International Journal of Engineering and Advanced Technology Studies

Vol. 1, No. 1, pp. 1-10, March 2013

Published by European Centre for Research Training and Development, UK (www.ea-journals.org)

DESIGN OF THERMAL LOOP OF A COMPACT RECTOR

Ahmad Hussain, Dheya AlOthmany,

Department of Nuclear Engineering Department, King Abdulaziz University, Jeddah-21589,

Kingdom of Saudi Arabia

Abstract: *The complete design of a nuclear power reactor is a complicated task involving many disciplines. Three main aspects of design of a reactor system include nuclear physics, heat removal and mechanical plus structural systems. This project is concerned with thermal hydraulics calculations, designing of a steam generator for this system and calculations for pump. In this project TRAN is used for the design of core thermal hydraulics. Steam generator is designed through code STEAMGEN whereas pump power is calculated by hand with some formulas. It is noted after calculations that max fuel temperature is less then fuel's melting point and max clad surface temperature is below saturation temperature. Water is leaving the core at 208.0^{o}C and entering in steam generator at same temperature. Water is leaving the steam generator at 203.2^{o}C and entering into core at this temperature. A pump of 15.38 kW is required to generate the required 276.86 kg/s flow and to overcome all the head losses in the piping and core.*

Keywords: Compact Nuclear Reactor, thermal loop, Nuclear desogn, TRAN Code, STEAMGEN Code

1.0 Introduction

There is revival of interest in small and simpler units for generating electricity from nuclear power, and for process heat. The interest is driven both by a desire to reduce capital costs and to provide power away from large grid systems. The technologies involved are very diverse. US experience has been of very small military power plants, such as the 11 MWt, 1.5 MWe (net) PM-3A reactors which operated at McMurdo Sound in Antarctica 1962-72, generating a total of 78 million kWh. There was also an Army program for small reactor development.

Generally, modern small reactors for power generation are expected to have greater simplicity of design, economy of mass production, and reduced siting costs. Many are also designed for a high level of passive or inherent safety in the event of malfunction.

The complete design of a nuclear power reactor is a complicated task involving many disciplines and of a magnitude that is comparable to aircraft and missile design. Because of the several areas where specialized knowledge is required any such project is more often broken up into subgroups: such as reactor physics, core thermal hydraulics, core structural design, shielding, metallurgy, chemistry and control equipment etc. At the beginning of almost every component's design phase, the very first task is to produce a conceptual or preliminary sketch delineating some crude but not too hypothetical specifications. Before the preliminary design can be commenced, purpose of the reactor must be specified.

Regarding this case the functional species of the plant has been selected with the viewpoint of providing energy at outposts to areas such as Siachine Glacier. An ultimate requirement in looking for the proposed reactor is that it should be small enough to be mounted on and transported easily. After the functional classification has been made the power level must be defined. The project provides calculations for a 1.5 MWe for which 6 MWt of heat is generated keeping in view a nominal efficiency of 25%.

Three main aspects of design of a reactor system include nuclear physics, heat removal and mechanical plus structural systems. Project is concern with thermal hydraulics calculations, designing of a steam generator for this system and calculations for pump.

In this project computer code TRAN is to be used to determine the temperature distribution and other required parameters with in the core to design the core thermal hydraulics. Heat transfer equations are used for calculations in TRAN. Since the reactor is design to give electrical power 1.5 MWe so by assuming the conversion efficiency 25% i.e. 6MWt. Initially the core dimensions, fuel dia, pitch and other required parameters for iterative calculations are taken from reactor physics calculations to optimize the minimum possible core dimensions compatible with neutronics (that will be done in another project).

By considering the optimal temperature and flow of coolant the number of tubes, dia of tubes, length and pressure of primary and secondary side etc. of steam generator is calculated by using a computer code STEAMGEN which uses J-L equations for boiling heat transfer Coefficient calculations. After designing the flow required for proper heat removal and calculating head loose in loop which consist of pipe, core and steam generator, power of pump is calculated by using some formulas and hand calculations which is required to produce the required flow and generate lost head.

To sum up this project would be expected to give the students a feel that how thermal loop calculations are performed for design of compact nuclear reactor. Get familiarity with the heat transfer code and interrelationship of different parameters of neutronics and shielding of a reactor in the design of a system.

1.2 Calculations for core thermal hydraulics:

In this project core thermal hydraulics is designed by using TRAN. TRAN is a computer program written in FORTRAN and gives us temperature distribution at different nodes of fuel channel in axial and radial direction. As an input deferent parameters related to neutronics are calculated in another project.
Complete description of different design parameters are illustrated in table 2.1.

Table 2.1: Different design parameters of core thermal hydraulics:

Radius of fuel pellet (cm) [5]	0.300
Cladding outer radius (cm) [5]	0.350
Lattice type [5]	Square
Fuel Rod Pitch (cm) [5]	1.4
Fuel rod length (cm) [5]	60
Fuel material	UO_2
Clad material	Stainless steel
Coolant material	H_2O
Coolant Inlet Temp. (^{0}C)	203.2
System pressure (MPa)	15.00
Total No. of fuel rods	701
No. of control rods	91
Coolant inlet mass flow rate per channel (gm/s)	350.0

Total electric power (MWe)	1.5
Efficiency	25%
Average power generated in one fuel rod (kilowatts)	8.56
Maximum power generated in one fuel rod (kilowatts) [2]	19.78
Radial power profile inside fuel	Flat
Radial power profile inside core	Bessel
Axial power profile	Chopped Cosine
Extrapolation Distance (cm) [1]	0.340
Number of nodes in radial direction in fuel	5
Number of nodes in radial direction in cladding	2
Number of nodes in axial direction	31

The average power rod gives us the average coolant outlet temperature to be used in steam generator calculations. The maximum power rod calculation gives us the maximum fuel center line temperature and maximum clad surface temperature. Maximum rod power is calculated by considering radial power profile in core as Bessel and by calculating maximum to average power ratio which is 2.3 [2]. Temperature distribution in average power rod is shown in Fig. 2.1 and 2.2. Temperature distribution for maximum power rod is shown in Fig. 2.3 and 2.4.

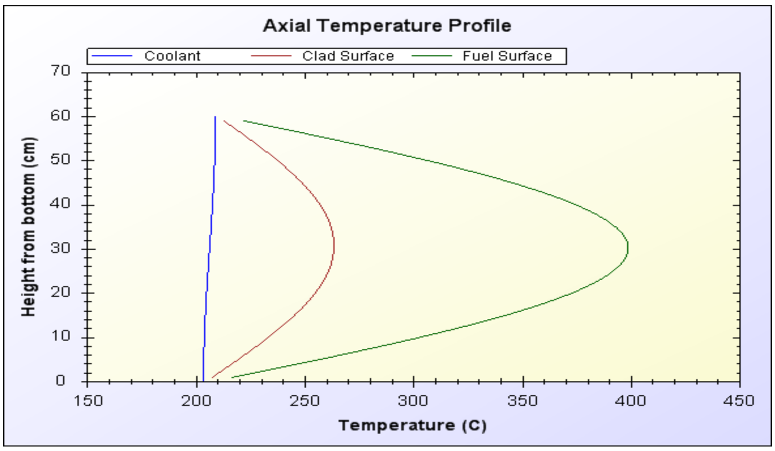

Figure.1 Axial temperature profile for Average power rod.

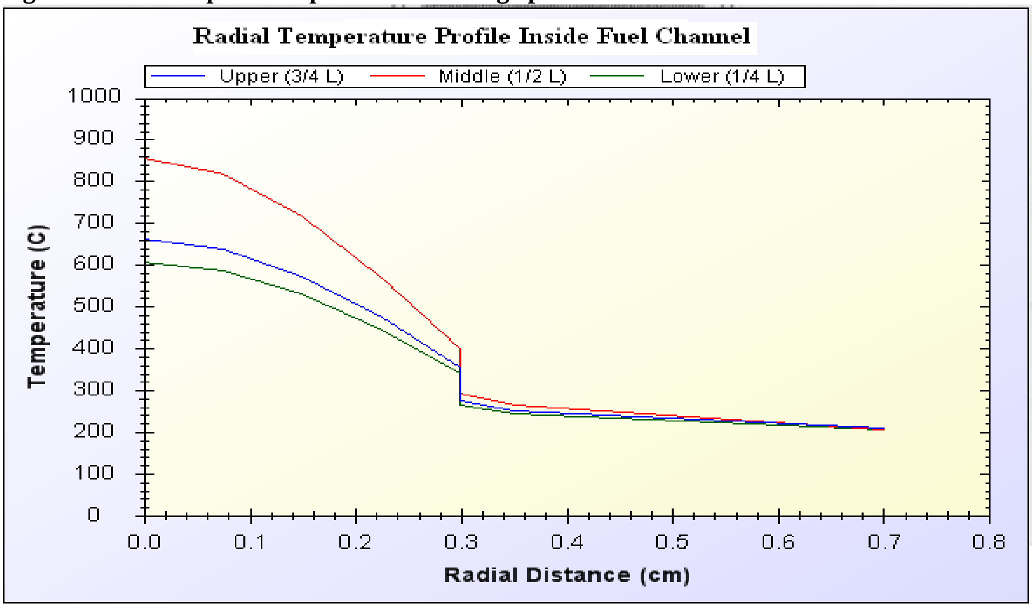

Figure.2 Radial Temperature profile of an average power rod:

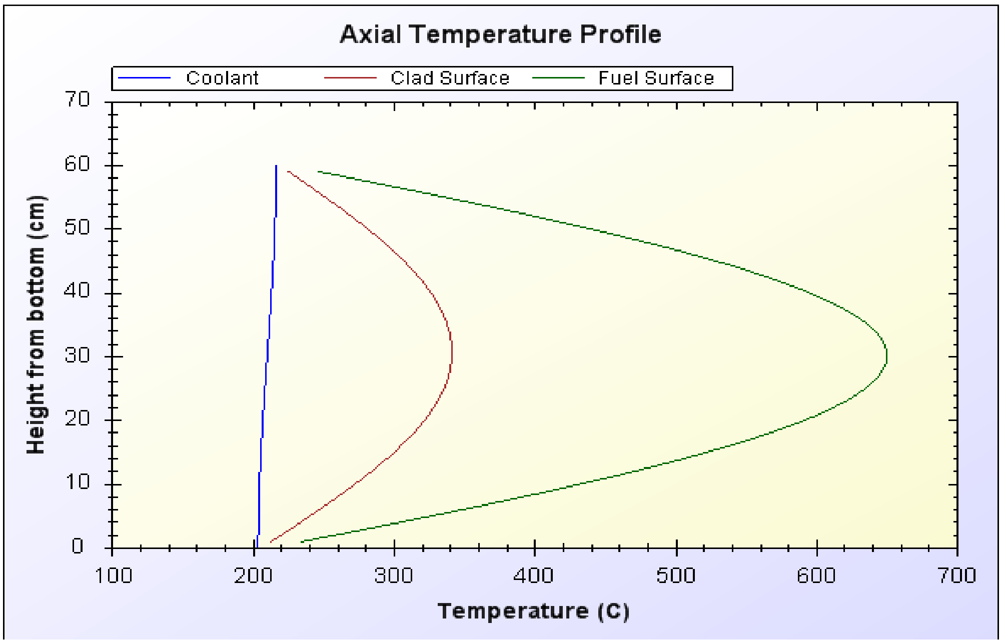

Figure 3 Axial temperature profile for Maximum power rod.

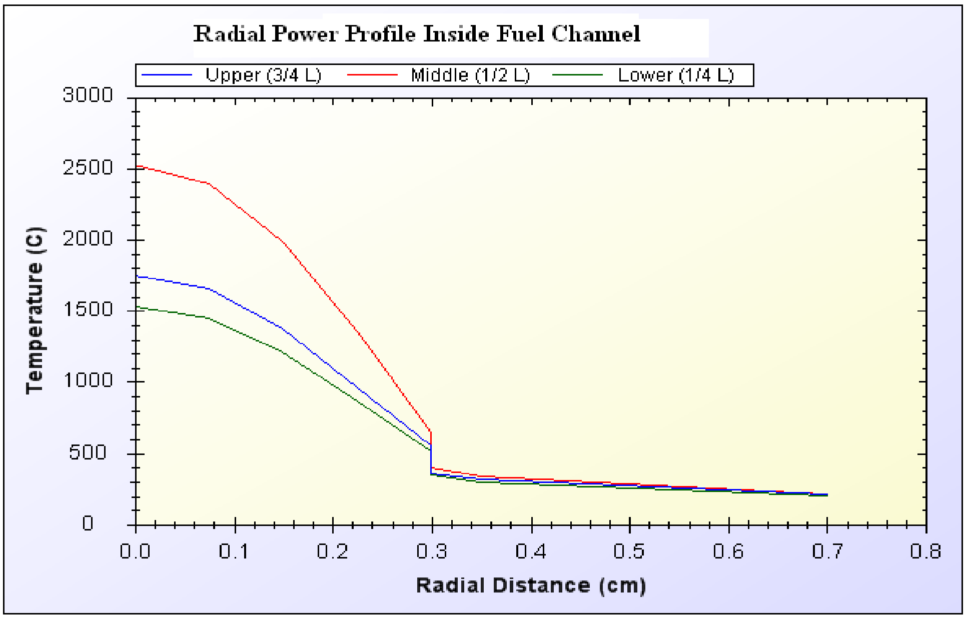

Figure 4 Radial temperature profile of Maximum power rod.

Axial temperature profile shows that fuel surface temperature and clad surface temperature increase up to the centre portion of fuel rod and then starts decreasing and follow nearly cosinic distribution. Coolant temperature goes on increasing from its entering point up to outlet. If we analyze the maximum power rod temperature distribution it is noted that it follow the same trends as that of average power rod. The only difference is the magnitudes of temperatures because of very high power produced in the maximum power rod.

The maximum fuel centerline temperature of maximum power rod is the maximum temperature of fuel of the whole core and clad maximum temperature of maximum power rod is maximum clad surface temperature of the whole core. It is noted that maximum fuel temperature is less then fuel melting point and maximum clad surface temperature is less then saturation temperature. Although the difference between maximum temperature and saturation temperature is low but it is acceptable because calculations are made by considering uniform flow in all channels of the core but in actual case temperature flattening is done in core by providing high flow to central channels and low at the corner so this process further reduce the temperatures of maximum power rod.

1.3 Calculations for steam generator:

Calculations for steam generator are made through a computer code STEAMGEN written in FORTRAN for designing of once through steam generator. Different parameters of steam generator are illustrated in table 3.1.

Table 3.1 Different parameters of steam generator.

Mass flow rate primary side (Kg/s)	276.85
Mass flow rate secondary side (Kg/s)	2.79

Inlet temp primary side (^{0}C)	208.0
Inlet temp secondary side (^{0}C)	150.0
Number of tubes	650
Pressure on primary side inlet (MPa)	15.0
pressure on secondary side inlet (MPa)	1.12
Tube I.D. (m)	0.018
Tube O.D. (m)	0.020
Tube (boiler) length (m)	2.5
Inner diameter of boiler (m)	3.5
Number of axial nodes in boiler	40
Primary Fluid	Tube side
Type of flow	counter flow

Primary and secondary fluid temperature, quality of steam, heat transfer coefficient and some other parameters are calculated through STEAMGEN and illustrated in Fig 3.1, 3.2 and 3.3.

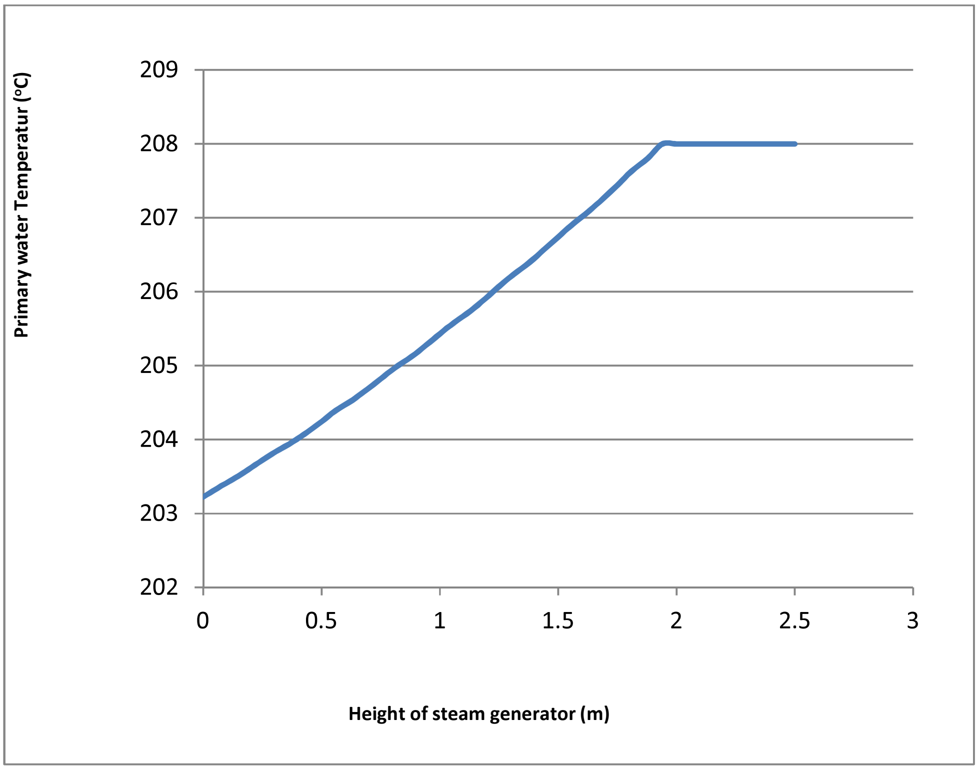

Figure 3.1 Change in primary water Temperature with height of steam generator.

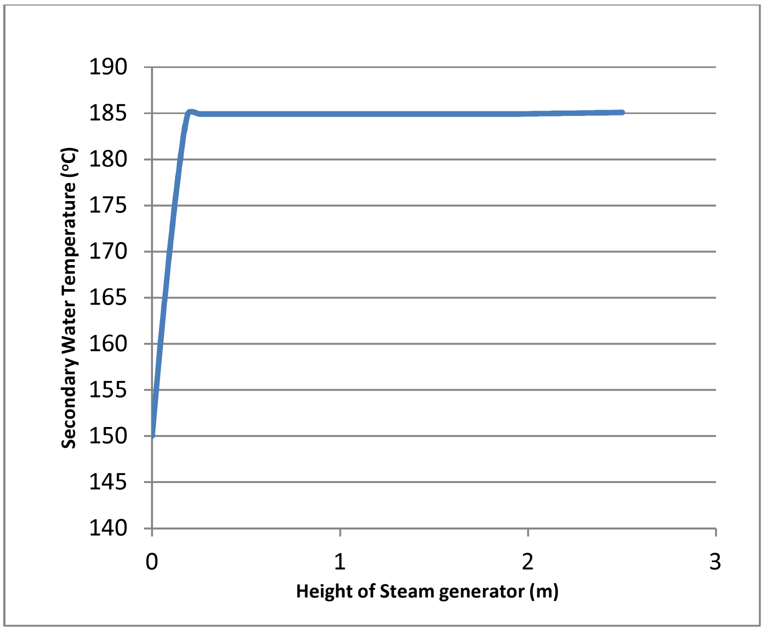

Figure 3.2 Change in Secondary water Temperature with height of steam generator.

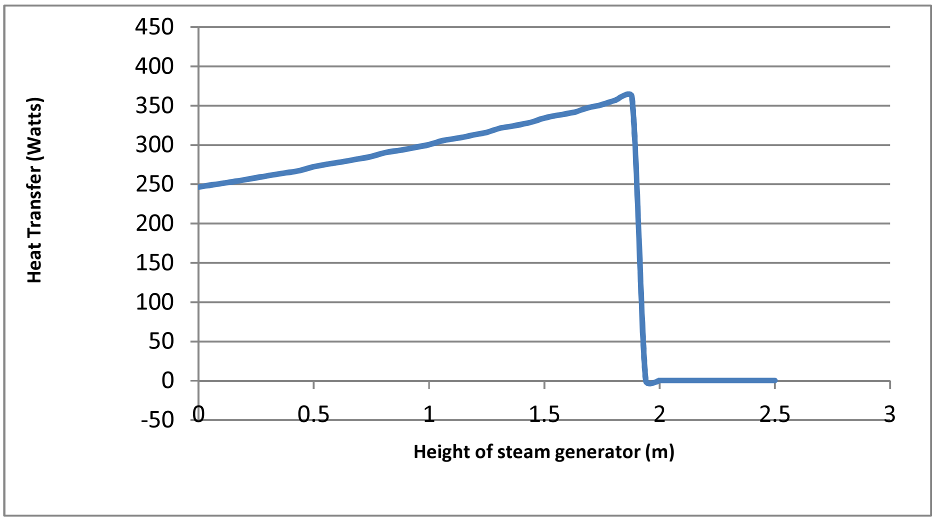

Figure 3.3 Change in Heat transfer with height of steam generator.

From STEAMGEN output it is clear that primary fluid is entering the steam generator at 208.0^{o}C which is equal to the temperature at which fluid is leaving the core and primary fluid is leaving steam generator at 203.2^{o}C which is coolant inlet temperature in core. Heat transfer is high in steam generation region and when steam is superheated heat transfer becomes very low. At about 0.19 m from bottom of steam generator steam starts to be produced which become completely dry at about 1.88 m from the bottom of steam generator and then superheating starts. So the region below 0.19 m is economizer and above 1.88 m is superheater.

1.4 Calculations for power of pump:

In order to create the required flow for heat transfer of core and to overcome the head losses in the loop we need to have a pump in our loop. So power utilized by that pump is calculated by using some formulas and hand calculations as under.

For the purpose of calculation of power first of all we have to calculate the total head loss in loop means sum of head losses in piping system, core and steam generator and then by using formula we can calculate power. Calculation is illustrated in table 4.1.

Table 4.1 Calculations for power of pump.

Total flow (kg/s)	276.85
Diameter of pipe (m)	0.2
Length of pipe (m)	10
Efficiency	80%

Area of pipe(m^2)	$A_c = \frac{\Pi D^2}{4}$	0.03
Velocity (m/s)	$V = \frac{Q}{A_c}$	9.2
Reynold No.	$R_e = \frac{\rho VD}{\mu}$	1.84E07
Pipe roughness (m)	E (steel)	0.018
Friction factor	E/D	0.00023
Darcy Co-efficient		0.014
Monometric Head (m) [3]	$H = \frac{fLV^2}{2Dg_c}$	3.24
Head loss in core (m)	ffrom Tran	0.716
Pressure loss in SG. (pa)[4]	$\Delta P_t = N_p \left[8 J_f \left(\frac{L}{d_i}\right)\left(\frac{\mu}{\mu_w}\right)^{-m} + 2.5 \right] \frac{\rho u_t^2}{2}$	5823
Head loss in SG. (m)		0.594
Total Head Loss (m)		4.55
Pump Power (kW) [3]	$\text{Power} = \frac{\gamma Q \text{H}}{1000\,\eta}$	15.38

Calculation in Table 4.1 shows that 15.38 kW power is required to overcome all head losses and to generate the required flow.

2 Conclusion:

In this project core thermal hydraulic, steam generator and pump is been designed for a compact reactor whose neutronics and shielding calculations are done in other separate projects. After making calculations of thermal loop of compact reactor and analyzing the results following conclusions are made:

1. It is noted that max fuel temperature is 2525.7°C which is much less than fuel’s melting point 2865 °C which means fuel remains intact.
2. Maximum Clad surface temperature is 340.8 °C which is less then saturation temperature it means there is no boiling. This temperature is close to saturation temperature and margin is low but it is acceptable because in calculations I consider the uniform flow through all channels of core but in actual case high flow is provided to the central maximum power channel which will further reduce the temperatures.
3. Average temperature of coolant at core outlet is 208.0 ^{0}C which is equal to Primary inlet temperature of Steam generator.
4. Primary outlet temperature of steam generator is 203.2 ^{0}C which is equal to the coolant inlet temperature.
5. Pump of 15.38 kW is required to generate the required flow and build the head loss in loop.

3 References:

[1]. Johan R. Lamarsh, *Introduction to Nuclear Engineering*, 2nd Edition, Addison-Wesley, New York, 1983.
[2]. M. M. El-Wakil, *Nuclear Heat Transport*, 3rd Edition, American Nuclear Society, USA, 1981.
[3]. F. J. Finnemore, J. B. Franzini, *Fluid Mechanics with Engineering Applications*, 10th Edition, Mittal Press, India.
[4]. R. K. Sinnott, *Coulson & Richardson's Chemical Engineering*, 3rd Edition, Butterworth, Johannesburg, 1999.

* E-mail of the corresponding author: ahassain@kau.edu.sa