Proceedings of the
International Conference on Mechanical Engineering 2009
(ICME2009) 26- 28 December 2009, Dhaka, Bangladesh

ICME09-TH-32

demand of I-131 is much higher than the current

NUMERICAL ANALYSIS FOR TEMPERATURE ASSESSMENT OF THE IRRADIATED TEO$_2$ POWDER IN THE DRY CENTRAL THIMBLE OF THE 3MW TRIGA MARK-II RESEARCH REACTOR

M.S.Islam[1], S.B.Samee[2], M.M.Uddin[1] and M.Mamun[2]

[1]Reactor Operation and Maintenance Unit, Atomic Energy Research Establishment, Ganakbari, Savar, , Dhaka, Bangladesh
[2] Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh

Abstract

Temperature assessment during irradiation of 50g TeO$_2$ powder in a sealed quartz vial holding with aluminum specimen container (Al-Can) in the dry central thimble (DCT) of the reactor core is performed numerically using a CFD tool. The reactor power is considered full power at 3MW(th). The geometrical configuration of the DCT is; length = 8 m, I.D = 33.88 mm and O.D = 38.1 mm and there is like a dog-leg bend. The length of the quartz vial as well as Al-Can are 75.2 and 95.1 mm, respectively. The gap between the quartz vial and Al-Can, Al-Can and DCT are 0.92 and 4.49 mm, respectively and there is air in the gaps. A 2D and 3D model geometry of the DCT with a narrow gap between quartz vial and Al-Can (0.92 mm) and Al-Can and DCT (4.49mm) is generated by simulating the existing cooling capacity of the DCT. The laminar viscous model and the turbulent RNG $k-\in$ model are applied for the 2D and 3D models. Radiative heat transfer was modeled using S2S model for the 2D case provided with no hole on the surface of the Al-Can and DTRM is used for the 3D case provided with several holes on the surface of the Al-Can. It has found that the highest centerline temperature of TeO$_2$ powder is found in the laminar viscous model of the existing cooling geometry which is about 662 ^{0}C when no hole is present on the surface of the Al-Can. On the other hand, RNG $k-\in$ model shows a maximum centerline temperature of 658 ^{0}C under the same condition. However, no significant difference has found in temperature distribution between the laminar viscous and the turbulent RNG $k-\in$ model. In the 3D modeling, when several holes present on the surface of the Al-Can under the same condition, it has found that the centerline temperature along with temperature at different zones decreases considerably. This is because of the more favorable heat transfer atmosphere than the sealed Al-Can (without hole). The detailed numerical analyses under different cases along with experiments under the same cases may really provide a better cooling technique for the DCT of the reactor which consequently does help increasing the I-131 production and other related R&D activities with assured safety of the reactor operation.

Keywords: Temperature assessment, Irradiation, Numerical analysis, Safety, Reactor Operation

1. INTRODUCTION

Iodine-131 is one of the most important radio-isotopes (RI) that are being used in the fourteen nuclear medicine centers of the country. It is produced by irradiating TeO$_2$ as a target material in the nuclear research reactor. Bangladesh Atomic Energy Commission (BAEC) is operating a 3MW TRIGA Mark-II research reactor where TeO$_2$ powder is loaded in a sealed quartz vial and irradiated in the DCT of the reactor core. One quartz vial containing about 40g of TeO$_2$ powder is irradiated in the DCT at a power level of 2.5 MW. At the end of the irradiation, about 300 mCi of I-131 is obtained by processing the irradiated TeO$_2$ powder. As the weekly production level, the need for increasing the production rate of I-131 is always there. One way of doing so is to increase the amount of irradiating TeO$_2$ in a single quartz vial. Another way is to increase the irradiating time. However the operating cost of the reactor is much higher than the cost of TeO$_2$ target material. So it is preferable to increase the amount of target material (TeO$_2$) loaded in a single vial in the reactor core. But, loading extra amount of target material will produce extra amount of heat energy. Therefore it becomes necessary to conduct a thermalhydraulic safety analysis and ensure that the temperature distribution inside the DCT of the reactor core is within the operating limit during reactor operation.

On March 19, 2002, the reactor was operated with 50 g TeO_2 powder at DCT at 3MW full power of the reactor power during 8 hours in order to check the cooling system performance of the newly installed plate heat exchanger by replacing shell and tube heat exchanger. After necessary cooling of the irradiated TeO_2 powder, during the unloading period, the level of radioactivity inside the DCT was found much higher than the usual level. After physical investigation, it was found that the lower portion of the Pyrex vial (used to be quartz vial) containing the target material was melted and the Al-Can containing the Pyrex vial was also damaged. To review and analyze the causes of the vial failure, an International Atomic Energy Commission (IAEA) expert mission was conducted at research reactor facility of Bangladesh. The mission recommended using quartz vial instead of Pyrex vial while irradiating TeO_2 powder in the DCT. But when the amount of target material was increased from 40g to 50g and the reactor was operated at full power level, the failure of quartz vial happened in December 2007. Due to these two vial failure incidents it became a necessity to analyze the heat transfer phenomenon inside the DCT of the reactor core with proper approach. In this study, it has evaluated the temperature distribution inside the DCT of the reactor core and determined the temperature at various zones and also checked whether these temperatures are within operating limit.

On the other hand, it is also possible to increase the production rate of I-131 by improving the cooling system in and around the CT. One of the ways is to use perforated Al-Can instead of sealed Al-Can. Furthermore, irradiation channel of central thimble (CT) with water filled is much better than the dry irradiation channel filled in air. This is possible through improving the heat transfer rate from the DCT of the reactor core to the external cooling media (water). For this purpose, it has been modeled and analyzed first only existing and then a modified cooling system. Heat transfer in a narrow channel is of high interest in both theoretical and experimental physics. Many researches have been conducted so far to analyze the thermalhydraulic conditions in the narrow channels. Numerical codes are also developed to conduct computational study.

GENGTC [1] was one of the first computer programs for calculating capsule temperature in cylindrical geometry. B.G. Jones, N.H. Schilmoeller, D.F. Hang, G.P. Beck [2] conducted a study on forced cooling of Illinois advanced TRIGA reactor. M.S. El-Genk, J.S. Philbin, and F.C. Foushee [3] investigated the heat transfer and fluid flow at low pressure in narrow channels. This research focuses on heat removal and fluid dynamics in flow regimes characterized by low pressure and low Reynolds number. The program was motivated by a desire to characterize and analyze cooling in a broad class of TRIGA reactors under: (a) typical operating conditions, (b) anticipated, new operating regimes, and (c) postulated accident conditions. It has also provided experimental verification of analytical tools used in design analysis.

M.S. El-Genk, et al. [4] also studied the air coolability of TRIGA reactors following a loss-of-coolant accident (LOCA). They conducted experiments on the air-coolability of a heated rod in a vertical open annulus at near atmospheric pressure and later imposed this analogy on to the coolability of reactor fuel rods that are totally uncovered in a LOCA. A.Z.Mesquita and H.C.Rezende [5] performed experimental and analytical studies at the Nuclear Technology Development Center to find out the temperature distribution in the IPR-R1 TRIGA Research Nuclear Reactor, as a function of power and position in the reactor core. The basic safety limit for the TRIGA reactor system is the fuel temperature, which is studied in both steady-state and pulsed mode operation.

E. Umar et al. [6] conducted the experimental study of natural convection in the hottest channel of TRIGA 2000 kW. The purpose of the experimental study was to verify the theoretical analysis, especially the temperature distribution in the hottest coolant channel using the STAT code. M.Q. Huda et al. [7] studied the thermal-hydraulic analysis of the 3 MW TRIGA MK-II Research Reactor under steady-state and transient conditions.

Thermal-hydrodynamic design and safety parameter studies of the TRIGA MK II research reactor were done by M. Q. Huda and M. Rahman [8] in 2003. PARET code was used to analyze important thermo-hydrodynamic design and safety parameters of the 3 MW TRIGA MK-II research reactor at Atomic Energy Research Establishment (AERE), Savar, Dhaka, Bangladesh. The loss-of-flow accident (LOFA) scenario of the reactor was also studied to ensure that the existing design and procedures are adequate to assure that the consequences from this anticipated occurrence does not lead to a significant accident. Investigation of thermo-hydraulic parameters during natural convection cooling of TRIGA reactor was done by M.Q Huda and S.I. Bhuiyan [9] in 2006. The experimental results were used for validating NCTRIGA code.

Studies on the overall safety aspects during irradiation of TeO_2 in the central thimble of the TRIGA research reactor was performed by M.Q. Huda et al. [10]. They identified safety issues relevant to I-131 radioisotope production and ensured that safety analysis and design are consistent. They evaluated threats developed within the facility during the irradiation process and ultimately ensures establishment of in-core safety limits and conditions at all stages of I-131 production.

TRISTAN, a numerical code for calculating the flow parameters in a coolant channel of reactor core, cooled by natural convection, was developer by I. Mele [11]. It was designed for steady-state thermo-hydraulic analysis of TRIGA research reactors operating at low power level of 1-2 MW in an open pool or tank, where normal pressures are not exceeding 2 bars. The objective of this study is to predict the temperature distribution accurately in and around the CT for sustainable I-131 production and other related R&D activities with assured safety of the reactor operation. Chapt. 2 describes the physical problem in detail and its numerical approach, Chapt.3 describes the numerical results and Chapt. 4 draws a conclusion over whole the investigation.

2. PROBLEM DESCRIPTION AND GEOMETRY

The thermal analysis for irradiated target materials of the TRIGA Mark-II research reactor is very necessary for its safe operation. Keeping the temperature of the CT of the reactor core within limit not only ensures safe operation but also strengthens the production of I-131. In the existing irradiation facility, the quartz vial loaded with TeO_2 is kept inside an Al-Can. The Al-Can is mounted on a stopper plate. Both the Al-Can and stopper plate is inside a CT which is dry. Outside the CT, the cooling fluid (water) is circulated by two primary pumps. Heat from the TeO_2 powder is first conducted through the quartz vial, and then convection occurs in the air gap between the quartz vial and Al-Can. After that, conduction through Al-Can, convection through air gap between Al-Can and CT and finally conduction through CT wall occurs.

If it is to be looked carefully to the heat transfer phenomenon, then it is obvious that the prime resistance to the heat transfer is the convection through air gaps. To produce I-131 at a higher rate than the present rate without disrupting the safety of the reactor, it needs to be focused on increasing the heat transfer rate through these convection mediums.

One of the ways is to drill sets of radial holes of small sizes (1 mm) at two different levels of the Al-Can for providing the venting in and out of the convective fluid to and from the Al-Can. Air of comparatively less temperature from the outside of the Al-Can enters the Al-Can by the lower level holes, takes heat from the wall of the vial, gets hot and the density decrease. So it climbs up and escapes through the higher level holes. As there is a motion between the inner and outer air of the Al-Can, the heat transfer rate increases to a certain degree. In this study, it is taken two cases; i. CT with no hole over the Al-Can and ii. CT with holes over the Al-Can to model and analyze the situation.

50 g TeO_2 is kept in a sealed quartz vial (Figs.1 and 2). The quartz vial is 1.75 mm thick. Its inner and outer radii are 9.38 and 11.13 mm, respectively. The height of the quartz vial is 75.2 mm. The quartz vial is kept in an Al-Can. The Al-Can has an inner radius of 12.05 mm and outer radius of 12.45 mm. The height of the Al-Can is 95.1 mm. The Al-Can is in rest on the top of a stopper plate of aluminum. This plate is 3.81 cm thick. Under the plate, there is water at 60 ^{0}C. The Al-Can is kept in the CT, which is also made of aluminum. The inner and outer radii of the CT are 16.94 mm and 19.06 mm, respectively. The height of the CT is 8 meter.

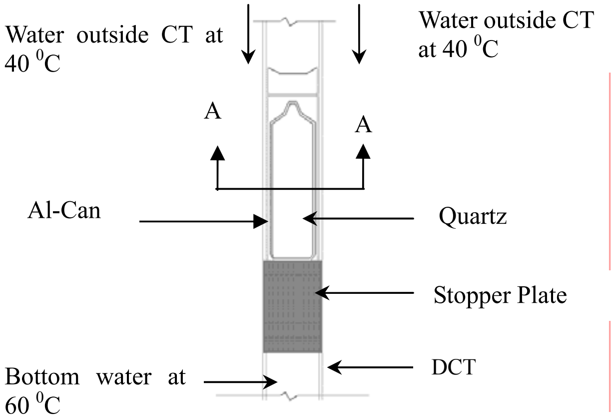
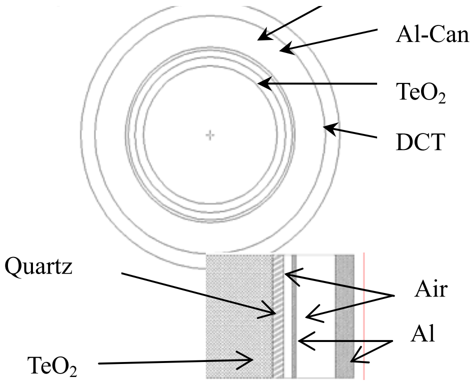


Fig.1 Schematic Diagram of TeO_2, Quartz Vial, Al-Can and DCT



r_0=0, r_1=9.38, r_2=11.13, r_3=12.05 Unit: mm
r_4=12.45, r_5=12.45, r_6=19.05

Fig. 2 Sectional View of Quartz, Al-Can and DCT

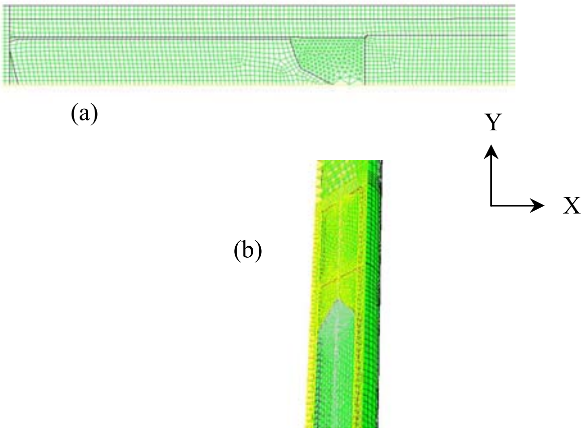


Fig.3 Modeling Geometry

(a) 2D Geometry
(b) 3D Geometry

Outside the CT, w move the heat. The temperature of the circulated water is 40 ^{0}C. Holes are drilled at the height of 20 mm and 70 mm of the Al-Can.

The vial is modeled as a heat source with a heat generation rate of 2.46×10^3 W/kg. Total 50g of TeO_2 is kept in the vial. The outside wall of the CT was modeled with a constant temperature of 40 ^{0}C. The bottom surface of the stopper plate is modeled with a constant temperature of 60 ^{0}C. Except these, all the walls are assumed of "no slip" condition. The top of the CT is assumed to be at 30 ^{0}C.

Table 4.1: Thermo-physical properties of the materials

Material	Density, ρ (kg/m^3)	Thermal conductivity, k (W/m/K)	Heat generation rate, q''' (W/m^3)	Emissivity, ϵ	Melting temperature (^{0}C)
TeO_2	4500	3	8.7×10^6	0.89	733
Quartz	2230	1	34.2×10^6	0.95	660
Air	1.2	7.6×10^{-2}	-	-	-
Water	1000	0.637	-	-	-
Al 6061	2700	230	0.597×10^6	0.18	630

First, CAD models are prepared for both "with hole" and "without hole" design. The "without hole" design is modeled as 2D axisymmetric (Fig.3.a). A symmetric 3D model is prepared for the "with hole" geometry (Fig.3.b). The CAD geometries are both transferred to a grid generation program. For the 2D geometry, the grid is made of map, pave and triangular mesh. The grid consists of 5119 nodes. The 3D model describes half of the physical domain with a symmetry boundary condition. The 3D grid consists of map, copper and tetrahedral mesh. The grid contains 225078 cells. One existing design and all three potential designs are analyzed. All the models are analyzed in both the laminar viscous and turbulent RNG $k-\in$ models. The turbulence is modeled using Renormalization-Group (RNG) $k-\in$ model.

Natural convection of the fluids is modeled by Boussinesq model. The effect of gravity in the motion of fluid is considered. For the "without hole" models, radiation heat transfer is modeled using Surface-to-Surface (S2S) radiation model. For the "with hole" models, radiation heat transfer is modeled using Discrete Transfer Radiation Model (DTRM). After applying the proper boundary condition to the computational models, flow, momentum and energy equations are solved for each case. Pressure is calculated by SIMPLE pressure-velocity coupling. The discretization of momentum and energy are done by 2nd order upwind method. Pressure is discretized by PRESTO! method.

3. RESULTS AND DISCUSSION

Temperature profiles are plotted for each case to reveal the temperature distribution inside the DCT of the reactor core. These contours of temperature provide an easy reasoning of the operating status and whether these conditions are within operating limit. There is not very much difference in temperature distribution of the laminar viscous model and turbulent RNG $k-\in$ model of each situation. It is seen in Fig. 4(a) that the highest centerline temperature is found in the laminar viscous model of the Al-Can without hole which is about 662 ^{0}C.

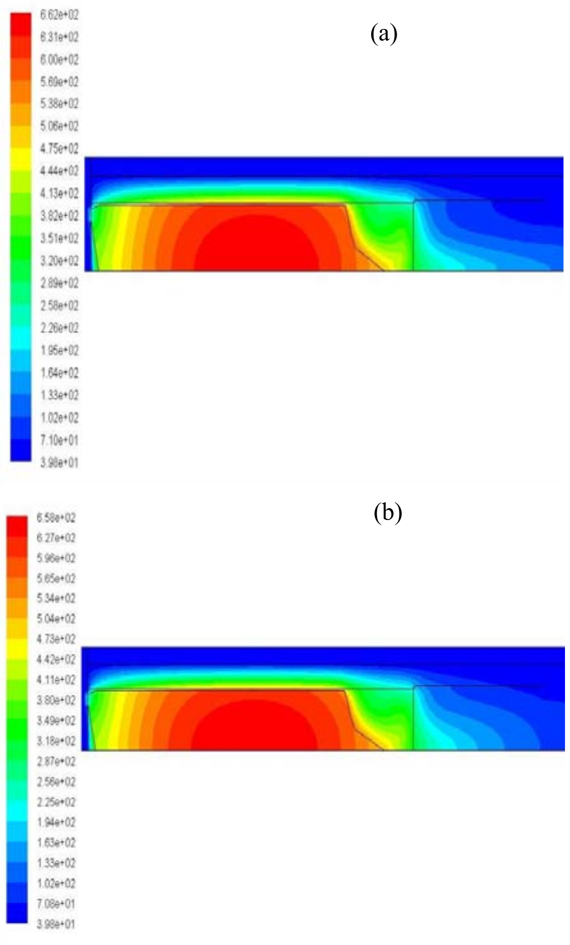


Fig. 4 : Contours of Static Temperature (^{0}C)

(a) DCT without hole over the Al-Can: Laminar Viscous Model

(b) DCT without hole over the Al-Can: Turbulent RNG $k-\in$ Model

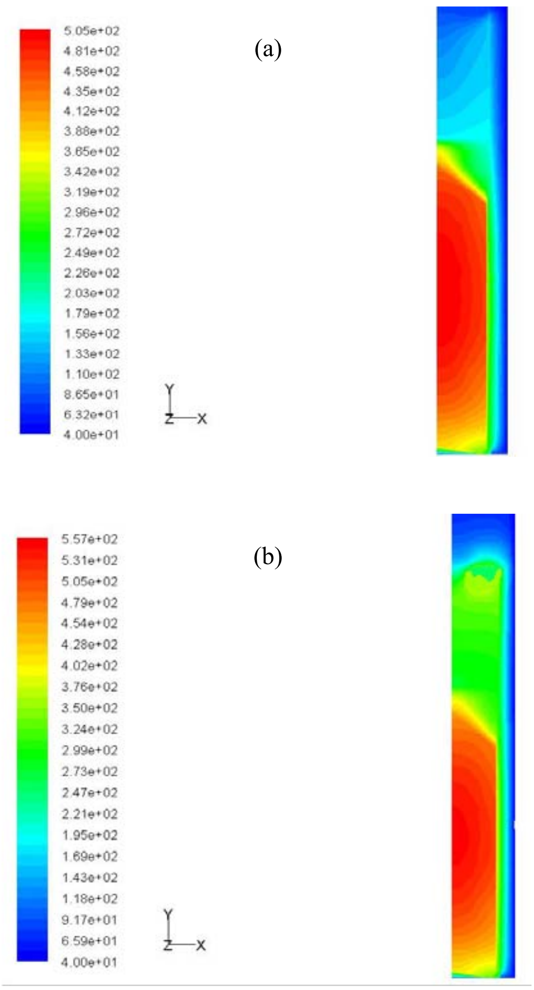


Fig. 5 : Contours of Static Temperature (^{0}C)

(a) DCT with hole over the Al-Can:
Laminar Viscous Model

(b) DCT with hole over the Al-Can:
Turbulent RNG $k-\in$ Model

In Fig.4 (b), the RNG $k-\in$ model shows a maximum centerline temperature of 658 ^{0}C under the same situation. In Figs. 5(a) and (b), for 3D model (Al-Can with several holes), laminar viscous model shows a centerline temperature of 505 ^{0}C and the RNG $k-\in$ model shows a centerline temperature of 557 ^{0}C. It is evident from the results that temperature goes down considerably when there are several holes over the Al-Can under the same condition. This is of course, the better situation from the heat transfer view point than that of the sealed Al-Can. The temperature in the walls of the quartz vial and Al-Can is also of great interest. These temperatures should be limited below the melting point of each material. Safety of the reactor core may be disrupted if any melting occurs either in the quartz vial or in the Al-Can. From Figs. 4 and 5, it is clear that the temperature gradient is very high in the radial direction than the axial direction. The maximum temperature is found to be approximately 35 mm to 45 mm Al-Can height in all zones and not exceeding the melting temperature both the Al-Can and quartz vial when Al-Can is having with several holes on its surface. From the predicted results, it can be mentioned here that perforated Al-Can with 50g TeO_2 powder at full power ($3MW_{th}$) of the reactor operation is a critical situation from the heat transfer view point whereas under the same condition but sealed Al-Can is a catastrophic situation.

4. CONCLUSION

Temperature assessment of the irradiated TeO_2 powder kept in a sealed Al-Can with hole and without hole has done by numerically using the laminar viscous model and turbulent RNG $k-\in$ model. It has found that the centerline temperature decreases considerably for the case of Al-Can with several holes. The holes are playing the very important role to convey heat from inside to the outside coolant media (water). It is to be mentioned here that irradiation of TeO_2 powder was carried out in the past with Al-Can without a hole over its surface. The situation was not good for transferring heat from inside the Al-Can since there is no hole. The heated air is simply confined inside the Al-Can and caused to elevate the temperature. Reactor power, quantity of TeO_2 powder, geometry of the quartz vial, dry/wet CT and corresponding gap size between the quartz vial and Al-Can, and Al-Can and CT are playing very important role for heat losses. The detailed numerical analysis considering these parameters along with experiments can really provide a better cooling technique for the CT of the reactor which consequently can help increasing I-131 production rate.

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