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 a 37-element fuel case, KAERI CANDU technology group decided to develop a 3-D post-blowdown fuel channel analysis model by using the CFD model based on commercial codes such as CFX and to validate it against an existing 28-element high temperature thermal-chemical CANDU fuel channel experiment such as CS28-1, 2, 3[6]-[7],[13]. Then the same CFD 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 a proper validation will be used to generate a benchmark problem for the 37-element fuel or even more advanced fuels such as CANFLEX, which can then be used to validate the CATHENA post-blowdown model for CANDU-6 or other future advanced CANDU plants under development including ACR and supercritical CANDUs[14]-[15]. Therefore, for this aim a 3-D CFD model based on the CFX code is being developed and a validation of this model against CS28-1, 2 has been performed with encouraging success [16]- [19]. This paper describes one of the recent advances in these studies to validate the CATHENA post-blowdown fuel channel model for the CS28-1 and 2 experiments. The motivation for 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 or those with larger-elements fuel channels would be essentially the same. So once the one for a 28-element channel is successful, it can also be applied to the 37-element or other advanced fuel cases without much difficulty.

As the major safety concerns of the post-blowdown fuel channel analysis are 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 thus how high the fuel and pressure tube temperatures can reach as a result of heat balance, and how much zirconium sheath would be oxidized to generate H_2 gas, the objective of this study has focused on understanding these phenomena, their interrelating physics, develop the appropriate CATHENA models and how to maintain a good accuracy of the temperature and H_2 generation rate prediction without losing the important physics of the involved phenomena, thus validating the CATHENA fuel channel model for the post-blowdown analysis of a Large Break LOCA without ECC injection.

The detail description of the CS28-1, -2 experiments is well described in other literatures [6]-[7],[13] and thus most of them will be omitted here except the cross sectional view and axial cutaway view of the CS28-2 test section, in Fig.1 and Fig.3 respectively, which are essential for the rest of this paper.

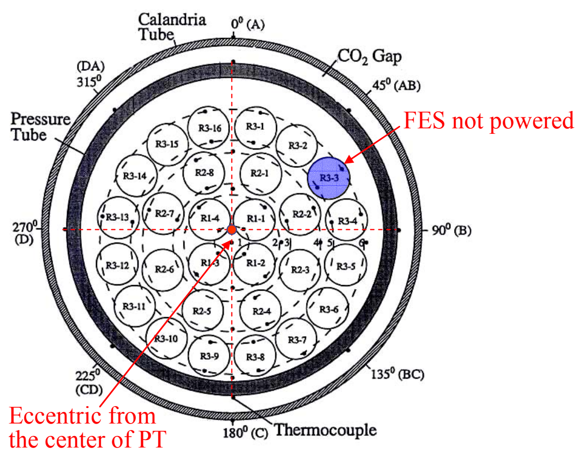

Fig.1 Cross section of the CS28-2 test bundle and failed heater location

2. Development of a CATHENA Model for a Post-blowdown Analysis

As the CATHENA code is a 1-D thermal-hydraulic code its application to the rather complicated fuel channel geometry as shown in Figure 2 can be viewed as inappropriate. If the convective heat transfer is dominant cooling mechanism, this may be the case. However in the case where the dominant heat transfer mechanism is radiation like in the steam-bound cooling channel of post-blowdown stage, it may not be necessarily the case as long as the view factors interrelating the segments of the fuels and the pressure tube, and other key parameters of radiation heat transfer can be correctly provided. It was the authors' concern if the radiation model of CATHENA is detailed and well-equipped enough to predict the heat transfer in this kind of complicated geometry fuel bundles with reasonable accuracy that the regulators can be satisfied. Fortunately to the authors surprise the newly developed CATHENA fuel channel model for the crept pressure tube with pseudo-subchannels as shown in Fig.2 is found to be able to predict the experimental data of the electric fuel simulators asymmetrically heated quite well with some adjustment of the CO_2 gap conductance. Another parallel studies performed for developing and validating a CFD model for the CS28-1, and -2 experiments also showed an encouraging results. The details of this CATHENA modelling have already been described in some of the previous papers of the authors [20]-[21], and will not be repeated here. The key findings of these series of studies are (1) the convection heat transfer of the fuel by the steam flow in the steam-bound subchannels, whether it be inner or outer, is not significant in determining the fuel surface temperatures as the radiation heat transfer dominates the convection. (2) If the view factors among the fuels and various segments of the pressure tube properly accounted, the fuel sheath temperatures can be accurately predicted throughout the transient as long as the pressure tube temperature is predicted accurately. (3) Adjustment of the CO_2 gas gap conductance is necessary to match the experimental data of the pressure tube, preferably in the form of enhanced CO_2 conductivity. (4) The reason why this adjustment necessary, and several possible arguments and most suitable one should be drawn.[21]

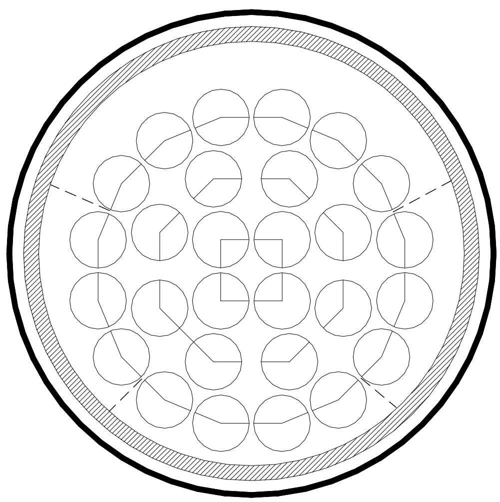

Fig.2. CATHENA solid structure model and pseudo-subchannel model for CS28-2 experiment

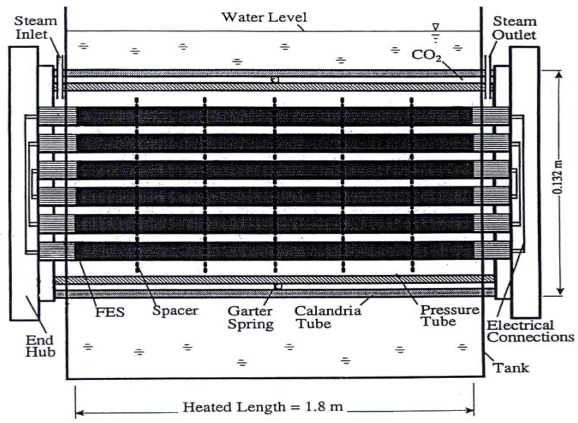

Fig.3. Axial cutaway view of the test section for both CS28-1 and 2 [13]

3. Transient Simulation for CS28-2 and Discussion

Due to the reason described at the end of the introduction section, only the experiment's inlet steam flow and exit pressure conditions, and the FES heater power condition are given in Figs.5 and 6. As for the model for the metal-water reactions and hydrogen/heat generation, the Urbanic and Heidrick correlation [22] and Just-Baker correlation [23] are used for the zirconium/steam reaction rate calculation on the fuel sheath and the inner surface of the pressure tube. This zirconium/steam reaction adds more heat generation both to the sheath's outside surface and the inside surface of the pressure tube, on top of the channel decay power. The thickness of the oxide layer, volume of the hydrogen produced, and the heat generation rate for the metal water reaction are calculated. The effect of the generated hydrogen in reducing the amount of steam available for the reaction is modeled.

Using the test conditions as the boundary conditions of the CATHENA simulation, the initial steady state conditions was simulated. However in case of the initial condition, even after accounting for most of the phenomena within the modeling capability of CATHENA by using the appropriate material properties and surface characteristics through using mathematical models for all the possible radiation heat transfers as well as the convective heat transfers of the CO_2 gas flow, possibly enhanced by a secondary type natural circulation flow between the hot pressure tube and the cold calandria tube[9][24], it was found that there still remains a significant discrepancy of about 100^{o}C between the measured pressure tube temperatures and those predicted by CATHENA. Therefore it was determined to introduce a multiplying correction factor to the CO_2 conductivity to match the measured pressure tube temperature, which is conjectured by the authors' engineering judgment to account for the unknown enhanced heat transfer effect between the pressure tube and the calandria tube as proved by the experiments of CS28-1 and the following ones [24]. As for the justification of using this adjusting multiplying correction factor, the readers are encouraged to read another paper of the authors' [21]. After this adjustment, the initial condition corresponding to t= 500 seconds after start of CS28-1 test as shown in the boundary condition figures of the pressure tube and the fuel sheath of various rings were predicted to match those of the measured ones with a reasonable accuracy as shown in Fig.6. Then the transient simulation using this adjusted initial condition and the transient boundary conditions were carried out and the result obtained.

The transient simulation results for the FES with three fuel rings and the pressure tube were reasonably good as shown in Figs.6 to 11. This is thought to be due to success in reproducing the initial steady state condition and due to the detailed modeling features of CATHENA code for the coupled heat transfer of conduction, convection, and radiation heat transfers in complex fuel bundle geometry.

The measured inner ring temperature slightly increases along the length of the test section as shown in Fig.6 with a rapid drop at the exit region, probably due to an end heat loss by a conduction whereas that predicted by CATHENA as shown in Fig.6 shows a slight decrease along the axial distance. This indicates that the heat transfer rate per unit length of the inner ring is fairly close to uniform axially, which was also observed in the previous experiment. Generally because of their closer proximity to the pressure tube, the middle ring FES elements are expected to be cooler than the inner ring FES elements, which are clearly shown in Figs. 6 to 11 where the number in the legend means the time in second and the legend "cath" represents the CATHENA prediction with Urbanic-Heidrick correlation whereas "cath_bj" with Baker-Just correlation. The outer ring FES element temperatures are strongly affected by the presence of the nearby pressure tube due to its close proximity. 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 governed by the temperature of the adjacent circumferential segment of the pressure tube as shown in the Figs. 8 and 9.

Considering that the uncertainty of the temperature measurement is ±1.2%, which corresponds to ±12.3^{o}C for a temperature of 750^{o}C, that of the electric power ±4.4%, and the uncertainties 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 for an adjustment of the gap 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 high 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 a secondary type natural circulation flow between the hot pressure tube and the cold calandria tube[25]. A few potential reasons for this enhanced heat transfer rate across the CO_2 gap are; (1) a conduction by the garter spring which is used to maintain the CO_2 gap thickness between two long zircaloy tubes supported at both ends only, (2) an enhanced cooling effect of the CO_2 flow agitated by the intrusion of the welded spot of the T/C embedded into the pressure tubes outside[24], (3) a possible deposition of the thermal radiation from the PT in the high absorptive medium of CO_2 gas, more than the CATHENA "transparent" radiation model can account for, and then cooled by a natural convection at the cold CT inside wall. However there is no indication of a pressure tube temperature which shows a sudden local drop anywhere along the test section, thus, this rejects the possibility of a garter spring effect. Also a deposition of the thermal radiation from the PT in the CO_2 gap is not persuasive enough either due to the small heat capacity of the gas and the small gas flow rate. The only possible explanation left is the second one or other unknown ones.

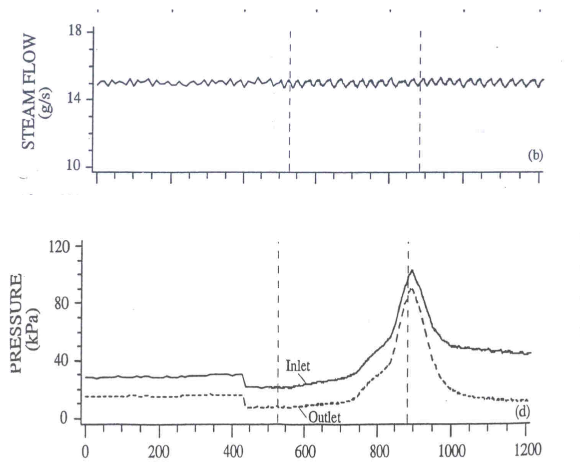

Fig.4. Inlet steam flow and pressure of the CS28-2 test section [24]

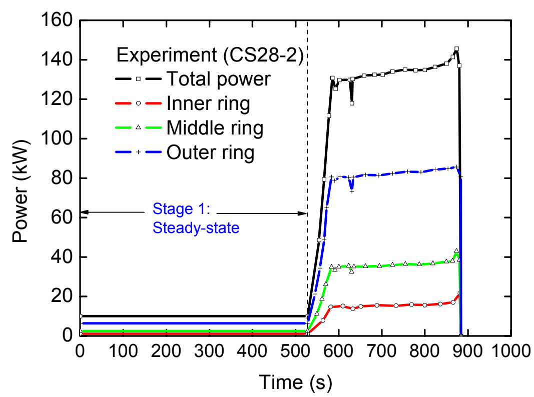

Fig.5. Electric power to the heaters of the CS28-2 experiment[24]

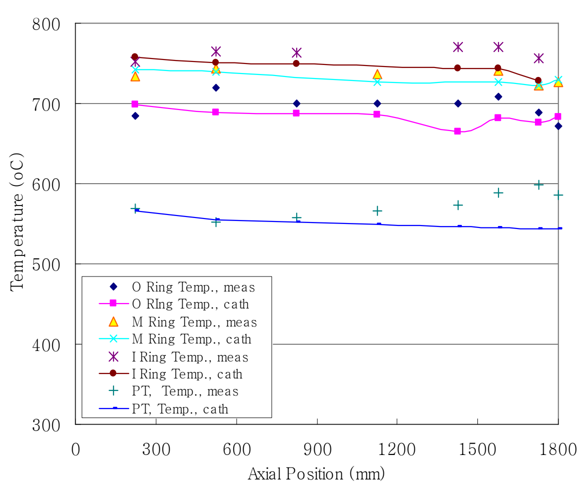

Fig.6. Measured vs. predicted inner, middle and outer ring FES and the PT temperatures along the axial direction for the initial steady state of CS28-2 Experiment

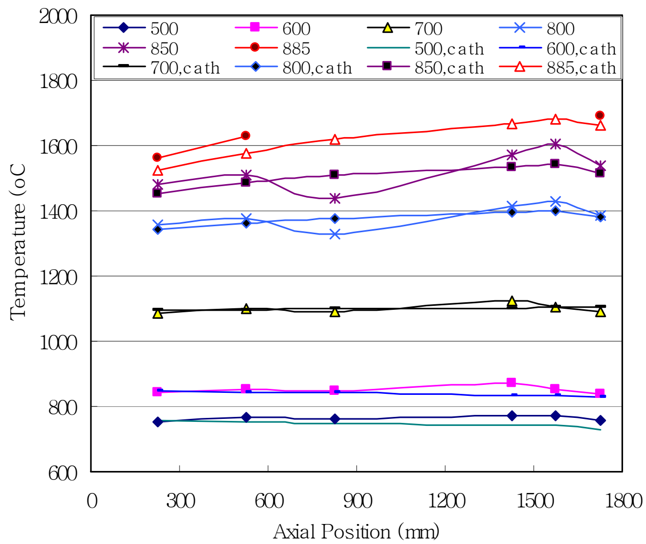

Fig. 7. Inner ring FES temperature along the axial direction compared with the measured one.

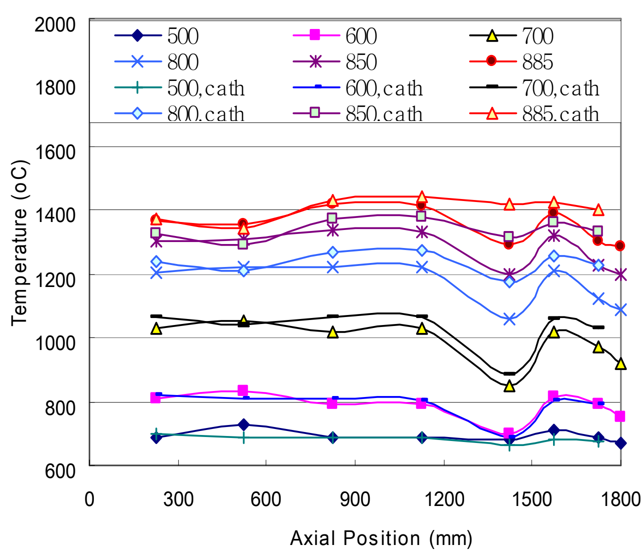

Fig. 8. Outer ring FES temperature along the axial direction compared with the measured one.

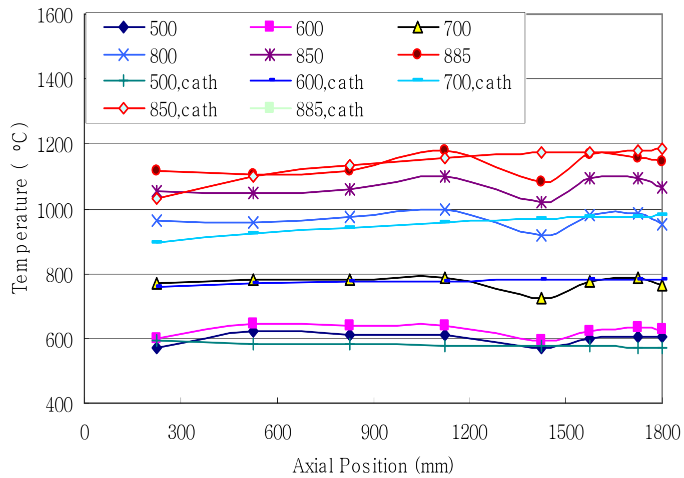

Fig. 9. Pressure tube temperature along the axial direction compared with the measured one at the bottom of PT

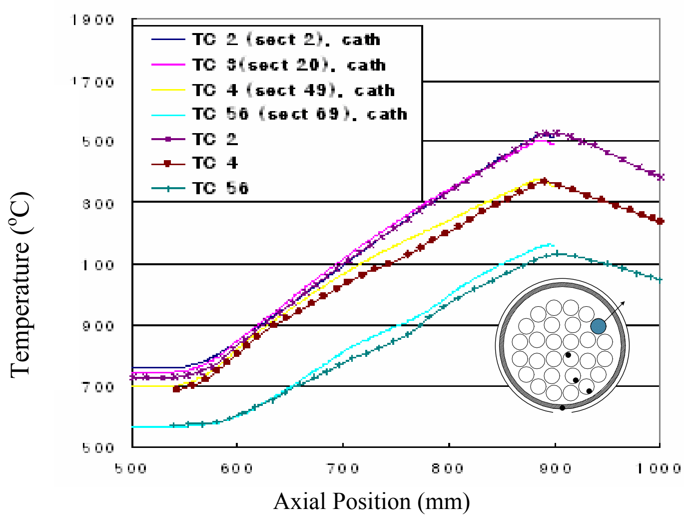

Fig.10. Comparison of the predicted FES temperature history of the inner, middle and outer ring with those measured at the axial location of 225mm into the heated zone

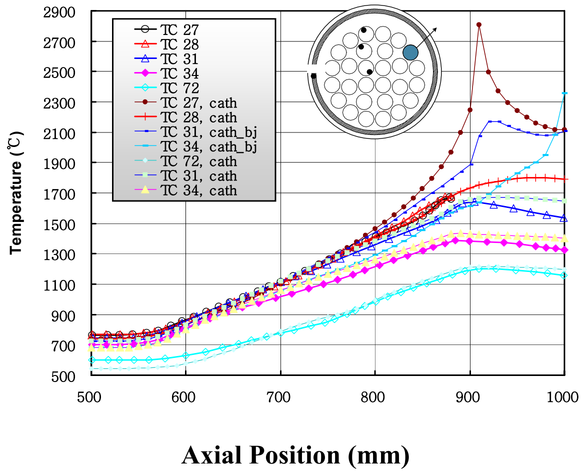

Fig. 11. Comparison of the predicted FES temperature history of the inner, middle and outer ring for Baker-Just and Urbanic-Heidrick correlations with those measured at the axial location of 1575 mm into the heated zone

4. Conclusion

From all the above mentioned facts and discussions, the authors have drawn the following conclusions: With the adjusted CO_2 gap thermal resistance, the current fuel channel model of CATHENA is shown to predict all the temperatures of the inner ring, middle ring, outer ring as well as the pressure tube satisfactorily, considering that the uncertainty of the temperature measurement is ±1.2%, which corresponds to ±22.5°C for a temperature of 1800°C, that of the electric power ±4.4%, and the uncertainties for the other boundary condition parameters. 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 other way in CATHENA code to account for the enhanced heat transfer between the PT and CT by using the currently available radiation heat transfer model. It was confirmed that neither a radiation nor the axial convective CO_2 cooling, with a radiation absorption accounted for, enhanced by the buoyancy driven secondary natural convective heat transfer in the gap confined by both a hot and a cold wall[2],[27][24][21] can explain this enhanced heat transfer observed in this experiment.

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. The reason for this discrepancy is not well understood yet. Also the modelling uncertainties due to various modeling assumptions, e.g., gray gas, black bodies, emissivity and diffusivity of pressure tube and calandria tube, conduction through the pressure tube wall and calandria tube wall, etc. need to be discussed, though they are not yet ready for quantitative evaluation.

Through this study, several possible reasons or factors could be identified as CO_2 gas gap conductance, emissivity of the solid surfaces, detailed modeling of view factors, accurate and comprehensive matching of the initial steady state temperatures that may significantly affect an accurate prediction of the initial steady state and the following transient temperatures of the experiment.

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