RERTR 2012 — 34th INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

October 14-17, 2012
Warsaw Marriott Hotel
Warsaw, Poland

An Analysis of Oxide Layer Influence on Heat Transfer Conditions in MARIA Reactor

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ABSTRACT

Within the framework of test fuel examination it has been performed the irradiation of one of fuel elements to high level of burnup (ca. 60 %). Post-irradiation examinations proved that under high burnup it comes to local detachment of oxide layer from the fuel element cladding. Unilateral breaking away of the oxide layer of strong isolating properties from cladding surface may lead to disturbance of conditions for heat removal from the fuel. This effect has been numerically modeled by means of ANSYS FLUENT code. The results confirmed the existence of heat flux redistribution in spot of oxide layer detachment. Since the phenomenon for breaking away of oxide layer appears at high fuel burnup the thermal load are getting lower than in most thermally loaded fuel elements so the safety margins for fuel operation are being preserved.

1. Introduction

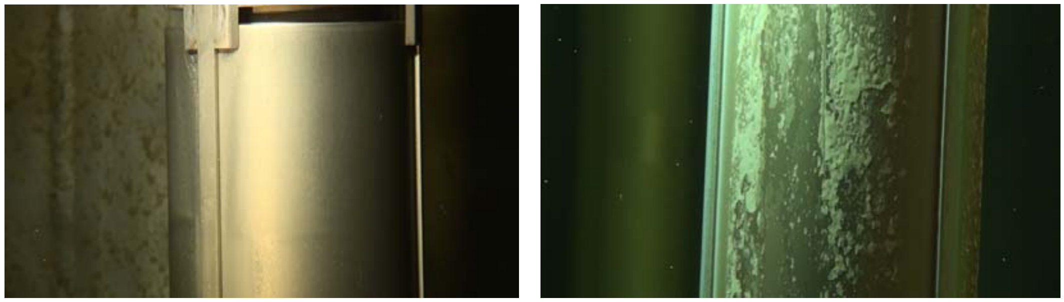
During the MARIA reactor operation on the surface of fuel elements' claddings it is created a layer of hydrated aluminum oxide to be defined as oxide layer. It is characterized by very low thermal conductivity. Its thickness increases gradually in time and through a certain interval of time this layer is strictly adhering to the cladding. On achieving the thickness of several tens of μm it breaks away and a creation process is starting anew.
Rate of oxide layer accretion mainly depends on temperature on the water – oxide boundary and on cooling water pH whilst it doesn't depend on pressure and velocity of water flow. Rate of increase of oxide layer thickness is to be determined by means of Arrhenius formula [2]:

$$v_b = v_0 \exp\left(-\frac{E_b}{k_B T}\right) \qquad (1)$$

where: v_0, Eb – constants, kb = Boltzmann constant and temperature is given in K degrees. Just this kind of relationship was earlier proven by American experimental examinations within the range of pH = 5 ÷ 5.5 and the matching constants are:

$$v_0 = 7.23 \cdot \frac{10^6 \mu m}{d}\,; E_b = 0.56 eV\,; E_b / k_B = 6490 K$$

On the picture below are shown photographs of MC fuel elements cladding surface in case when the cladding in total is covered by oxide layer and in case of partial separation of this layer.



a b

Photographs of external surface of MC fuel element No 6 [2]: a – cladding totally covered by oxide layer; b – cladding with oxide layer partially breaking away.

2. Description of calculations

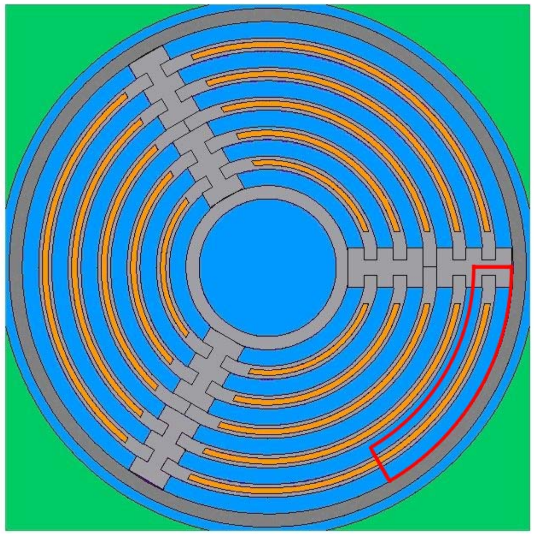
A number of computer simulations was accomplished to determine temperatures and denity of heat flux on fuel element cladding. All calculations were made for a selected fragment of the 6th tube for MC fuel element. This type of fuel element consists of 15 bent fuel plates joint in 5 fuel tubes.

On the attached drawing the zone for which a series of calculations was performed using ANSYS FLUENT 13.0 code has been marked by red lines. One can see on this drawing only dimensions of the zone, however, it is considered as a volume.

Tube No 6 was chosen since on its surfaces the highest temperatures are present. Besides, from that tube a fragment of 10 cm length was chosen (the total length of the fuel contained tube segment is 100 cm) for which there has been noticed the greatest heat generation because presumably just in this place the oxide layer will break away earliest. Especially interesting is the inner surface of the 6th tube because there occur slightly greater temperatures than in the outer surface. Because of that the calculations were made for the events with detachment of oxide layer fragments only for inner side of the 6th tube.

The three-dimensional region consists of fuel tube fragment over the length 10 cm and water layers on both its sides. Water in both gaps flows downwards. The region encloses half thickness of aluminum connecting link and half of fuel plate width. From outside this region is constrained by inner surface of fuel channel tube and from inside by an arc passing through the center of water gap between tubes 5 and 6.

On the drawing one can see that the tube consists of three regions separated from each other by aluminum connecting links. Detachment of oxide layer fragment from cladding surface in one of these three regions has minimal impact on heat exchange in the remaining regions. Besides, it has been assumed that oxide layer detachment will occur exactly in half fuel plate width on inner surface of the 6th tube and in half length of the examined segment and that it will have shape of wheel. Due to that calculations were made only for 1/6 of circumference of 6th tube. In the center of linking connector and in half fuel plate width the plates of symmetry are placed. The region analyzed is constrained from inside by bend passing through the water gap center as it was assumed the lack of heat exchange between water to be at one side of this bend and the water at the other its side. It is substantiated by fact that heat is generated in tube 5 and in tube 6. Because of this assumption a symmetry condition indicating lack of heat exchange through this surface has been applied on the surface to be in half distance between these two tubes.



Cross-section for the fuel element with marked region being analyzed.

The calculations were performed for cases when:

a) Oxide layer is distributed on both sides of tube (symmetrical layer);
b) Oxide layer appears only on outer side of tube (asymmetrical layer with total separation in inner side);
c) Oxide layer of the wheel shape with 10 mm diameter was breaking away on the inner side;
d) Oxide layer of the wheel shape with 5 mm diameter was breaking away on the inner side;
e) Detachment of oxide layer of the wheel shape with 2 mm diameter occurred on the inner side.

The regions' geometry as well as the three-dimensional discretization lattices for all above emphasized cases were created by GAMBIT code.

Calculations were completed for the steady mode.

It has been assumed that oxide layer to be braking away doesn't cause decreasing the thickness of aluminum fuel cladding.

Calculations were completed for oxide layer with thickness equal to 50 µm.

It has been taken into consideration that between fuel layer and aluminum cladding as well as between cladding and oxide layer there is no thermal or contact resistance because these materials fit tight to each other.

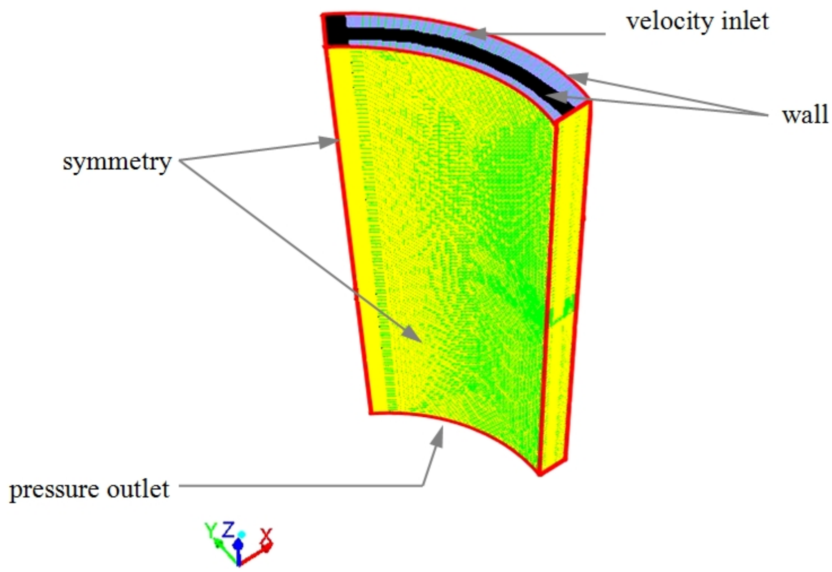
Gradient for linear generation of thermal power in selected segment of the 6th tube is very small so it was assumed that the linear thermal power generation is a constant value.

In the spots where are surfaces of symmetry doesn't undergo heat exchange. It has been assumed a scarcity of heat exchange through upper and lower area of fuel plate and aluminum linking connector and through the outer surface of the region.

The following boundary conditions were applied:

- "velocity-inlet" on the inlet surfaces where inlet temperatures and inlet velocity profiles have been declared (light blue color on the drawing);
- "pressure-outlet" on the outlet surfaces where the values of static outlet pressure have been declared;
- "symmetry" on inner surface of the region to be investigated as well as on two adjacent to it side surfaces (yellow color on the drawing);

- "wall" on surfaces of all solid bodies (black color) beyond the two side surfaces of linking connector and the oblong fuel plate for which the symmetry condition was applied.



Region to be considered along with boundary conditions marked.

On the above drawing is shown that for the outer surface of the considered region the condition of "wall" type was applied. This surface exhibits an inner wall of fuel channel which has been already earlier described.
If it is to be used condition "wall" type based, presumably is being set the null value for heat flux penetration through the surface for which it has been declared under the condition that it is a surface placed on the brink of region (e.g. outer surface). In other case when the surface is located between two zones presumably is being set the coupled thermal condition and in such situation the heat may be exchanged through the surface between adjacent to it zones.
For the calculations the following data were used:

- Linear generation of thermal power inside the fuel layer: Q_l = 6.79 kW/cm (for the whole tube circumference);
- Volumetric capacity of the internal heat source in fuel layer: $S_b = Q_l/(6A)$ = 4.5918 GW/m^3 (has been divided by 6 because the calculations refer 1/6 th of tube perimeter), where A is half surface area of the cross-section for fuel layer for the 6th plate of fuel tube;
- On inner wall side:
  - Inlet temperature: T_{6in} = 64.3 ^{o}C;
  - Mass flux: m_6 = 631.1 g/(cm^{2}s);
- On outer wall side:
  - Inlet temperature: T_{7in} = 56.3 ^{o}C;
  - Mass flux: m_7 = 568.8 g/(cm^{2}s);
- The inlet pressure on both sides is 1.61 MPa;
- Thermal conductivity of aluminum cladding is: λ_{Al} = 132 W/(mK);
- Thermal conductivity of fuel layer is: λ_{pal} = 60 W/(mK);
- Thermal conductivity of oxide layer is: λ_b = 2.25 W/(mK);

- Thermal conductivity, density, specific heat and dynamic viscosity of water were scooped from tables [4, 5] and they depend upon temperature, their values were defined by linear interpolation.

Water flow through the region to be analyzed is turbulent, then it was necessary to use the Reynold's equations which were being the averaged Navier's – Stoke's equations. In this case the ANSYS FLUENT code applies the following conservation equations:

Mass conservation equation (continuity equation):

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{2}$$

Equation for conservation of momentum:

$$\rho \frac{\partial}{\partial x_j}\left(u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \tag{3}$$

where $\delta_{ij} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$

Equation for conservation of energy for liquid:

$$\nabla \cdot \left(\vec{v}\left(\rho E + p\right)\right) = \nabla \cdot \left(k_{eff} \nabla T\right) \tag{4}$$

where: k_{eff} – effective thermal conductivity,

$$k_{eff} = k + k_t \tag{5}$$

where k_t is the turbulent thermal conductivity.

For the solids the equation for conservation of energy is of following form:

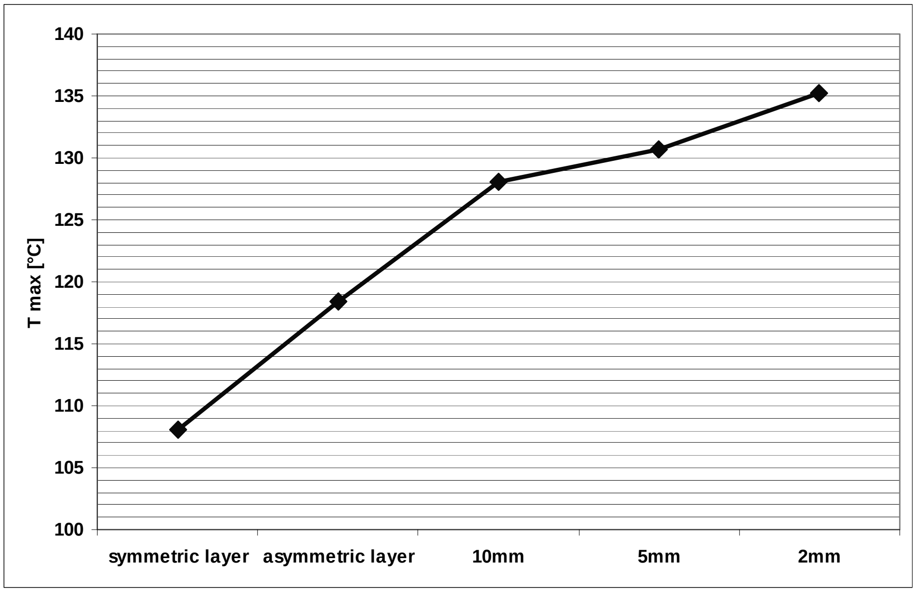
$$\nabla \cdot \left(k \nabla T\right) + S_h = 0 \tag{6}$$

where S_h is the volumetric capacity for inner heat source.

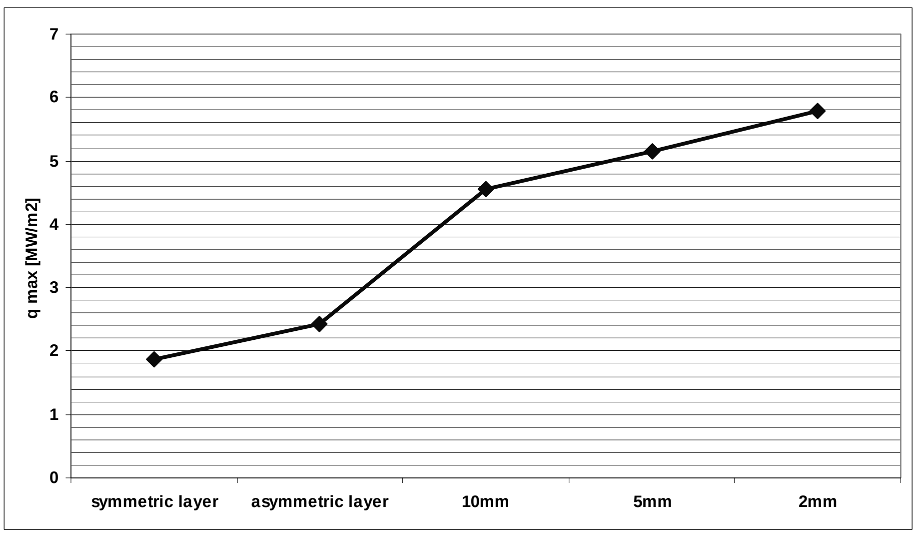
In equations has been applied Einstein's contracted summation notation in which the indexes to be repeated denote summation in the entire range of their variation. To closing Reynold's equations it is necessary to apply one of the turbulence models. It has been applied the two-equations turbulence model SST-kω (Shear Stress Transport kω).

3. Computer simulation results

On the below enclosed drawings the maximum temperature values as well the heat flux densities for 5 investigated cases are shown.



Values of maximal temperatures for the 5 considered cases.



Values of maximal heat flux densities for the 5 considered cases.

To verifying whether in the fuel elements' channels there won't occur boiling of water it has been also determined the temperature for onset of subcooled bubble boiling T_{ONB} (Onset Nucleate Boiling) as well the ONBR parameter for the line of openings' symmetry:

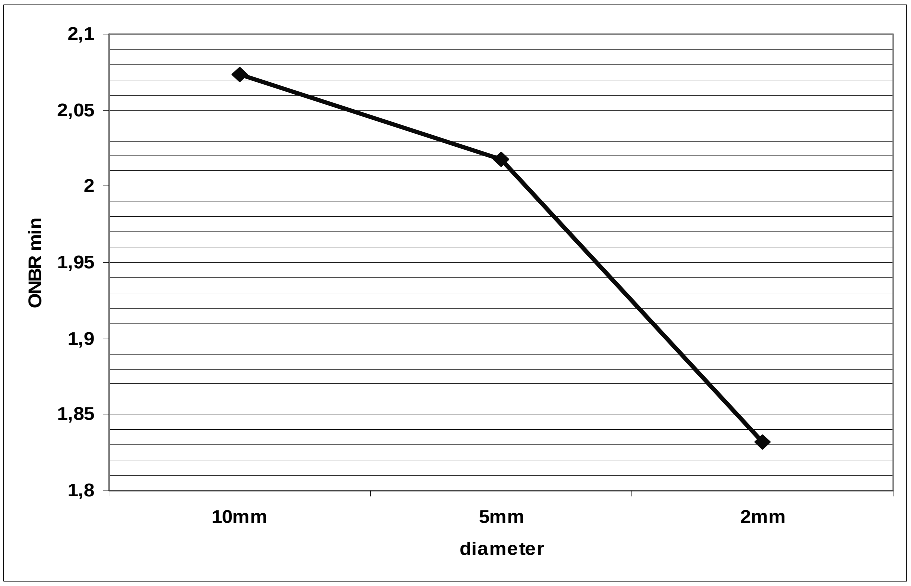
$$ONBR = \frac{T_{ONB} - T_{wl}}{T_{k,\max} - T_{wl}} \tag{7}$$

where $T_{k,max}$ and T_{wl} are the maximum temperature for fuel element cladding and water temperature at the inlet to the fuel channel, respectively.

In the safety analyses there are being used two safety limits [2]: exclusion of surface boiling on the fuel element cladding as well to provide the limit ONBR > 1.2. The onset temperature for subcooled bubble boiling T_{ONB} is determined by means of Forster's-Greif's correlation [2]:

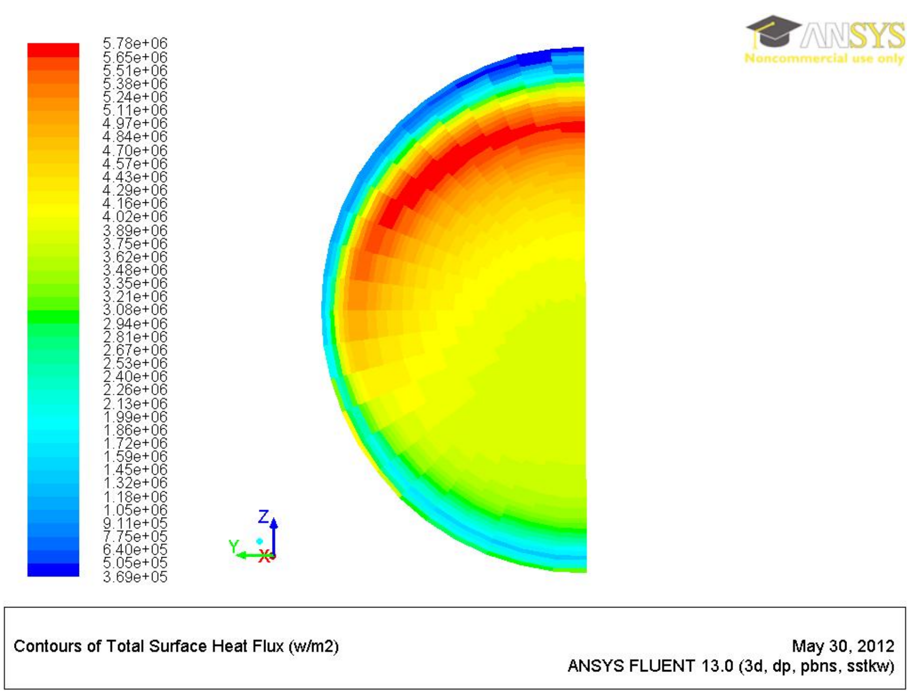
$$T_{ONB} = T_{SAT} + 0.182 \frac{q^{0.35}}{p^{0.23}} \tag{8}$$

where: T_{SAT} – saturation temperature, q – heat flux on the wall [W/m^2], p – water pressure [bar].
On the below enclosed drawing the minimal values of ONBR parameter for 3 cases of oxide layer detachment.



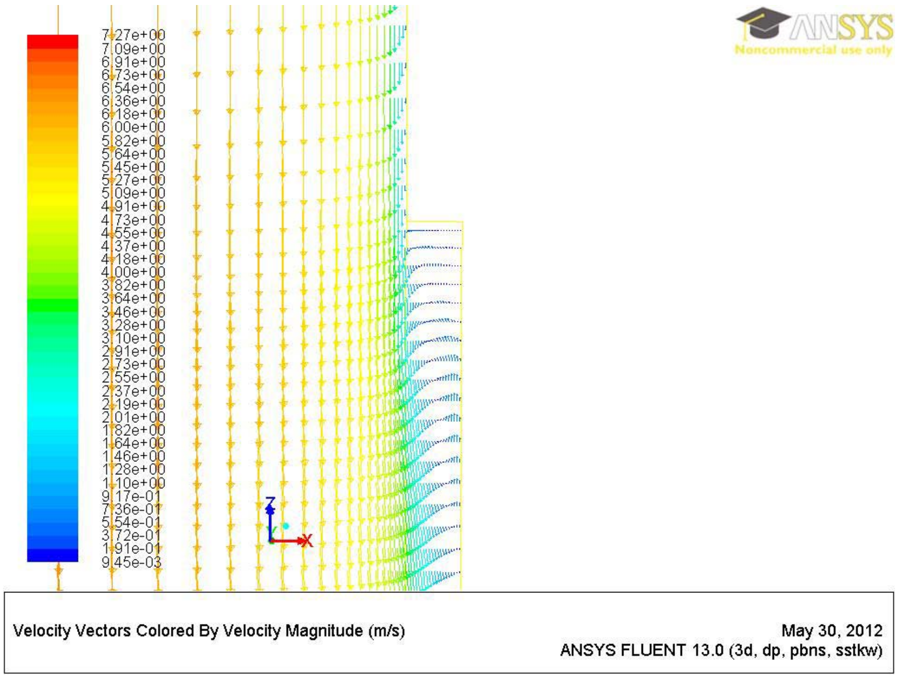
Minimal values of ONBR parameter for 3 cases of oxide layer detachment.

On the below attached drawing the heat flux density in the opening to be arisen after detachment of oxide layer for 2 mm diameter is shown.



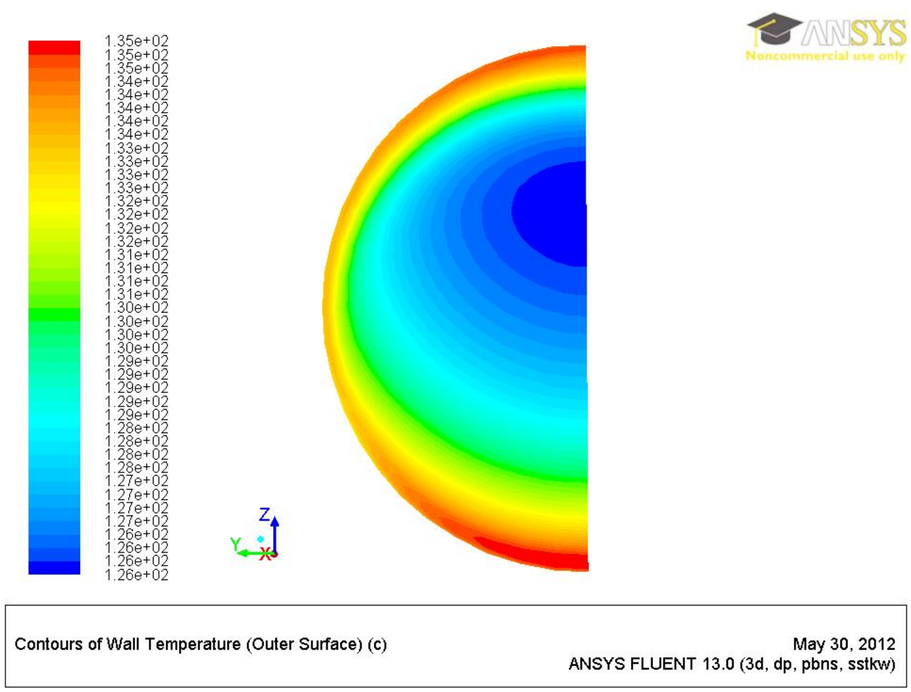
Heat flux density in the opening for the detachment diameter 2 mm.

It is well seen that the highest values appear in the upper part of the opening. It is caused by creating a vortex in this spot which is to be shown on the drawing attached below.



Velocity vectors on the symmetry plane at the top of the opening for opening diameter 2 mm.

Below is presented temperature distribution in the opening to be created after detachment of oxide layer for the separation diameter 2 mm.



Temperature distribution in the opening for detachment diameter 2 mm.

4. Conclusions

An analysis of computer simulation allow to formulate the following conclusions:

- Occurrence of oxide layer detachment significantly affects the distribution of heat flux density and temperature on the surface of fuel cladding;
- In the separation spots comes out to the temperature and heat flux density increase;
- It has been unveiled that with smaller detachment diameter there are higher maximum values of temperature and heat flux density;
- Maximum value of heat flux density was 5.78 MW/m^2 whilst maximum value of fuel element cladding temperature was 135.2 ^{o}C. Both of these quantities appeared in case of the detachment diameter to be 2 mm;
- The above cited maximum values are much higher than the values for symmetrical layer;
- For any of investigated cases there have not been noticed the drop of ONBR parameter value below 1.2. It means that in any of analyzed cases it will come out to boiling of cooling water;
- The smallest value of ONBR parameter occurred in case of detachment diameter to be 2 mm and it was equal 1.83;
- In subsequent calculations it would be worth to examine the heat flux density as wel the temperature for other shapes of opening detachment.

5. References

[1] "ANSYS FLUENT 13.0 Documentation", SAS IP, Inc., Canonsburg 2010.
[2] "Conversion of MARIA Reactor Core on MC Fuel", Annex 2011/1 to Operational Safety Report for MARIA Reactor, under editing of K. Pytel, Otwock-Świerk 2011 (in Polish).
[3] "Operational Safety Report for MARIA Reactor", under editing of K. Pytel, Otwock Świerk 2009 (in Polish).
[4] "Heat Transfer. Tables and Graphs", W. Gogół, WPW, Warsaw 1991 (in Polish).
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[6] "Investigation of Oxide Layer Impact on Heat Exchange in MARIA Reactor Fuel Elements",M.Sc. thesis, Suchcicki S., Faculty of Power and Aeronautical Engineering, Warsaw University of Technology, June 2012 (in Polish).
[7] "An introduction to computational fluid dynamics. The finite volume method", Versteeg H.K, Malalasekera W., Pearson Education Ltd., Harlow 2007.
[8] "Heat Transfer", Wiśniewski S., Wiśniewski T. S., Warsaw 2009 (in Polish).