Thermo-Hydraulic Modeling Of The ITER Radial Neutron Camera

Ryszard Kantor[1, a)], Przemysław Młynarczyk[1], Jerzy Kotuła[2], Dariusz Bocian[2], Fabio Crescenzi[3], Basilio Esposito[3], Daniele Marocco[3], Giuseppe Mazzone[3] Giorgio Brolatti[3], Fabio Moro[3] Cristina Centioli[3], Danilo Dongiovanni[3] and Domenico Marzullo[4]

[1]*Cracow University of Technology, Warszawska 24, 31-155 Kraków, Poland*
[2]*Institute of Nuclear Physics Polish Academy of Sciences, Radzikowskiego 152, PL-31-342 Kraków, Poland*
[3]*ENEA, Department of Fusion and Nuclear Safety Technology, I-00044, Frascati (Rome), Italy,*
[4] *Consorzio CREATE, Via Claudio, 21 , 80125 Napoli, Italy*

[a)]Corresponding author: Ryszard.Kantor@mech.pk.edu.pl

Abstract. The ITER Radial Neutron Camera (RNC) is a diagnostic system designed as a multichannel detection system to measure the uncollided neutron flux from the plasma, generated in the tokamak vacuum vessel, providing information on neutron emissivity profile. The RNC consists of array of cylindrical collimators located in two diagnostic structures: the ex-port system and the in-port system. The in-port system, contains the diamond detectors which need a temperature protection. Feasibility study of the efficiency of the cooling system for the In-port Detector Modules of the RNC during baking process was the main goal of thermo-hydraulic numerical modeling. The paper presents the concept of the cooling system layout and the original way of integration of numerical thermo-hydraulic analyses of the in-port detector cassette. Due to the large extent of the detector cassette it is impossible to include all relevant thermal and hydraulic effects in one global model with sufficient level of details. Thus the modelling strategy is based on the concept of three stage modelling from details to global model. The presented paper includes results of numerical calculations made with ANSYS Fluent software in order to provide the final answer, including calculation of heat loads in the detector cassette from adjacent walls during baking and normal operation conditions.

INTRODUCTION

The ITER Radial Neutron Camera (RNC) is a diagnostic system located in the Equatorial Port Plug 1 (EPP1) in the ITER thermonuclear reactor located in Cadarache (France). It is designed as a multichannel detection system to measure the uncollided neutron flux from the plasma, generated in the tokamak vacuum vessel, providing information on neutron emissivity profile. The RNC consists of array of cylindrical collimators located in two diagnostic structures: the ex-port system and the in-port system. The ex-port system, detects and measures the plasma core. The in-port system, enclosed in a dedicated cassette within the EPP1 diagnostic shielding module, is used for measurement of neutron flux generated in the plasma edge. It consists of two sets of lines of sight, lying on two neighboring cross-section planes. Geometry of the RNC layout is presented in Fig. 1.

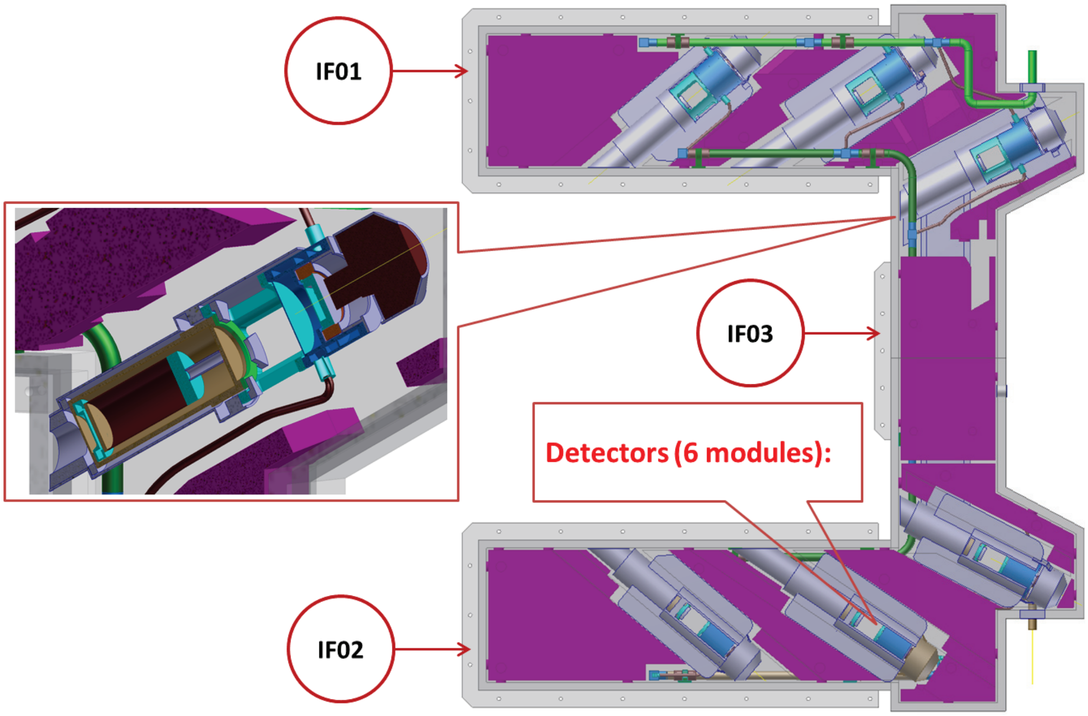

FIGURE 1. RNC layout with water cooling system with presented types of boundary conditions – interfaces (IF)

During ITER normal operating conditions (NOC) the maximum expected temperature in ITER equatorial ports is <126°C. During the ITER baking process the maximum water outlet temperature from the DSM (Diagnostic System Module) in ITER equatorial ports is ~240 °C, causing the maximum temperature of the DSM structure at the same level. The maximum target temperature for the diamond detectors used in RNC is set at 150 °C. The in-port RNC diamond detectors need a temperature protection during the ITER baking phase since they may not survive the associated prolonged and repeated thermal load. These detectors will not be in operation during baking of the port plug (EPP1). The cassette includes the detector cooling system active during baking phase, based on the concept of a water jacket for each detector module. The water jacket concept has been presented and analyzed in referenced papers [1,2].

THERMAL LOADS

Thermal loads are the crucial boundary conditions in the presented investigations. In the considered RNC In-port system thermal loads can be divided into two different groups:

- Normal Operation loads which consist of two phenomena – nuclear heating load and thermal load due to normal full power plasma operation (temperatures about 77 ˚C); the nuclear load has been presented in referenced paper [3]
- Baking scenario – Thermal load due to baking process (temperature about 240 ˚C)

In Table 1. temperature values for the cassette interfaces are described.

Analyzing thermal conditions can be assumed that since maximum allowed temperature for detectors is set to 150 °C an active cooling system, working during Baking, is necessary.

TABLE 1. Thermal loads at interfaces of the RNC In-port system (EU03 - Embarked Unit)

Magnitude	Normal Operation	Baking scenario
Temperature at EU03.IF01	T_{min}=70 ˚C, T_{max}=73 ˚C	T_{mean}=234 ˚C
Temperature at EU03.IF02	T_{min}=77 ˚C, T_{max}=78 ˚C	T_{mean}=217 ˚C
Temperature at EU03.IF03	T_{min}=75 ˚C, T_{max}=75 ˚C	T_{mean}=225 ˚C

The calculations were divided into several models, so there is different number and type of boundary conditions for every model.

MODELLING STRATEGY FOR BAKING SCENARIO

To calculate RNC In-port system (EU03) the whole system is calculated in three levels of details, as it is presented in Figure 2.

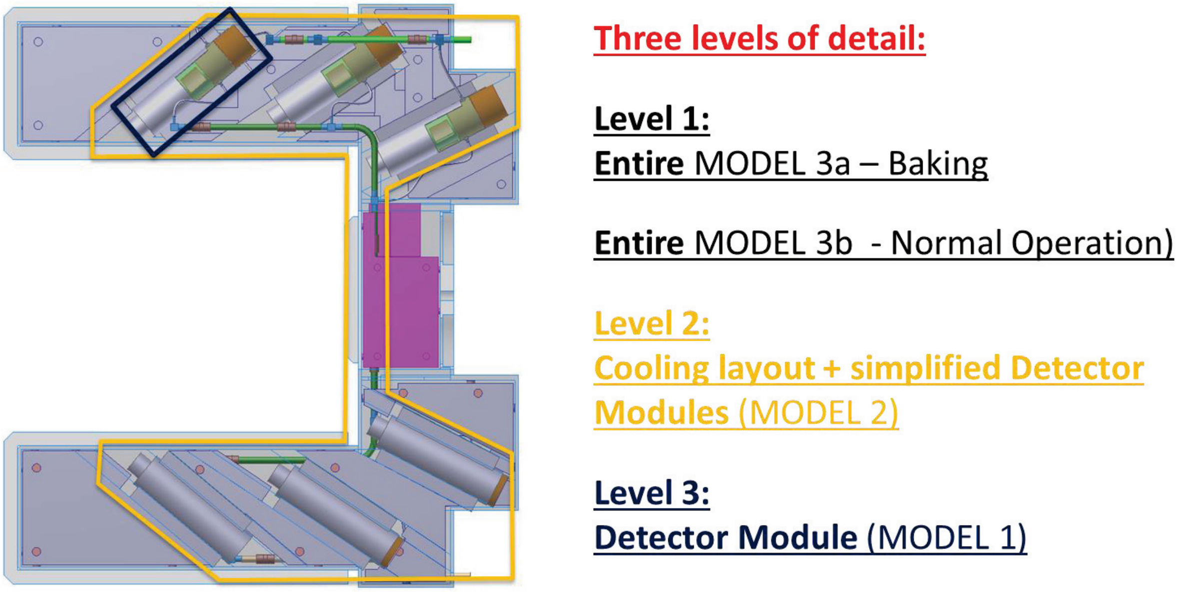

FIGURE 2. RNC layout with water cooling system with presented types of boundary conditions

The simulation general assumptions of the EU03 models is as follows:

- It is sufficient to analyze the most adverse scenario, defined by steady state simulations,
- The external surfaces of the Detector Cassette during the Baking Process are at a temperature of 240°C,
- The temperature of the external surfaces of the Detector Cassette during the Baking Process cannot be lower than 200°C,
- The Detector Modules should be maintained at a maximum temperature of 150°C.

The strategy assumes an efficient heat removal from all Detector Modules (and from detectors) by conduction and radiation by using a Water Jacket based thermal shields. It serves as a thermal barrier between high and low temperature environments cooled internally by water. The Water Jacket should be, as much as possible, thermally isolated from the high temperature structure. The most efficient thermal insulation system is based on a vacuum layer enclosed by surfaces characterized by low emissivity coefficient. In practical applications the thermal barrier is not fully efficient and gains heat from the hot adjacent walls. The excessive heat must be removed from the thermal barrier, to maintain it at the required temperature and this is made by water circulated along walls of the thermal barrier.

The practical application of the Water Jacket, designed for the purpose of the present analysis, is based on two axisymmetric cylinders made of stainless steel, one inserted into another, forming a thin layer between their walls, filled with circulating water.

For the normal operation and baking conditions the model is decomposed into sub models as it is presented in Fig. 3.

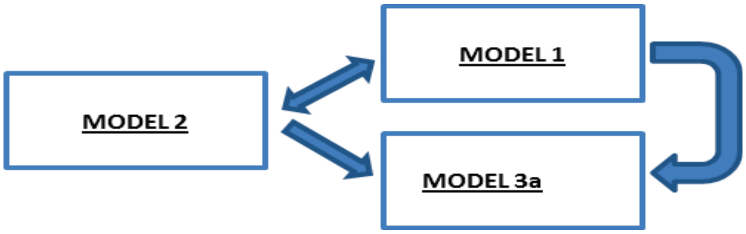

FIGURE 3. Data flow diagram

Forthcoming sub models presents:

a) MODEL 1 – Single Cooling Water Jacket + Detector Module (Steady state thermo-hydraulic 3D simulation during Baking)
b) MODEL 2 – Cooling Water Layout (Steady state thermo-hydraulic 3D simulation during Baking)
c) MODEL 3a – Simplified EU03 (Steady state thermal 3D simulation during Baking)

Calculations are performed as a step-by-step sequence as follows:

1) MODEL 1 – **1st iteration**, which results are:
- Local water pressure drop,
- Temperature map during baking,
- Verified cooling water mass flow rate [kg/s],
- Heat Flux [W/m^2] which is used in MODEL 2 as a boundary condition on the IFDM1,

2) MODEL 2 - **1st iteration**, which results are:
- Water pressure drop in whole cooling system,
- Map of temperature in the entire cooling water layout during baking,
- Water flow distribution in the cooling water layout (parallel channels),
- Total water mass flow rate,
- Conductive Heat Flux through pipes supports to be used in MODEL 3a,
- Conductive and Radiation Heat Flux to be used in MODEL 3a as a boundary condition,
- Inlet water mass flow rate and temperature to be used in model 1 – **2nd iteration,**

3) MODEL 1 **– 2nd iteration**, which results are:
- Heat Flux which is used in model 3a as a boundary condition on the IFDM2,

4) MODEL 3a – FINAL, where is assumed that the water is modelled as a “frozen” liquid. Results are:
- Map of temperature in the entire model during baking,
- Total Heat Transfer Rate [W],
- Surface Total Heat Flux [W/m^2].

The Total Heat Transfer Rate through a boundary is computed in ANSYS Fluent by summing the Convective Heat Transfer Rate and the Radiation Heat Transfer Rate. The Heat Flux to the wall is computed as:

$$q = h_{ext}(T_{ext} - T_w) + \varepsilon_{ext}\sigma(T_\infty^4 - T_w^4) \tag{1}$$

Where:
h_{ext} - external heat transfer coefficient,
T_{ext} - external heat-sink temperature,
T_w - wall surface temperature,
ε_{ext} - emissivity of the external wall surface,
σ - Stefan-Boltzmann constant,
T_w - surface temperature of the wall,
T_∞ - temperature of the radiation source or sink on the exterior of the domain.

Provided that on all faces adjacent to high vacuum voids the convective heat flux is neglected, the radiation heat flux is the only calculated in the domain.

The computation of the conduction heat transfer on a constant-temperature wall face is the product of the thermal conductivity of the domain and the temperature gradient

MODEL 1. Single cooling water jacket

Model 1 consist of simplified single cooling water jacket for one detector module. Boundary Conditions and selected names of results imposed on the cross-section of the MODEL 1 are presented in Fig. 4. The selected surface IFJS (IF Jacket Support) is an interface for data export to MODEL 2 and MODEL 3a according to the scheme in Fig. 3. Major boundary conditions for this model are presented in Table 2.

TABLE 2. Major boundary conditions

Boundary Condition	Value
Inlet Water Mass Flow Rate	0.0188 kg/s
Inlet Water Total Temperature	T= 37 ˚C
IFDM (IF Detector Module) temperature BC:	T= 240 ˚C
All external surfaces BC:	radiation from source 240 ˚C, emissivity = 0,7

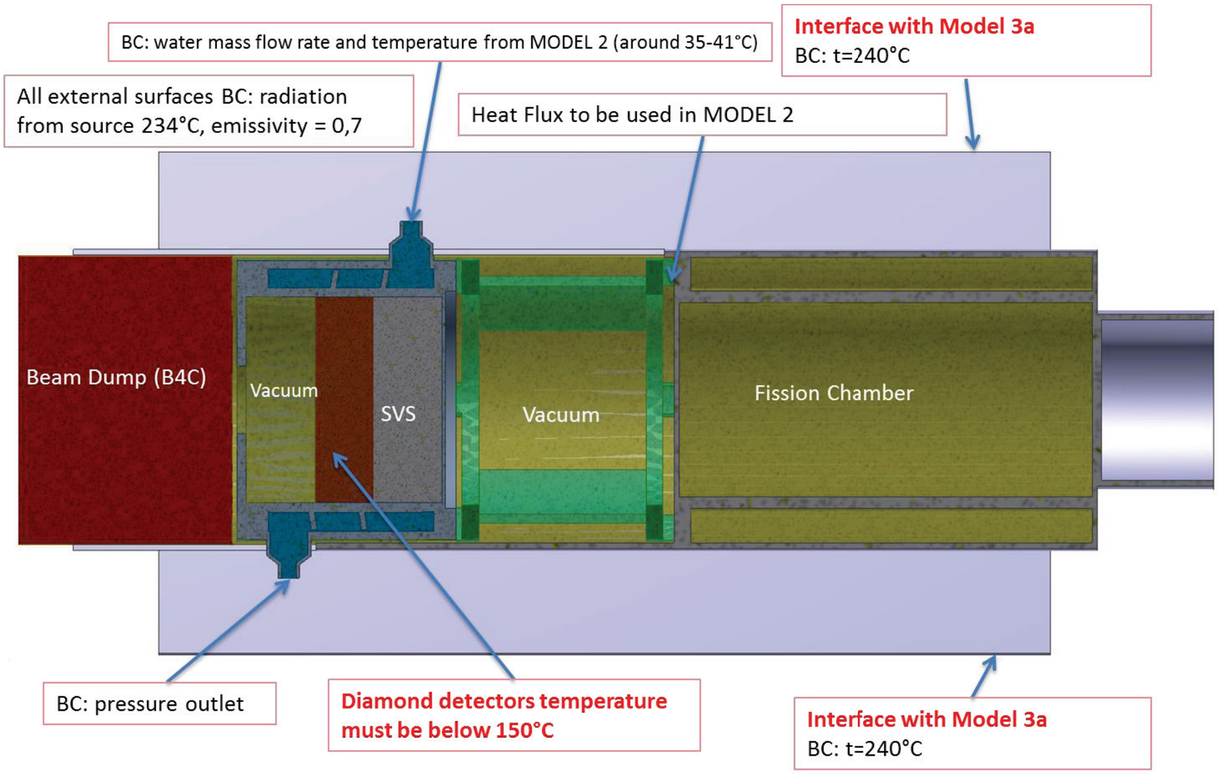

FIGURE 4. Single cooling Water Jacket CFD simplified model with boundary conditions

MODEL 2. Cooling water layout and detector modules

Boundary Conditions and selected names of results imposed on the MODEL 1 are presented in Fig. 5. The Boundary Conditions on selected surfaces IFJS (IF Jacket Support) is derived from MODEL 2 according to the scheme in Fig. 3. Interfaces IFPS1÷ IFPS10 (10 brown pipe supports) are the contact surfaces with MODEL 3a. The Heat Flux calculated in MODEL 2 is used in MODEL 3a as a Boundary Conditions.

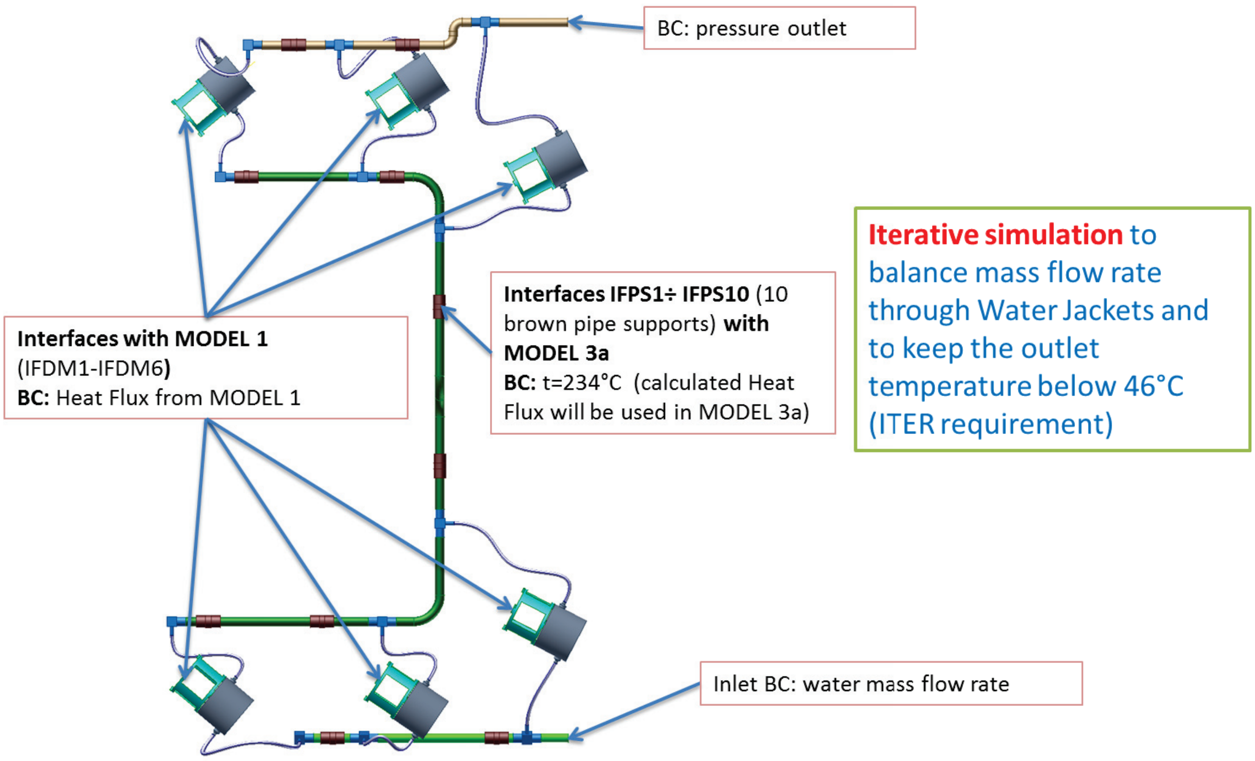

FIGURE 5. Thermal Boundary Conditions of the MODEL 2.

Iterative simulation will be conducted to balance mass flow rate through Water Jackets and to keep the outlet temperature below 46°C (ITER requirement).

MODEL 3a. EU03 for Baking

Temperature of external surfaces during Baking is close to 240°C. The cooling water stream inside the cooling layout (MODEL 2) makes its external surfaces as a heat sink absorbing heat from Detector Cassette structure by both conduction and radiation ways. In MODEL 3a only heat transfer by conduction is numerically simulated while radiation effect is imposed manually on participating surfaces as a boundary condition. Two parameters are defined, temperature of radiating external surface and emissivity coefficient of participating surface.

The Heat Rate and Heat Flux values from MODEL 2 are transferred to MODEL 3a as it is presented in Fig. 6.

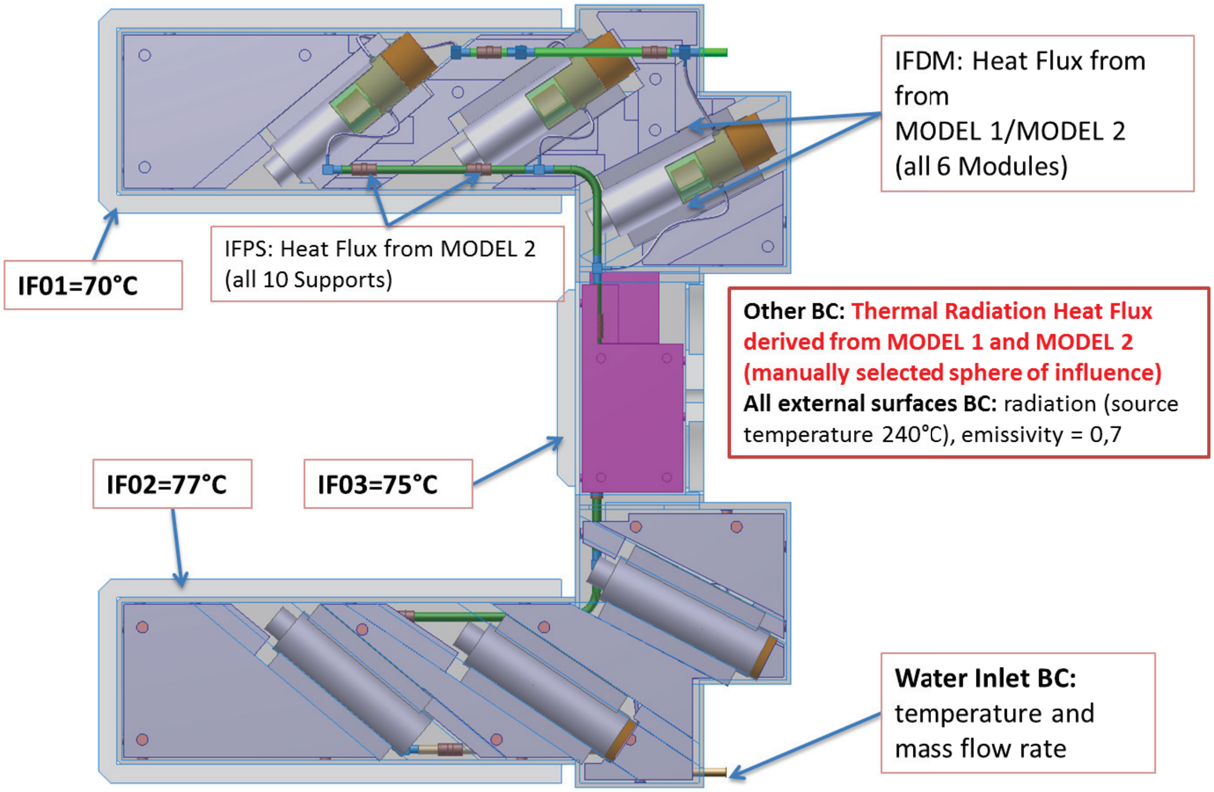

FIGURE 6. Thermal Boundary Conditions of the MODEL 3a

RESULTS

Global results obtained, for the In-port Detector Cassette during baking, in the MODEL 3a final simulations are presented in Fig. 7, Fig. 8 and Fig. 9. Please take a note, that in the presented figures temperature is in Kelvin scale, unlike the rest of the content of the paper. Temperatures obtained on different faces and interfaces are presented in the Table 3.

TABLE 3. Temperatures of faces and interfaces

Boundary	Average Temperature [°C]	Heat Transfer Rate [W]	Heat Flux [W/m^2]
IF01	234 (BC)	115	1207,3
IF02	217 (BC)	-171,6	-1799,5
IF03	225 (BC)	-7.4	-430,9
Upper Radiation surface	226,1	591	284
Central Radiation surface	227,7	117	260
Lower Radiation surface	219	865	422,9
Net value		1565,6	

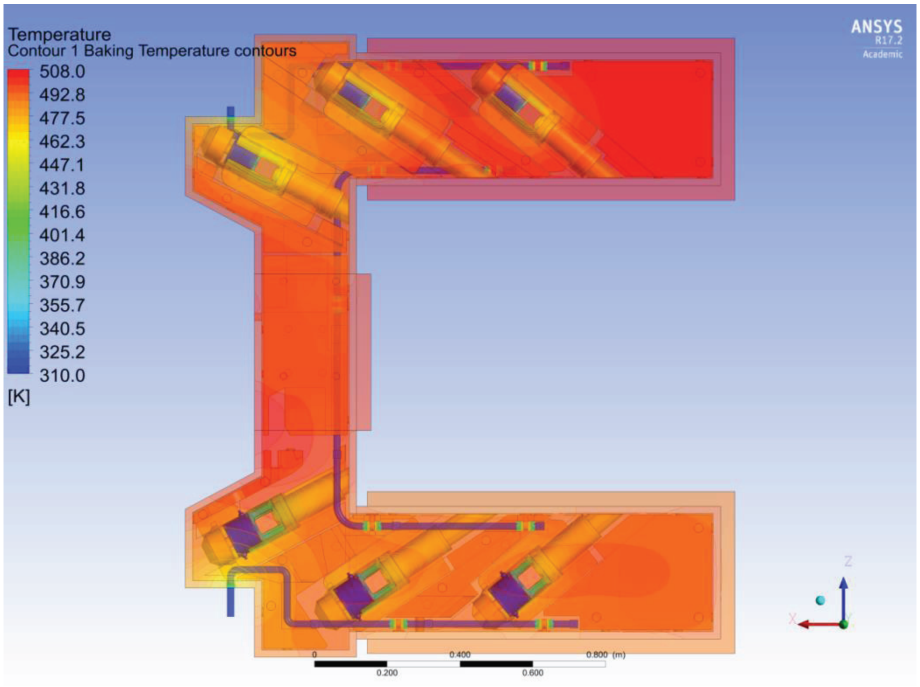

FIGURE 7. MODEL 3a (Baking) - global temperature contours.

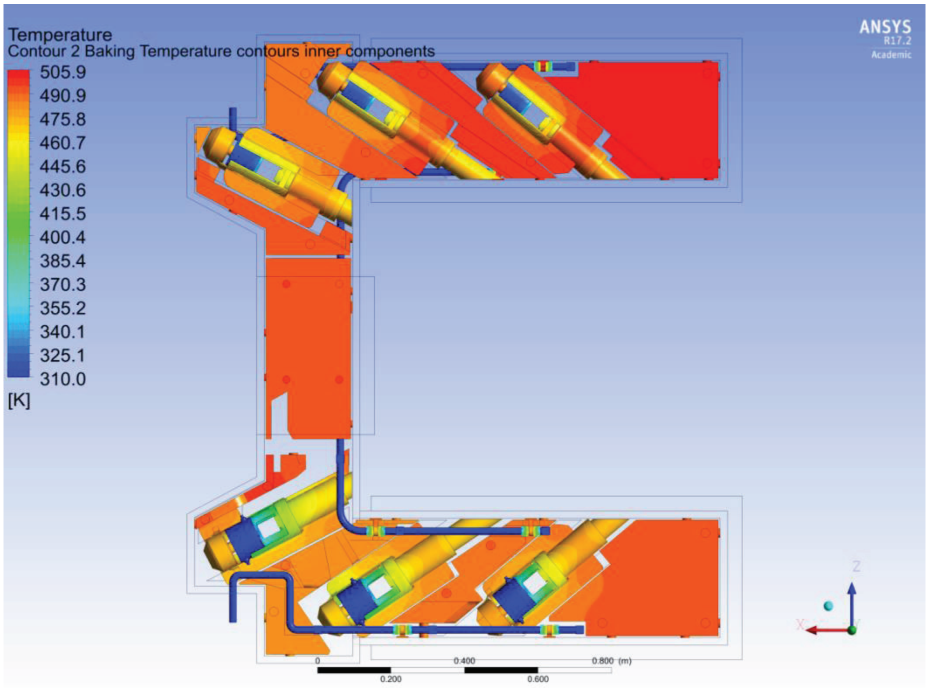

FIGURE 8. MODEL 3a (Baking) - temperature contours of inner components – side view.

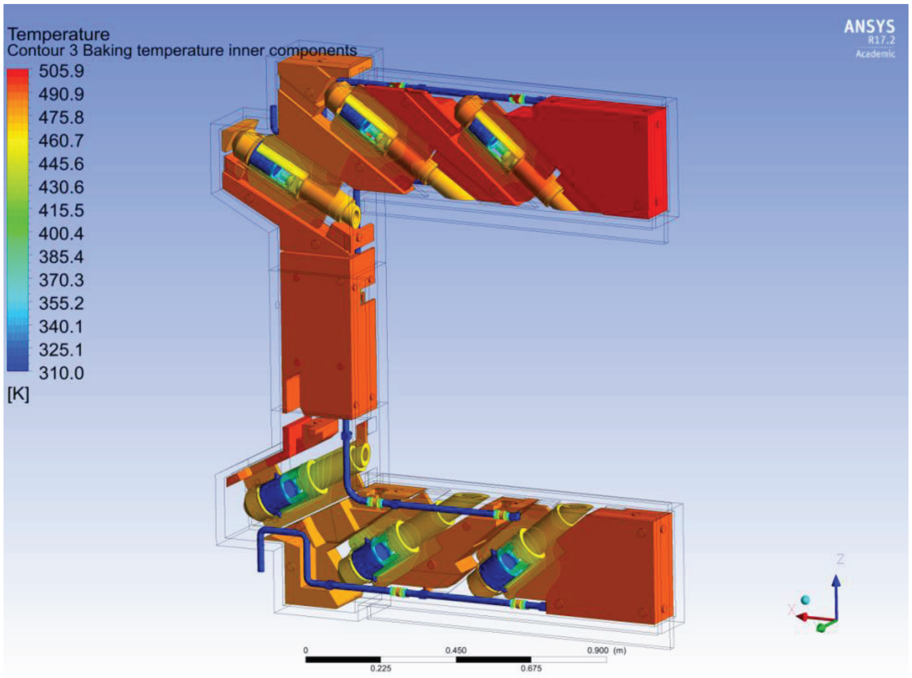

FIGURE 9. MODEL 3a (Baking) - temperature contours of inner components – iso view.

As it has been presented in Fig. 7, Fig. 8 and Fig. 9, temperature of detectors under baking conditions with the use of water cooling system are below assumed limit of 150°C.

CONCLUSIONS

Feasibility study of the efficiency of the cooling system for the In-port Detector Modules of the RNC during baking process has been presented. The CFD thermo-hydraulic numerical modeling provides input data to a preliminary design of the RNC. The CFD modeling was processed in accordance with the ITER Instruction for Computational Fluid Dynamic Analyses and reviewed by internal revision process including the analytical global thermal balance calculations.

CFD models show that each Detector Module equipped with an individual Water Jacket, with forced water flow and acting as a Heat Shield is a fully efficient method of temperature stabilization. Detector Modules within the Detector Cassettes can be maintained during Baking at a maximum temperature 46.3°C. The aggregated temperature rise along the path through the Detector Cassette and the inlet and outlet feedthroughs is 15.4°C. The use of the temperature maps derived with the present cooling circuit layout is suitable for structural analysis purposes.

ACKNOWLEDGMENTS

The work leading to this publication has been funded partially by Fusion for Energy under the Specific Grant Agreements F4E-FPA-327 SG03/SG06.This publication reflects the views only of the authors, and Fusion for Energy cannot be held responsible for any use which may be made of the information contained therein.

REFERENCES

1. R. Kantor, Procedia Engineering **157**, 271-278 (2016).
2. R. Kantor and P. Młynarczyk, Technical Transactions. Mechanics **1-M**, 121-128 (2016).
3. F. Moro, *et al.*, Fusion Engineering and Design **146 A**, 236-241 (2019).
4. F. Pompili *et al.*, Nuclear Instruments and Methods in Physics Research **A 936**, 62-64 (2019).
5. F. Moro *et al.*, Fusion Engineering and Design **123**, 1033-1038 (2017).