NUMERICAL STUDY OF THE HEATING IN A PNEUMATIC IRRADIATION SYSTEM

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Abstract. *Pneumatic irradiation system rigs are used in nuclear research reactors to provide a fast means of sending materials to irradiation positions located near the reactor core. Capsules containing the sample materials are sent through pipes using a gaseous fluid propellant. Upon reaching the desired position, the capsule undergoes exposure to radiation from the reactor enabling the transformation of the material allocated inside, but as a consequence of exposure, its thermal heating also occurs. This study has investigated this system numerically, using computational fluid dynamics (CFD). The results showed that for irradiation times on the order of 1 minute, considering a constant heat generation rate, can occur an increase in the capsule temperature up to critical values for the materials that are commonly used for their manufacture. Also, the numerical study was realized using four turbulence models and their results were compared to the experimental results.*

Keywords*: Pneumatic transport, Irradiation systems, CFD, Turbulence models*

1. INTRODUCTION

Pneumatic irradiation systems are usually used in Nuclear Research Reactors to obtain sample materials submitted to a neutron flux from reactor core. The main advantage of the pneumatic irradiation system is related to the velocity to send the sample materials in comparison than the other conventional ways. This characteristic is important to produce specific radioisotopes and for the Neutron Activation Analysis (NAA). In these two applications the sample materials are located in capsules, common called as rabbit, and sent to positions near the reactor core through pipes. A gaseous fluid, usually Nitrogen or Air is compressed and used as propellant that flows through the pipe carrying the capsule by the drag effect.

One of the main problem of the pneumatic irradiation system refers to the heating of the capsules during the irradiation period. The materials commonly applied on their manufacture are Aluminum and HDPE (High Density Polyethylene), especially for the last material, the increase of temperature can be dangerous because the melting point of the HDPE is between 90ºC and 120ºC.

Chung (2006) describes in his work that in the HANARO (High-Flux Advanced Neutron Application Reactor) the temperatures of the capsules are limited to 80ºC during the irradiation period and this temperature value corresponds to an irradiation time between 10 to 80 seconds. The capsules are exposed to a heat generation rate (5W/g) caused mainly for the gamma rays interaction with matter (Gamma heating).This heat generation rate (5W/g) also is described by Dyer (1987) in his work about the HFIR (High Flux Isotope Reactor) from the ORR (Oak Ridge Research Reactor). Other references about the use of pneumatic irradiation systems could be found on the papers and works developed by the authors Sheibley (1974) about the PBR (Plum Brook Reactor), Carpenter et. al. (2012) describing the facilities of MITR-NRL (Massachusetts Institute of Technology - Nuclear Reactor Laboratory), Fernando (2011) that designed the new pneumatic transport system for the IEA-R1, a Brazilian reactor from the IPEN (Nuclear and Energy Research Institute), and Chung (2013) that presents the irradiation system from the JRTR (Jordan Research and Training Reactor).

The study of the heating in the capsules is difficult due the installation of the measuring instruments because the researches and operators are exposed to the irradiation. Then the numerical analyses can be an alternative and safe method to study this phenomenon.

2. DEVELOPMENT OF THE STUDY

This study was realized based on the irradiation system developed for the reactor OPAL (Australia's Open Pool Australian Lightwater). An irradiation tube or rig (that is a mechanical device installed in the reflector vessel of reactor) that receives the capsules during the irradiation process was designed and built. This device was developed following the work of Hosokawa et. al. (2008) with small differences in geometrical dimensions and materials selection (Aluminum alloys were applied), but keeping the functional similarity and the main components. The irradiation tube can be seen in the Fig. (1).

The irradiation tube receives two distinct and isolated flows during the irradiation process with the purpose of heating removal for the capsule and the self irradiation tube. First, continuously light water flows through inside the irradiation tube without contact with the capsule to remove heat caused by gamma ray interaction in the tube itself. Also a small flow rate of the propellant used to transport the capsule flows to remove heat mainly from the capsule during the irradiation.

A numerical study was realized using the commercial software of computational fluid dynamics Ansys CFX® and ICEM® CFD for mesh development. The Ansys CFX® software uses the Finite Volume Method with Finite Element Approach to realize the interpolations of the numerical quantities and a Fully Implicit Solver to solve the algebraic equations system.

Three unstructured with prismatic layers meshes (coarse, medium and fine) with 1435387, 3362856 and 9190599 elements were developed, considering different sizes of refinement, and the General Grid Convergence Method technique was used to evaluate the convergence and independent mesh solution based on the work published by Celik et. al. (2008).

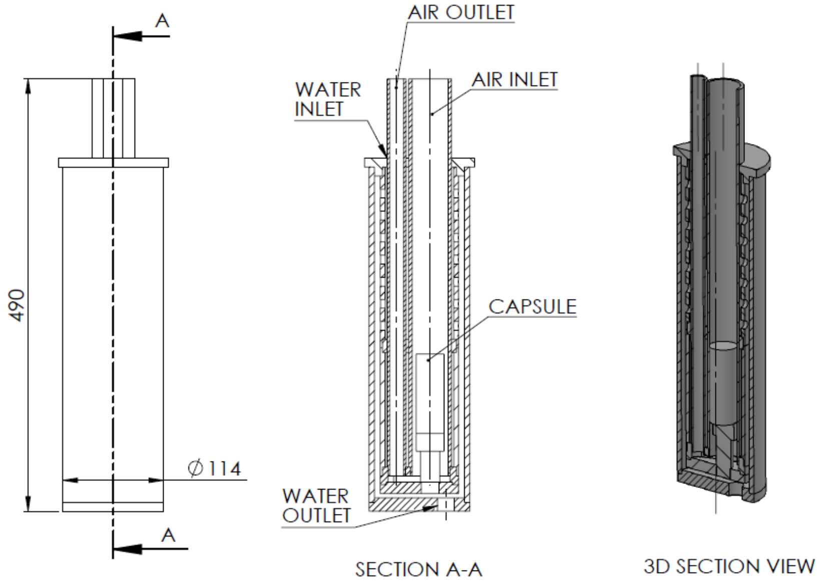


Figure 1. Irradiation tube (rig) developed. Dimensions are in millimeters.

This method calculates three errors, respectively called as approximated $e_a{}^{21}$, extrapolated $e_{ext}{}^{21}$and convergence index $GCI_{fine}{}^{21}$.These errors are calculated according to the Eq.(1) to Eq. (3), being ∅ the temperature, *r* the refinement ratio – Eq. (4), N being the number of the mesh elements, *h* the mesh size – Eq.(5) and *p* the apparent order of the method – Eq. (6). The indexes 1,2 and 3 correspond to the coarse, medium and fine meshes and the indexes "j" and "i" are related to respectively from the finest to the coarsest mesh. Finally ε represents the difference between the temperatures (Ø) obtained by the different meshes and *s* is the signal function of $\varepsilon_{32}/\varepsilon_{21}$.

$$e_a{}^{21} = \left|\frac{\phi_1-\phi_2}{\phi_1}\right| \quad (1)$$

$$e_{ext}{}^{21} = \left|\frac{\phi^{12}{}_{ext}-\phi_1}{\phi^{12}{}_{ext}}\right| \quad (2)$$

$$GCI_{fine}{}^{21} = \frac{1.25\, e_a{}^{21}}{r_{21}^p-1} \quad (3)$$

$$r_{ji} = \frac{h_j}{h_i} \quad (4)$$

$$h = \left(\frac{N_j}{N_i}\right)^{1/3} \quad (5)$$

$$p = \frac{1}{\ln(r_{21})}\left|\ln|\varepsilon_{32}/\varepsilon_{21}| + \ln\left(\frac{r_{21}^p-s}{r_{32}^p-s}\right)\right| \quad (6)$$

All the simulations were realized with convective scheme High Resolution for continuity, momentum and energy equations and Upwind (First Order) to the turbulence equations. The time-step used in the transient simulations was 0.2

seconds and the maximum RMS (Root Mean Square) residual in the iterative calculation was 1.0e-4. The turbulence models applied in this study were k-ε, RNG k-ε, k-Ω and SST (Shear Stress Transport).

The capsule was modeled as an electrical resistance (cylinder with 90mm x Ø21.6 mm) and two thin layers with 3 mm of magnesium oxide and 2 mm of steel. The thermal contact resistance between the interfaces was adopted as 0.0009m^{2o}C/W (average value estimated in accordance with the resistance manufacturer). This procedure was realized to forward comparison of the obtained results with experimental study data of the Oguma and Pimenta (2016) work. The authors realized a simplified experimental study using an electrical resistance to simulate the capsule and its heat generation. The boundary conditions applied to the numerical study are described in the Tab. (1).

Table 1. Boundary conditions

Location	Boundary condition
Air inlet	Flow rate = 3.33e-3 (m^3/s) Reynolds = 6738 Temperature = 22ºC
Air outlet	Atmospheric discharge (Relative pressure = 0 Pa)
Water inlet	Flow rate = 2.83e-4 (m^3/s) Reynolds = 16 926 Temperature = 22ºC
Water outlet	Relative pressure = 0 Pa
Capsule and stop contact	Thermal contact resistance = 11400 W/m^{2o}C
Heat generation	Heat generation rate = 5 W/g (total 140W for the capsule)

Three temperatures probes have been installed (T1, T2 and T3) according with the Fig. (2), on the surface of the capsules, downstream of the capsule in the air domain, and near the air outlet were analyzed to forward comparison between the turbulence models. The heat generation of the irradiation tube was neglected because the experimental study cannot reproduce this phenomenon.

The process conditions were adopted following some preliminary assumptions for the fluid flow rates used on the development of the RMB (Brazilian Multipurpose Reactor) conceptual project, the heat generation rate was chosen accordingly to the already quoted studies published by Chung (2006) and Dyer (1897).

The heat transfer between the irradiation tube and the other components of the reflector vessel of the reactor was disregarded and the external temperature of the irradiation tube surface, which is in contact with heavy water of the reflector vessel, was adopted as 22ºC. Initially, this value was regarded as 33.1ºC (related to the light and heavy water stabilized temperatures in the RMB reactor), according Navarro et. al. (2011) which studied numerically the flow behavior in the reactor pool. But following the experimental study, there were no impact in the air flow and capsule temperature results using this temperature (33.1ºC). The authors Oguma and Pimenta (2016) adopted 22ºC (average ambient temperature) to avoid the thermal heating of the water in the experimental tests.

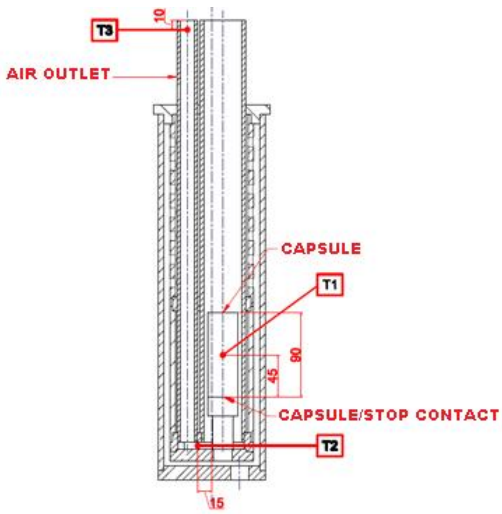
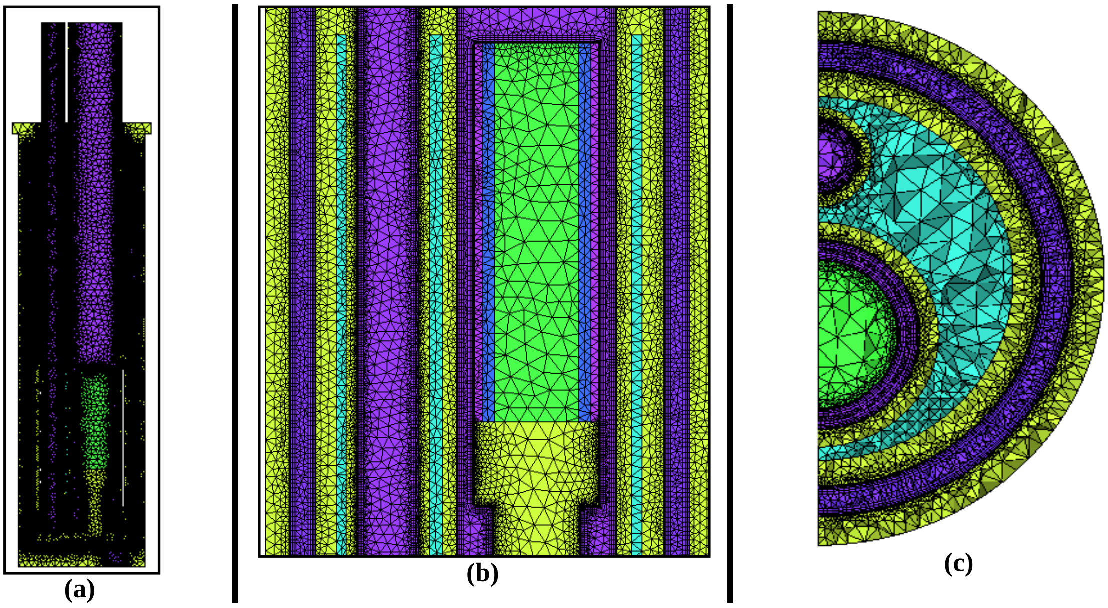


Figure 2.Temperature measurement points. Dimensions are in millimeters.

5. RESULTS

The results of the mesh refinement process under the Grid Convergence Method are showed in Tab. (2) and illustrations of the fine mesh are presented in Fig. (3). It is possible to see according the Tab. (2) that the three meshes produced similar results of temperature for all the measurement points for the final simulation time (60s) and the Grid Convergence Index was calculated showing values less than 1%.



(a) **(b)** **(c)**

Figure 3. Fine mesh developed. (a) General, (b) Capsule detail, (c) Capsule middle section

Table 2. Results of the Grid Convergence Method

Temperature positions	$T1_{60}$	$T2_{60}$	$T3_{60}$
$r_{mid/gcoarse}$	1.328	1.328	1.328
$r_{fine/mid}$	1.398	1.398	1.398
T_{coarse} (°C)	73.22	30.97	27.52
T_{mid} (°C)	73.43	30.96	27.51
T_{fine} (°C)	72.91	30.47	27.57
p	2.85	13.74	7.20
$T_{mid/coarse}ext$	73.05	30.97	27.52
$T_{fine/mid}ext$	73.76	30.97	27.50
$e_{mid/coarse}a$	0.29%	0.02%	0.02%
$e_{mid/coarse}$ ext	0.23%	0.00033%	0.0029%
GCI	0.29%	0.00041%	0.0036%

The temperatures increase for the three points (T1, T2 and T3) are presented in the Fig. (4) to Fig. (6) respectively for all the turbulence models. It is possible to check that for the T1 position, there was no difference between the results because the predominant physical phenomenon is thermal conduction through the walls of the capsule and also the numerical results had a good accuracy with the experimental results.

For the temperatures T2 and T3 it is possible to check significant difference between the results. For all the turbulence models, the temperature T2 showed good agreement with the experimental results and except for RNG k-ε model, all the numerical results kept inside the error range of the experimental data. For the temperature T3 is possible to see that all the numerical results showed a good qualitative response with similar aspect with experimental curve, but the values of temperature diverged since the initial time (t=0s) until the end of simulation. This probably was caused due to ambient temperature influence during the experimental and the proximity of the measurement point T3 with the far field according the authors of the experimental study.

Another important observed detail from the results of the simulations was concerning about the different prediction of the fluid flow inside the transitional region between the inlet and outlet tube of air. This region was predicted with different patterns of fluid flow as can be seen in Fig. (7) and Fig. (8). Probably this difference, mainly in the recirculation flow zones in the corner ahead the capsule stop, caused the observed values in the temperature measurement point T2 for the turbulence models.

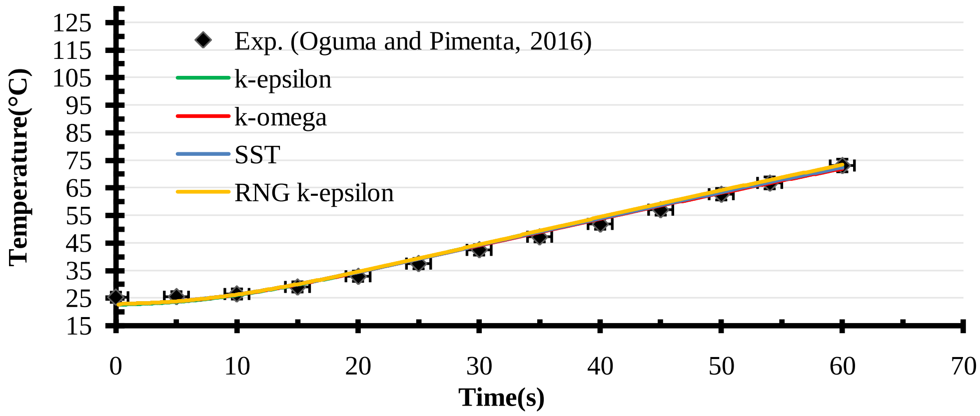


Figure 4. Increase of temperature for the measurement point T1

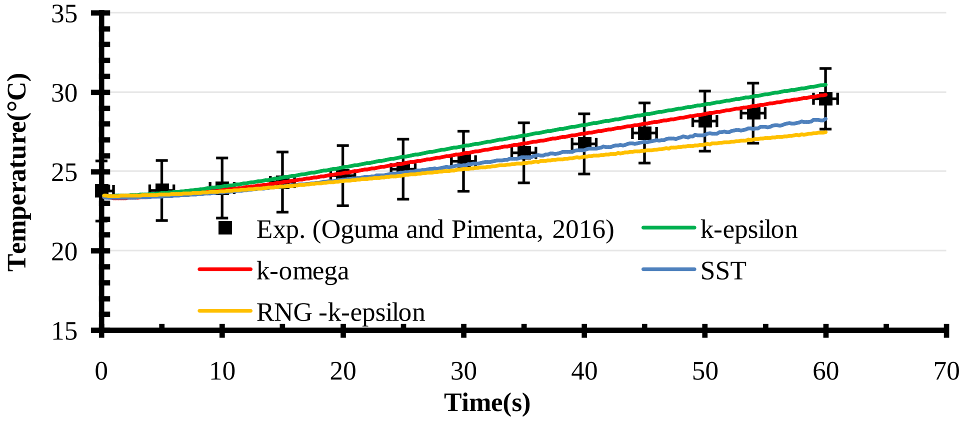


Figure 5. Increase of temperature for the measurement point T2

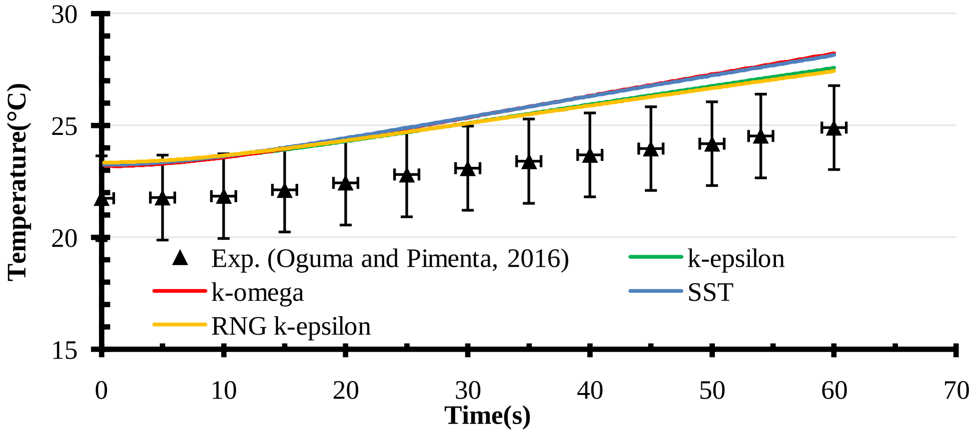


Figure 6. Increase of temperature for the measurement point T3

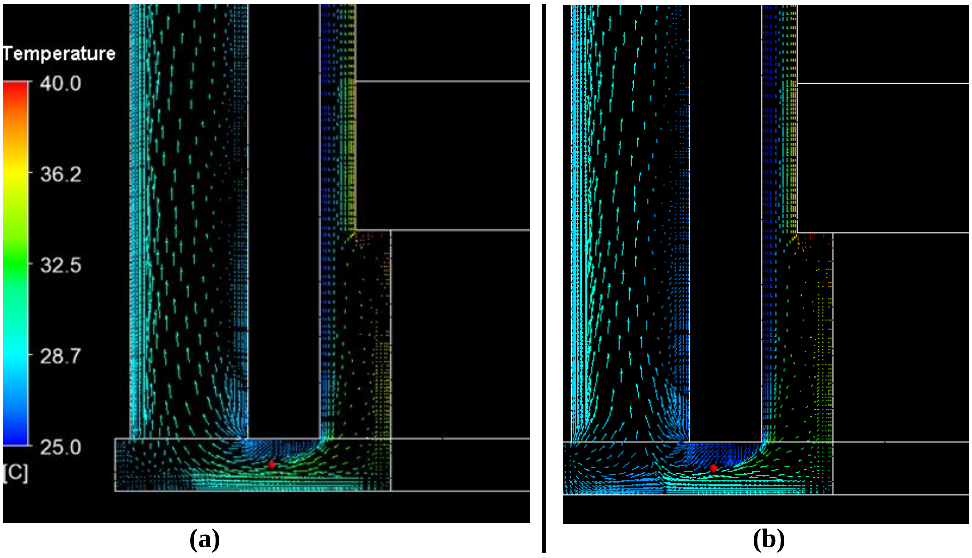


Figure 7.Velocity vectors for the transitional geometry after the capsule. Measurement point T2 represented as a red circle. (a) k-ε model, (b) RNG k-ε model.

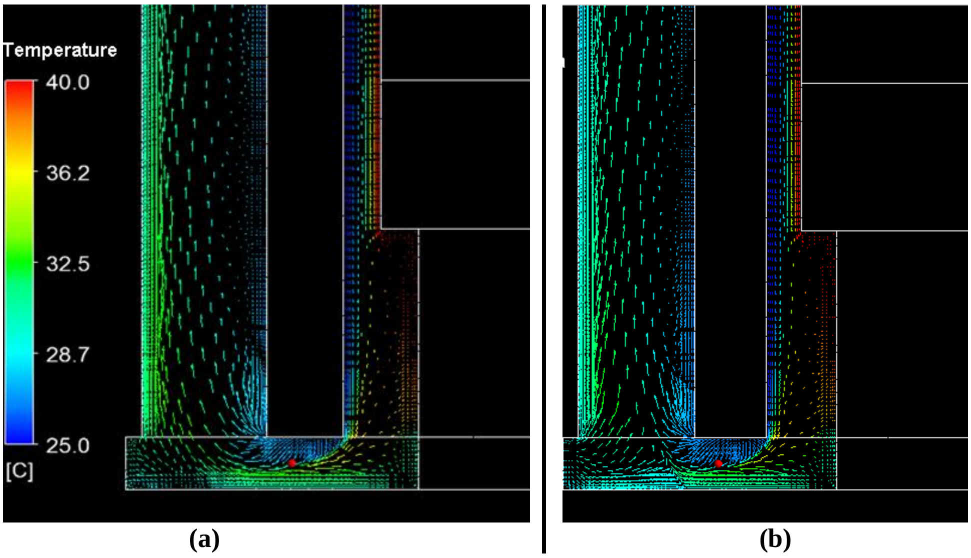


Figure 8.Velocity vectors for the transitional geometry after the capsule. Measurement point T2 represented as a red circle. (a) k-Ω model, (b) SST model.

6. CONCLUSION

This work studied the increase of temperature in specific points of a generic irradiation tube developed following similar equipments described in the literature using computational fluid dynamics (CFD). Four different turbulence models were used in the simulations and their results were compared to the experimental data.

All the turbulence models showed a good agreement with the experimental results with almost exact results for the measurement in the surface of the capsule and small divergence in the quantitative results for the measurement points and the flow pattern located in the cooling air, especially for the transitional geometry region after the capsule.

The temperature on the surface of the capsule, simulated as an electrical resistance, increased to values almost 74ºC that is not enough to melt materials as HDPE, but considering that the internal temperature of the resistance may be raised up to values above the surface, the application of real materials, instead an electrical resistance, probably can achieve near values of the melting point of HDPE as discussed by Oguma and Pimenta (2016).

5. REFERENCES

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5. RESPONSIBILITY NOTICE

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