NATURAL CONVECTION COOLING OFTAJOURA NUCLEAR CORE AFTER LOSS OF OFF-SITE POWER

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الملخص

أجريت هذه الدراسة لتقييم سلامة قلب مفاعل تاجوراء للأبحاث النووية في حالة انقطاع التيار الكهربائي والتوقف الفجائي لجميع مضخات تبريد الدائرة الأولى والذي يتبعه توقف تشغيل المفاعل ذاتياً. في مثل هذه الحالة، سيتناقص معدل تدفق المبرد داخل المفاعل مع الزمن وينتقل من تدفق بالحمل القسري باتجاه الأسفل إلى تبريد بالحمل الطبيعي نتيجة فرق درجات الحرارة بين حوض المفاعل وقلب المفاعل المغمور به. هذه الدراسة تسلط الضوء على احتساب معاملات السلامة الناتجة من تبريد قلب المفاعل بالحمل الطبيعي وذلك بإنشاء برنامج MATLAB. تم تنفيذ التحليل الهيدروليكي الحراري داخل الخلية الساخنة لقلب المفاعل وذلك بإجراء محاكاة لقلب المفاعل بافتراض تشغيل المفاعل بقدرة تساو ي 10 ميغاوات بواقع 72 ساعة تشغيل قبل حدوث انقطاع الكهرباء وتوقف المفاعل. تم حساب تغير العوامل الهيدروحرارية للخلية الساخنة بالمفاعل لمدة 6 ساعات بداية من توقف المفاعل وأوضحت النتائج أن درجات حرارة سطح غلاف الوقود في الخلية الساخنة وصلت إلى أقصى درجة حرارة وهي حوالي 94.16°م بعد توقف المفاعل ثم تناقصت إلى 60.89°م بعد مرور 6 ساعات. أي أن أقصى درجة حرارة لغلاف الوقود لن تتجاوز أقصى درجه حرارة مسموح بها لسطح غلاف الوقود وهي 102°م [1].وعليه، أثبتت النتائج المتحصل عليها من هذه الدراسة ضمان تبريد قلب مفاعل تاجوراء بعد توقف مضخات الدائرة الأولى عن التشغيل وضمان حدود السلامة.

ABSTRACT

For safety evaluation of the core of reactor at Tajoura Nuclear Research Centre (TNRC), a special case has been investigated when the power supply is cutoff and all primary circuit pumps are stopped and scram is occurred. In this case, the coolant flow through the core decreases from a forced convective flow to zero flow and at last becomes an upward flow due to natural circulation flow induced between the core and the reactor pool in which the core is submerged, hence, a core flow reversal occurs. This study focuses on the calculations of the safety parameters during the core cooling by natural convection via constructing a MATLAB program. The transient thermal hydraulic analysis was carried out for the hottest cell in the core. The simulation is performed when the operating power of the core equals to 10 MW and the operation time before scram equals to 72 hr. The results are obtained at the hottest channel for almost 6hr after scram and showed that the maximum clad surface temperature during cooling by pure natural convection decreases from 94.2°C to 60.9°C. The maximum clad surface temperature does not exceed the maximum allowable value of the clad surface temperature which is

102°C [1]. This study proves the capability of cooling the reactor core at TNRC after loss of off-site power.

KEYWORDS: TNRC; Thermal Hydraulic Analysis; Loss of Off-Site Power; Natural Convection; MATLAB Program; Hottest Channel.

INTRODUCTION

The cooling system of the reactor of the Tajoura Nuclear Research Centre (TNRC) consists of three major circuits [2]: a primary circuit, a secondary circuit, and a third circuit which is cooled by a cooling tower. The TNRC reactor is a pool type reactor with a compact core consists of 36 cells in total [2]. The recent fuel of the TNRC reactor is Low Enriched Uranium (LEU) fuel and the material of the fuel meat is UO_2-AL with 19.7% of U^{235}.The design type of the fuel assemblies is IRT-4M fuel. At the normal operation of the core, the primary circuit pumps work to provide coolant to the core (downward flow). When the electric power supply to the core is suddenly interrupted, the pumps of the primary circuit are consequently stopped and the scram of the reactor occurs automatically. The generated heat as a result of the decay of the fission products must be extracted to avoid any damage of the core. For the sake of safety, an emergency tank is provided to compensate the loss of cooling of the reactor by the primary circuit for almost 80 seconds after scram. The core is cooled by forced convection during filling of the emergency tank. Then the core is cooled by the natural convection after the emergency tank is completely full. The main purpose of this study is to calculate the main safety parameters by simulating the cooling of the core by the natural convection when the off-site power is occurred and to consider the evolution of the main safety parameters. The calculations are performed at the hottest cell of the core.

COOLING BY THE NATURAL CONVECTION

At the normal operation, the coolant flow through the core is downward. There are valves in the reactor pool to allow the circulation of coolant during the natural circulation process. The natural circulation valves are closed when the primary circuit pumps are in operation. The closed natural circulation valves and the reactor pool at the normal operation of the primary circuit pumps are shown in Figure (1).

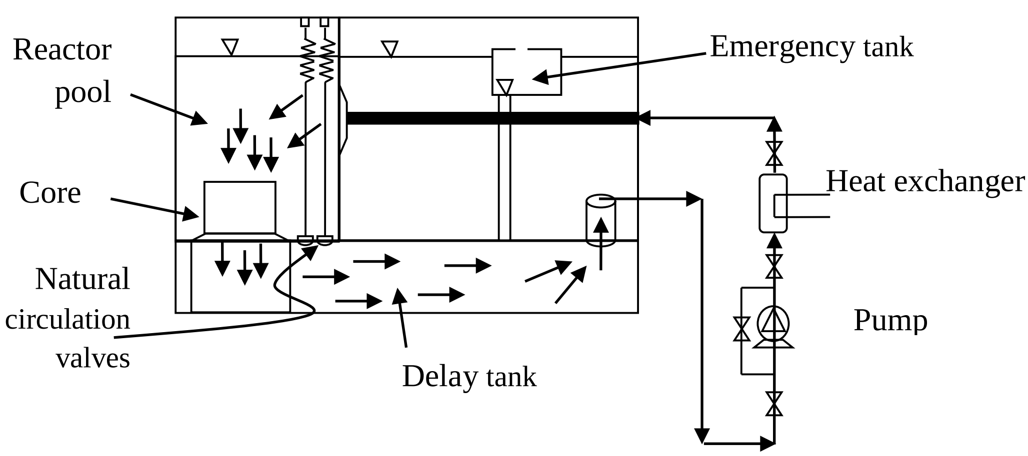

Figure 1: Schematic diagram of the cooling system at the normal operation.

Because of the electric power cut-off, the scram occurs and the primary circuit pumps stop. At that moment, the cooling of the core by natural convection is started while filling of the emergency tank but the dominant is the forced convection. During filling of the emergency tank, the pressure above the natural circulation valves,P_1, is greater than the pressure under the natural circulation valves, P_2, due to the difference in the level of water at the reactor pool and that in the emergency tank ($P_1 > P_2$) see Figure (1).
When the emergency tank is nearly full of water i.e. $P_1 \cong P_2$, the natural circulation valves openleading to further core cooling by natural convection as shown in Figure (2). A mixed convection between forced and natural convection appears at that stage until the emergency tank is completely full. At that point, and the pure natural convection becomes the main mode of cooling.

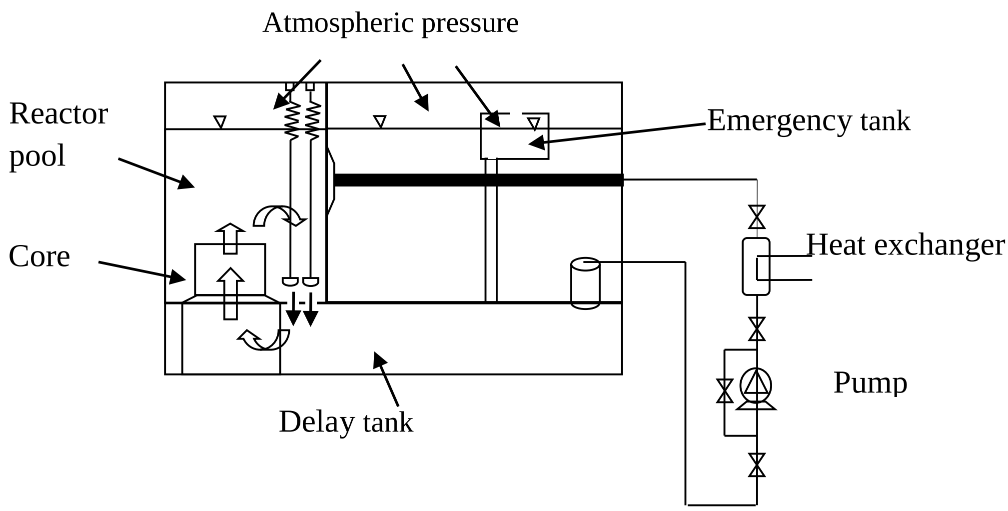

Figure 2: Coolant flow during the filling of the emergency tank.

The natural convection is observed as a result of the motion of the fluid due to density changes arising from the heating process, a velocity field is set up within the fluid as a result of the buoyancy force. The general analysis of heat transfer by natural convection is a complicated matter. However, transient thermal hydraulic analysis of the hottest cell of the core during the cooling by pure natural convection has been achieved.

NATURAL CONVECTION IN A NARROW VERTICAL RECTANGULAR COOLANT CHANNEL

In the case of free convection, the heat transfer in a narrow vertical rectangular coolant channels is due to the buoyancy-induced flow because of the temperatures differences between the clad surface and the bulk temperature of water. Figure (3) gives an idea on the flow direction.

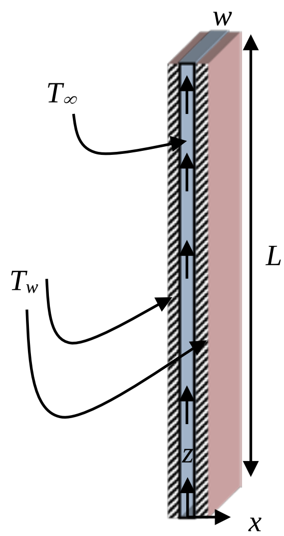

Figure 3: Coordinates for the narrow vertical coolant channel.

For natural convection in the vertical narrow channel, the governing equations of continuity, momentum and energy for transient state and one-dimensional flow (*z*-direction) can be written as [3]:

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial u}{\partial z} = 0, \quad (1)$$

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial z} = -\beta \rho (T_{\infty} - T_w) g \ , \quad (2)$$

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial z} = \frac{q'''}{\rho c_p} .(3)$$

Where, ρ is the coolant density(kg/m^3), *z* is the axial coordination (m), *u* is the axial velocity component(m/s), *P* is the pressure(Pa), *T* is the temperature(°C), $T_w$is the temperature of the surface of the fuel tube (°C), and T_∞ is the temperature of the coolant (°C), q''' is the decay heat density(W/m^3), μ is the dynamic viscosity(kg/m-s), *g* is the gravitational acceleration(m/s^2), $c_p$is the specific heat of the coolant(kJ/kg-°C), and *t* is the time (s). The volumetric coefficient of thermal expansion, β, is defined as [5]:

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P = -\frac{1}{\rho}\frac{(\rho_\infty - \rho)}{(T_\infty - T)}. \quad (4)$$

Where,ρ_∞ is the density of coolant outside the boundary layer (kg/m^3).The heat generation after scram results from the decay of the fission fragments and may be evaluated as [6]:

$$Q_s = Q_o([0.1(t_s + 10)^{-0.2} - 0.087(t_s + 2 \times 10^7)^{-0.2}] - [0.1(t_s + t_o + 10)^{-0.2} - 0.087(t_s + t_o + 2 \times 10^7)^{-0.2}]). \quad (5)$$

Where,Q_s is the decay heat after scram (W), $Q_o$is the operating power before scram(W), $t_s$is time after scram (s), and t_o is the operating time before scram (s).

Coolant velocity

The evolution of the coolant velocity caused by the natural convection is obtained using the conservation and the momentum equations. Since the gap of the coolant, channels at the reactor of TNRC are very small compared to the active length of the core. Therefore, the flow starts as a fully developed immediately at the entrance of the coolant channels [7]. The average velocity over *x*-direction, $\overline{u_o}$, is evaluated as:

$$\overline{u_o} = \frac{g\beta(T_w - T_\infty)w^3}{12\nu}. \quad (6)$$

Where, ν is the kinematic viscosity (m^2/s). The velocity due to the natural convection at any time, $u(t)$, is evaluated using the momentum equation as follows:

$$\rho\frac{\partial u(t)}{\partial t} - u(t)\frac{\partial \rho}{\partial t} = -\beta\rho g(T_\infty - T_w). \quad (7)$$

Heat transfer coefficient

The natural convection can be laminar or turbulent depends on the difference of temperatures between the coolant and the heated surface. The clad surface temperature is calculated from the bulk temperature of water using the Newton's law of cooling [8],

$$q'' = h(T_w - T_\infty). \quad (8)$$

Where, q'' is the heat flux(W/m^2), $h$is the heat transfer coefficient(W/m^2-°C). The heat transfer coefficient, *h,* is calculated using a Nusselt number, *Nu*. The Nusselt number for natural convection is a function of dimensionless parameters; a Prandtl number, *Pr*, and a Grashof number, *Gr*, [9].

$$Gr = \frac{g\beta(T_w - T_\infty)w^3}{\nu^2}. \quad (9)$$

Nusselt number along the narrow vertical coolant channel is investigated by [7] for both upward and downward flow and it can be written as:

$$Nu = \begin{cases} 0.568Ra^{*0.22}(Ra^* > 10^{13}), & \text{for turbulent} \\ 0.587Ra^{*0.20}(Ra^* \leq 10^{13}), & \text{for laminar.} \end{cases} \quad (10)$$

Where, *Ra* is called a Rayleigh number (*Ra*= *Pr*× *Gr*), Ra^* is named as a modified Rayleigh number (Ra^* = *Pr*× *Gr*× *Nu*).

INLET COOLANT TEMPERATURE OF THE CORE

After the scram, the cooling is achieved by forced convection then by mixed forced and natural convection. Finally, pure natural convection starts and the core flow reversal occurs. At that point, the hot water flows upward from a delay tank to the reactor pool through the core. The cold water flows in the downward direction from the reactor pool through the natural convection valves to the delay tank as shown previously in Figure (2). The average temperature at both the delay tank and the reactor pool, $\bar{T}$, is taken as the inlet coolant temperature to the core. The transient energy equation is solved to obtain the evolution of the inlet temperature. The energy equation at both the delay tank and the reactor pool can be written as:

$$\frac{\partial \bar{T}}{\partial t} = \frac{Q_s}{\rho c_p(V_d + V_r)}. \quad (11)$$

Where, $V_d$and V_r are the volume of the delay tank (m^3) and the volume of the reactor pool (m^3), respectively.

NUMERICAL SOLUTION

In this study, a MATLAB program has been constructed to perform the transient thermal hydraulic analysis of the core during cooling by pure natural convection. The analysis has been focused on the hottest cell. The cell is divided axially into N segments (N = 10) of length, Δz as shown in Figure (4). The interval of the time, Δt, is also discretized wisely into K time steps according to courant faucet number, CFL, to assure the stability of the analysis as follows:

$$\boldsymbol{\Delta t = CFL \frac{\Delta z}{u_{max}}}, \tag{12}$$

where u_{max} is the maximum coolant velocity and CFL has been adopted equals to 0.6 for the simulation. Since the flow is upward during the cooling by the pure natural convection then the calculations have been started from the bottom of the core.

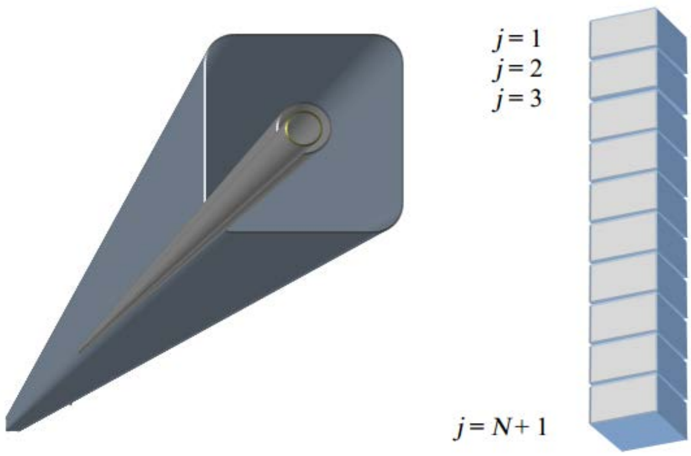

Figure 4: Axial segments.

The parameters values were calculated at the end of mixed convection are used as the initial data to the simulation of the cooling of the core by pure natural convection. At each time step, the following computations have been performed:

- The core heat generated, Q_s^{K-1}, is calculated at each time increment K.
- The average inlet coolant temperature to the core is calculated as:

$$T_d^K = T_d^{K-1} + \frac{Q_s^{K-1}}{\rho c_p (V_d + V_r)}$$

- The heat generated within the hottest cell at any time step K after scram is evaluated using eq. (5).
- The initial coolant velocity caused by the natural convection is obtained as follows:

$$u_{j+1}^{K-1} = \frac{g\beta (T_{w,j+1}^{K-1} - T_{\infty,j+1}^{K-1}) w^3}{12\nu}$$

- The transient coolant velocity is computed using the momentum equation as:

$$u_{j+1}^{K} = u_{j+1}^{K-1} - u_{j+1}^{K-1} \frac{u_{j+1}^{K-1} - u_j^{K-1}}{\Delta z} \Delta t - \beta \left(T_{\infty,j+1}^{K-1} - T_{w,j+1}^{K-1}\right) g \Delta t$$

- The axial coolant temperature at any increment, $j+1$, and at any time step K is found numerically as follows:

$$T_{\infty,j+1}^{K} = \left(1 - u_j^{K-1}\frac{\Delta t}{\Delta z}\right)T_{\infty,j+1}^{K-1} + u_j^{K-1}\frac{\Delta t}{\Delta z}T_{\infty,j}^{K-1} + \frac{q'''^{K-1}_j}{\rho_j^{K-1}c_{p_j}^{K-1}}\Delta t$$

- The axial pressure at any increment, *j+1*, and at any time step *K* is calculated as:

$$P_{j+1}^{K} = P_j^{K} - \rho g \Delta z$$

- The dimensionless parameters, *Gr, Pr, Ra*, and Ra^*, are obtained at the coolant temperature $T_{j+1}^{K}$and pressureP_{j+1}^{K}.
- The Nusselt number is attained by investigating the flow whether it is laminar natural convective flow or turbulent natural convective flow as follows:

$$Nu_{j+1}^{K} = 0.568Ra^{*0.22}(Ra^* > 10^{13})$$

$$Nu_{j+1}^{K} = 0.587Ra^{*0.20} \qquad (Ra^* \leq 10^{13})$$

- The heat transfer coefficient is computed using the following equation:

$$h_{j+1}^{K} = \frac{kNu_j^{k}}{D}$$

- Clad surface temperature is calculated using the Newton's law of cooling:

$$T_{w,j+1}^{K} = T_{\infty,j+1}^{K} + \frac{q'''^{K}_{j+1}}{h_{j+1}^{K}}$$

RESULTS AND DISCUSSION

Cooling by the natural convection starts immediately after the sudden cut-off of the electric power supply causes the stop of the primary pumps. Thermal hydraulic results of the core at TNRC during cooling by the natural convection are investigated. The hottest cell has been used to carry out the examinations of the basic safety parameters based on a previous modeling (steady state thermal hydraulic analysis of TNRC reactor [10]). The calculations have been performed at the hottest cell of the core as summing operating power of the core equals to 10MW and the operating time with this power is 72hr. The results are obtained for more than 6 hrs. after scram.

The decay heat generated in the core after scram is shown in Figure (5). As shown in Figure (5), the decay heat at the core drops to about 50 kW after 6 hrs. from the scram.

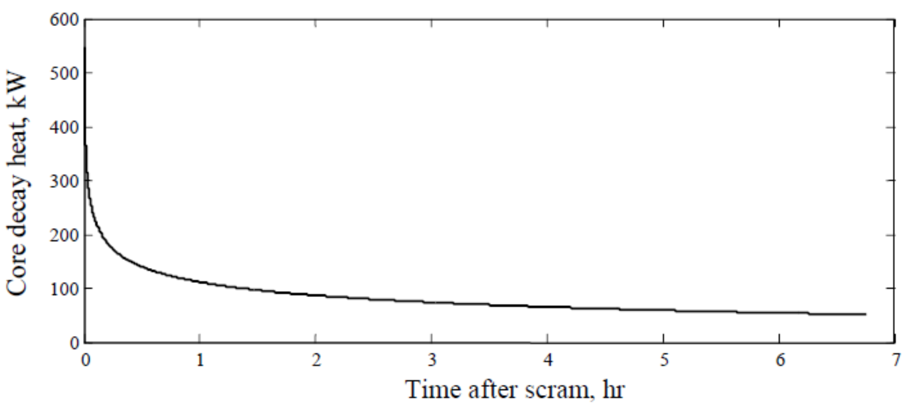

Figure 5: Core decay heat as function of time.

Hottest cell calculations

The decay heat at the hottest cell after scram is indicated in Figure (6) and it is clear that the decay heat at the hottest cell becomes 5 kW after 6 hr. From the previous thermal hydraulic analysis of the reactor at the TNRC during the steady state operation

[10], the hottest position is obtained where *j*=8. Therefore, the results are plotted at that position.

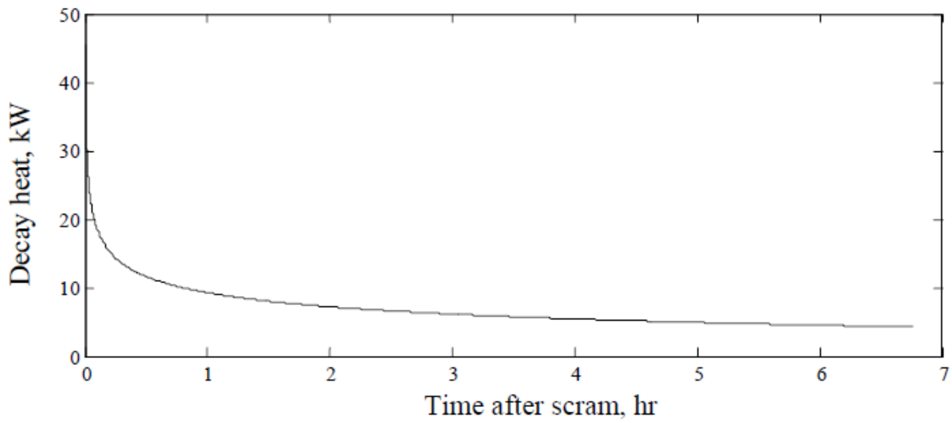

Figure 6: Hottest cell decay heat vs. time.

The evolution of the coolant velocities as a result of the buoyancy forces nearby the plate parts of the coolant channels during the first seconds after the scram (forced and mixed convection) are shown in Figure (7). The first few seconds after scram is a transition period from the steady state to the transient state where the coolant velocities are increased rapidly as shown in Figure (7). After that, the coolant velocities are increased slightly as a result of a slight increase of the clad surface temperature at that period of time. At the last seconds, the increase of the coolant velocities caused by the buoyancy force is significant due to the sharp increase of the clad surface temperature (mixed forced and natural convection).

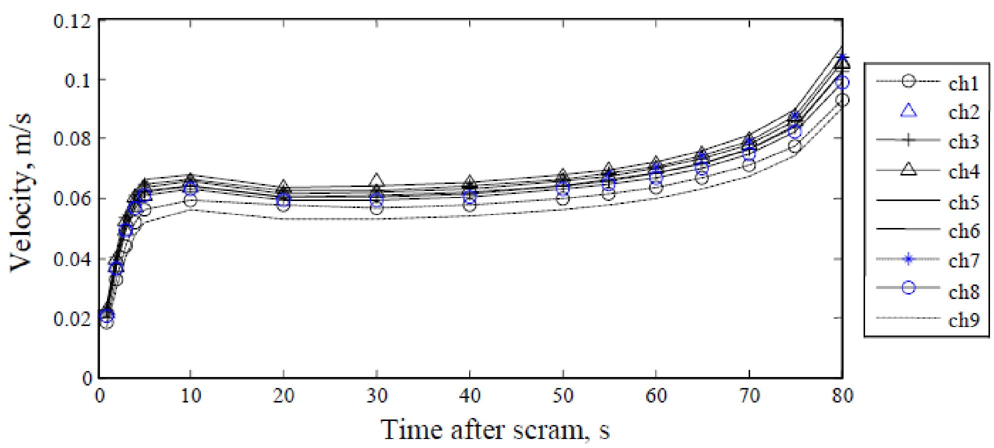

Figure 7: Coolant velocities caused by buoyancy forces after scram for first seconds.

The variations of the coolant velocities caused by pure natural convection are presented in Figure (8). It can be seen from Figure (8) that the coolant velocities decrease when the pure natural convection is acted and the velocities are continually decreased since the difference of temperature between the clad surface and bulk of water is decreased with time.

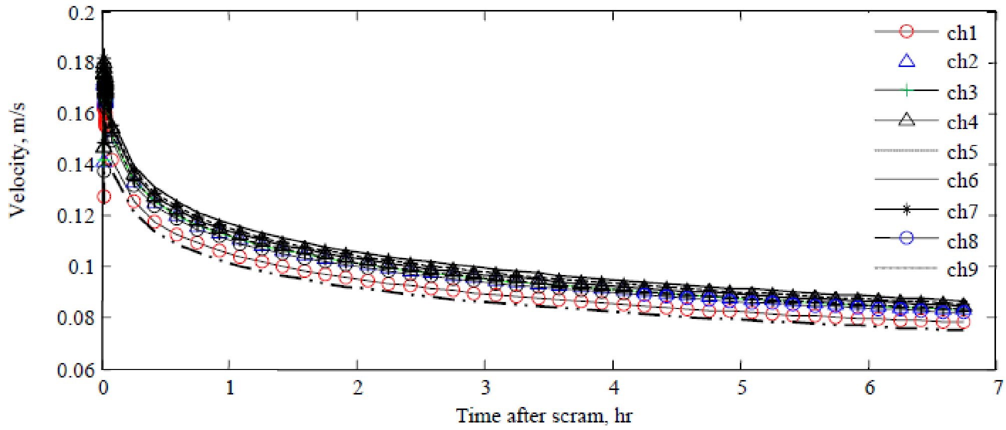

Figure 8: Coolant velocities during cooling by natural convection.

Hottest coolant channel

The hottest cell has nine coolant channels. Based on the previous study [10], the maximum clad surface temperature occurs at the coolant channel number (4). All the following results during cooling of the core by the natural convection are determined at the coolant channel number (4) of the hottest cell. Figure (9) shows the outlet average coolant velocity at the coolant channel number (4) as a function of time. Moreover, the outlet flow rate as a result of the pure natural convection from the hottest channel as a function of time is demonstrated in Figure (10).

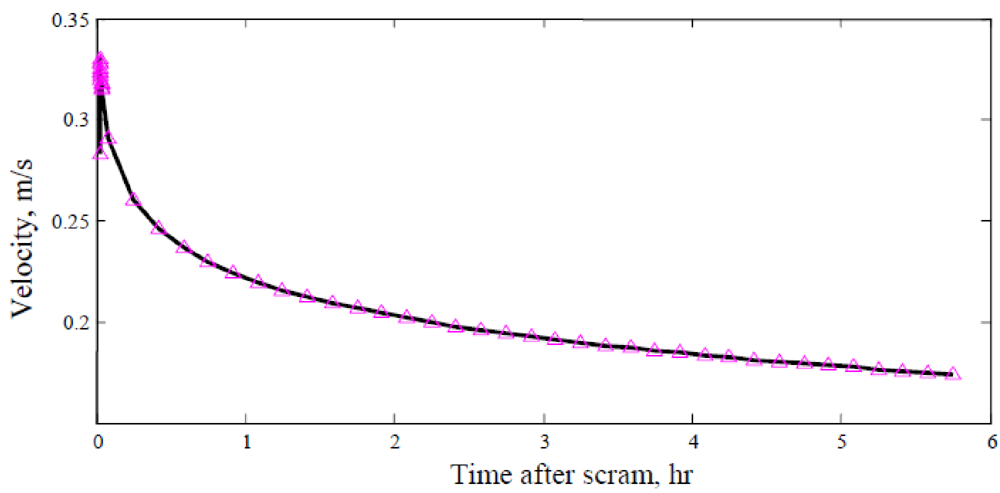

Figure 9: Outlet average coolant velocity caused by pure natural convection.

The average inlet coolant temperature to the core is presented in Figure (11). The differences between the outlet and the inlet coolant temperatures are shown in Figure (12). It is obvious from Figure (11) and Figure (12) that the inlet and outlet temperatures of the coolant at the hottest channel decrease with time and the difference of these temperatures reduces by time and it equivalents to less than 5°C at 4 hr after scram.

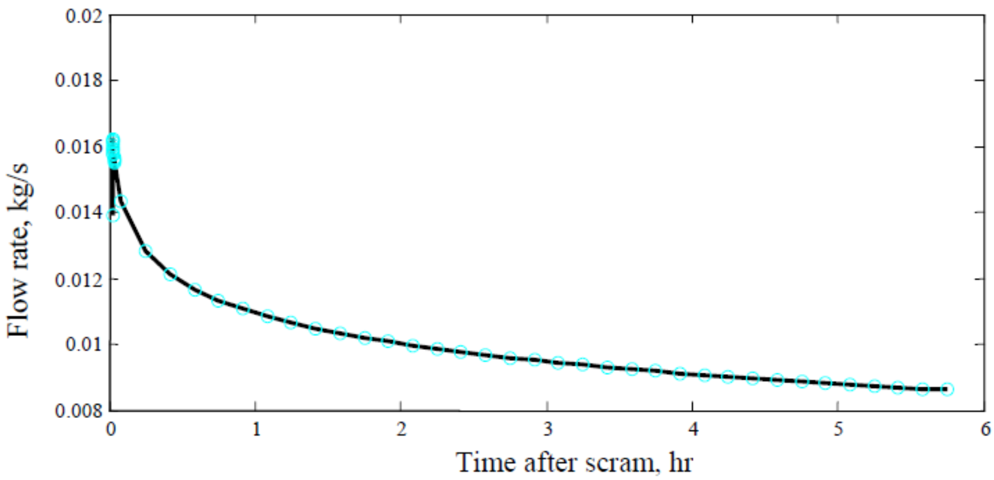

Figure 10: Variation of the outlet flow rate caused by the pure natural convection forchannel number (4).

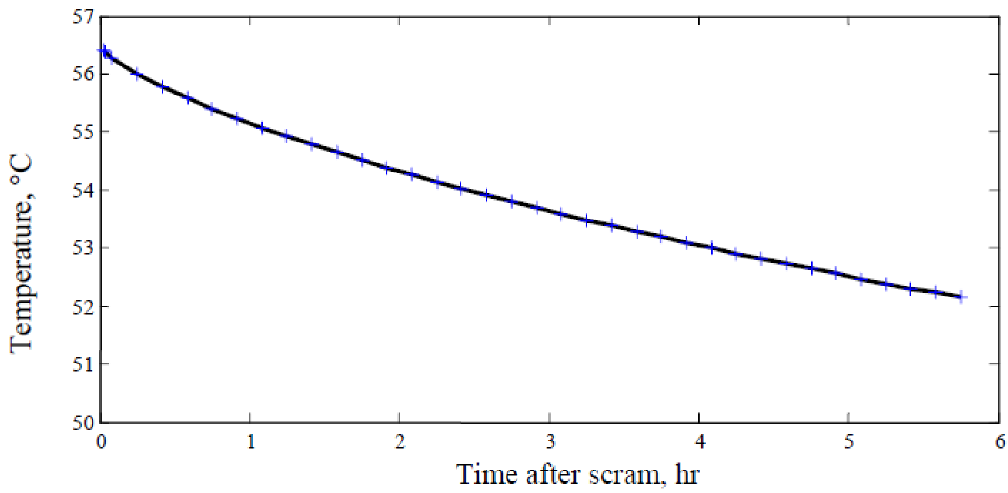

Figure 11: Average inlet coolant temperature vs. time.

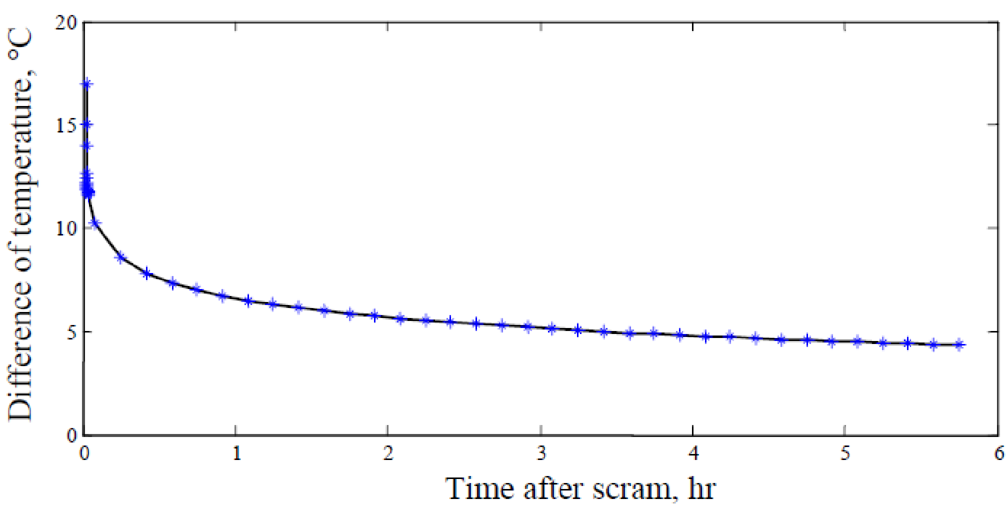

Figure 12: TemperatureDifference between outlet and inlet for the hottest channel.

Variation of the Nusselt number with time at the hottest position (j = 8) is indicated in Figure (13). In addition, the modified Rayleigh number and the Rayleigh number of the hottest channel are demonstrated in Figure (14). It is clear that the flow is laminar natural convective flow since the modified Rayleigh number is less than 10^{13} as shown in Figure (14). Therefore, the Nusselt number is calculated using the laminar natural convective flow equation.

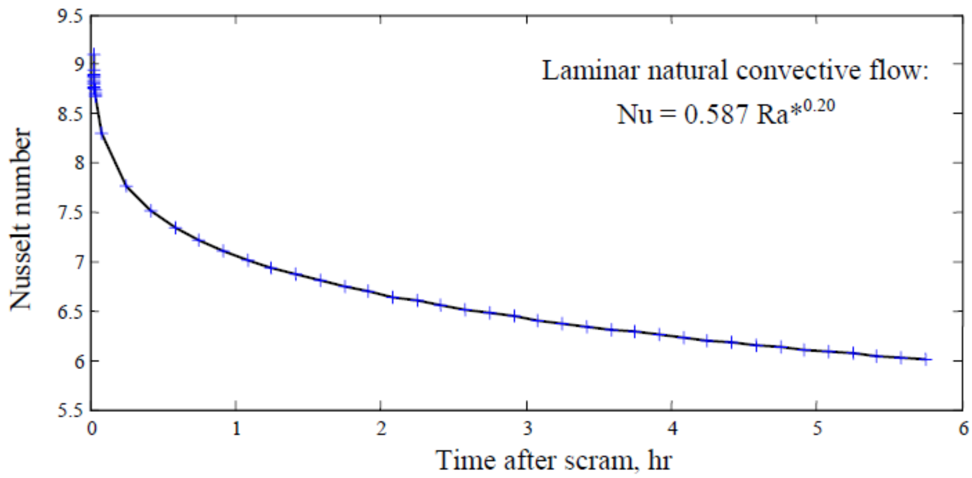

Figure 13: Nusselt number vs. time for pure natural convection.

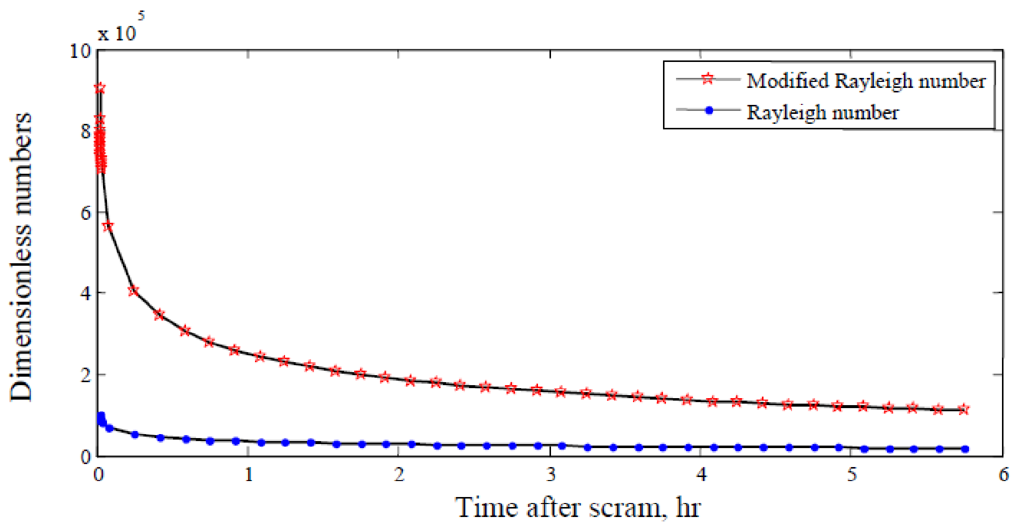

Figure 14: Modified Rayleigh number and Rayleigh number.

Furthermore, the evolution of both the maximum clad surface temperature and the bulk temperature of water at the hottest location are presented in Figure (15). It can be noted from Figure (15) that the maximum clad surface reaches 94.16 ^{o}C when the pure natural convection is started and the clad surface temperature is considerably decreased during the first hour of cooling the core by pure natural convection. After that, it is slightly declined and reaches to 60.89 ^{o}C at 5.75 hr past the scram which prove that the cooling of the core following the pump coast down is attained and the reactor is safe (the maximum allowable value of the clad surface temperature is 102 ^{o}C [1]). It can be deduced from Figure (15) that the difference of temperature between the maximum clad surface and the coolant temperatures is significantly decreased during the first two hours after scram then that difference remains roughly constant for which means the pure natural convection will continue until the thermal equilibrium is finally approached at the core and the temperatures are equal.

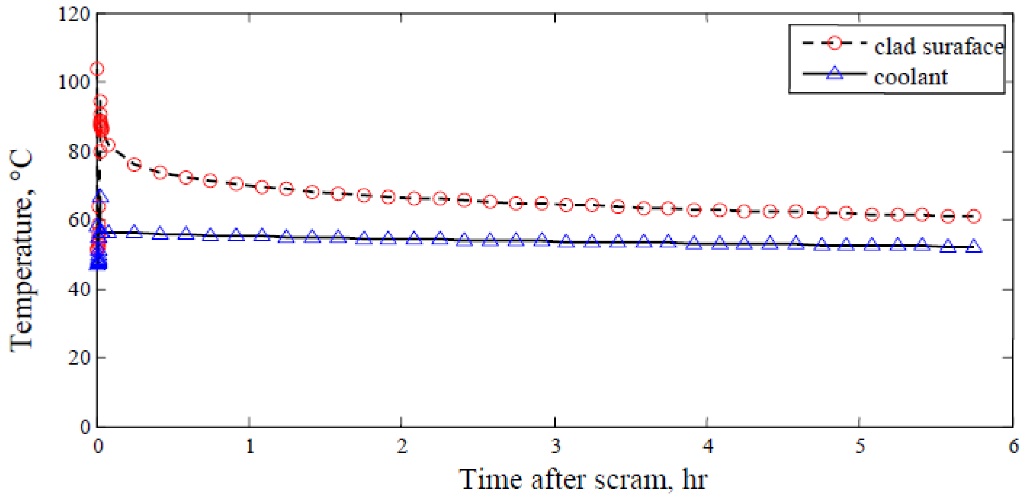

Figure 15: Maximum Clad surface and coolant temperatures vs. time at j=8.

A comparison between the current results and the results of the Argonne National Laboratory (ANL) has been investigated. Figure (16) shows some results of the ANL's team for the peak coolant and clad temperatures in the hot channel for three pump loss of flow in LEU Core using PARET for the simulation [11].

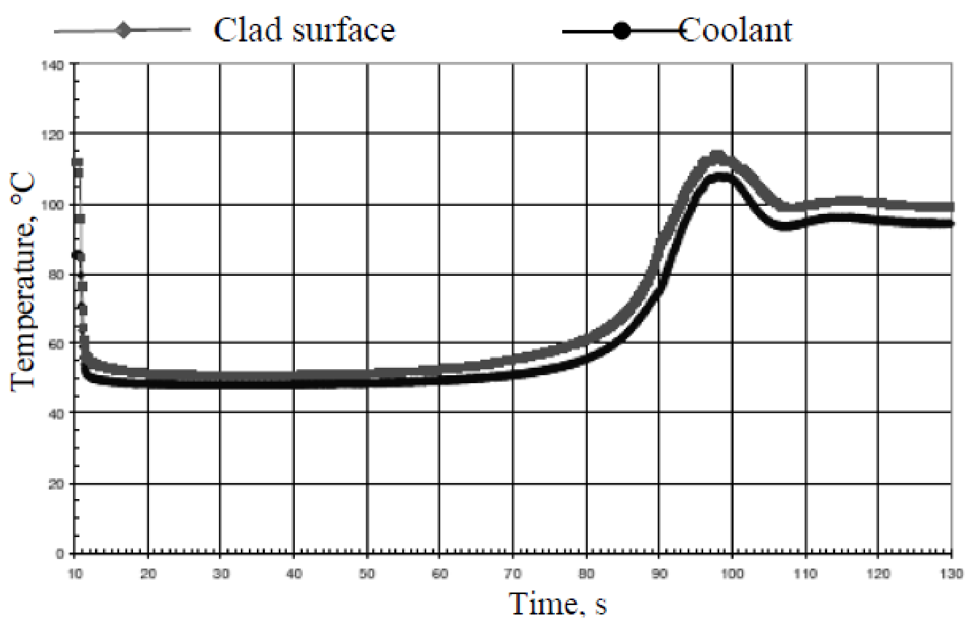

Figure 16: Peak Coolant and Clad temperatures in Hot Channel for3 Pump Loss of Flowin LEU Core (ANL) [11].

Figure (17) presents the current equivalent results for the same period of time after scram at the hottest channel. It is noticeable that the results do not agree exactly since

PARET code which is used by the ANL assumes the shape of the fuel of the core at TNRC as a slap shape while the current model is designed especially for the hottest cell of the TNRC's reactor. In addition, another evaluation has been examined with the results of the thermal hydraulic analysis of the new core of Tajoura reactor [12]. By comparison between the current clad surface temperatures with the clad surface temperature values [12], the comparison show a relative agreement between the results.

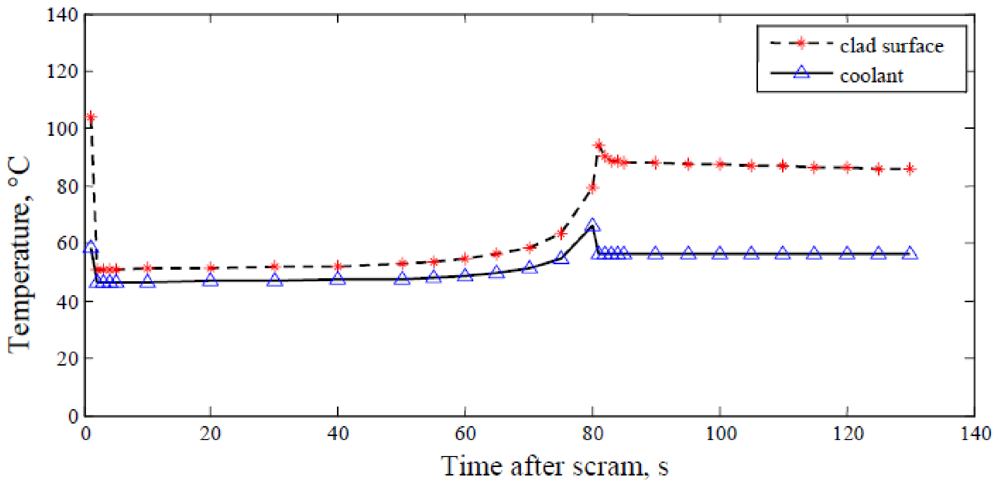

Figure 17: Clad surface and coolant temperatures for first 130 seconds after scram for the hotteset channel.

CONCLUSIONS

Based on the results obtained in this work, it can be concluded that the safety parameters of the TNRC's reactor with LEU (19.7%) have been satisfied since all-important temperatures do not exceed the maximum allowable values. It has also been realized that the implemented numerical algorithm worked reasonably well for the present case. Despite the dangerous situation of losing the off-site power during the operation of the core at maximum power, the results showed that the cooling of the core by forced convection for the initial several seconds followed by cooling by pure natural convection is safe. The conclusions of this study can be summarized in the following points:

- The difference of temperature between the inlet and outlet coolant for the hottest channel during the pure natural convection processes approaches less than 5°C at time equals to 4 hr after scram.
- Since the modified Rayleigh number is less than 10^{13}, the flow regime during natural convection cooling is laminar.
- The maximum clad surface temperature during cooling by pure natural convection decreases from 94.16°C to 60.89°C, which does not exceed the surface clad temperature safety limit (102°C).
- The difference of temperature between the maximum clad surface and the coolant decreased with time; however, thermal equilibrium is not achieved during the transient because it requires longer time.

AKNOWLEGEMENT

I sincerely express my thankful attitude to the staff of the reactor department at the Tajoura Nuclear Reactor Research Centre for their collaboration. Additionally, I genuinely appreciate the cooperation of the members of the department of the energy generation techniques at the Libyan Atomic Energy Establishment.

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