SMALL MODULAR NUCLEAR REACTOR- A PROMISING APPLICATION OF FLUIDIZED BED

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Abstract - Nuclear power could make great contribution towards the coveted goal of carbon free sustainable society by replacing fossil fuels for energy and chemical production. It can produce electricity as well as hydrogen in clean environmentally friendly way. Yet instead of seeing a growth nuclear power is witnessing relative decline worldwide. Concern about safety and high cost are two major factors that prevent our society from deriving the full benefit of nuclear power when it is needed most. Accidents in Fukushima, and Chernobyl have made society sceptic about nuclear power. Traditional nuclear power plants are very large (>1000 MWe), takes years to build and need billions of dollars of investment. Small modular nuclear reactors are typically less than 300 MWe size that could be built in modules with minimal site work. This reduces the capital investment and project implementation time. Generation IV nuclear plants are moving towards this goal using pebble bed of spherical nuclear fuel particles (Carelly & Ingersoll, 2015), but fluidized bed could provide even more improved and safer design. A conceptual inherently safe design of 40 MW (thermal) nuclear plant based on fluidized bed reactor is developed. Such units could be located underground either in remote location or in the outskirt of a town to feed local community with heat or electricity. Low temperature waste heat from the plant can be utilized to produce hydrogen from water in efficient manner utilizing copper chloride cycle.

The design extends previous work (Rots et al, 1996, Sefidvash & Mohamad, 2002) on helium fluidized reactor subcritical plant with supercritical water based fluidized bed reactor. Basic design of fluidized bed nuclear reactor, overall efficiency and analysis of safety aspect of the design is discussed.*Keywords: Small modular nuclear reactor, Fluidized bed, Helium, Generation IV*

1. INTRODUCTION

There is close link between the life quality and energy use (Ingersoll, 2015). The growing population and improved economies have thus increased energy demand particularly in non-OECD countries, which in resulted in rise in consumption of fossil fuels. This naturally led to higher carbon dioxide (CO_2) emission to the atmosphere. Utilizations of nuclear power instead of fossil fuel for power generation could help in reduction of CO_2 emission.

The energy per unit mass (kWh/kg) in nuclear fuel is 24,000,000 million whereas, it is only 8 million for coal (Ingersoll, 2015; McCombie & Jefferson, 2016). Many renewable energy sources are dispersed and highly seasonal. The power density (W/m^2) for nuclear is higher than that of renewables (McCombie & Jefferson, 2016), and its availability is neither seasonal nor limited to use close to its geographical source. Return on investment (ROI) is more for nuclear than renewable energy (Hall et al. 2014; Jefferson, 2013; Jefferson 2015; McCombie & Jefferson, 2016). Despite such advantages over other energy sources the use of nuclear power for the generation of electricity and hydrogen production is not growing as expected. Two major shortcomings; high cost and safety concern are the causing a decline in nuclear growth worldwide. The incidents of Fukushima, Chernobyl nuclear plants have raised the safety concern to a level that has made nuclear power almost a pariah in the society.

Small modular reactor (SMR) could potentially avoid some of those major shortcomings that is preventing the nuclear fuels from providing carbon free affordable energy to the world. These plants are typically in the range of 10 to 300 MWe in capacities as opposed to 1000 MWe capacity of traditional nuclear power plant. Such small capacity of plants could result in reduction in both installation time and initial capital investment cost. Small capacities could allow for mass production of modules in factories greatly reducing on-site construction. This would not only reduce the total plant cost it could significantly reduce the time for building the power plant. Apart from being affordable and its greater flexibility in plant design, another advantage of SMR is that it provides greater safety (Ingersoll, 2015). Generation IV nuclear plant with fluidized bed SMR also known as FBNR (fluidized bed nuclear reactor) could provide more improved and safer design. In the event of a loss of coolant accident (LOCA), the fuel in the movable cores could be removed by gravity from the core back to the fuel chamber, this is not the case for rigid cores reactors (Sefidvash, 1996). FBNR is thus inherently safe as shutdown of the reactor does not depend on anything but gravity which not likely to fail under any circumstance. Unlike traditional nuclear fuel rods, FBNR uses small spherical particles of graphite with small core of nuclear fuel. This makes its transportation much safer.

Apart from producing electric power, the waste heat recovered from the condenser of the plant can be utilized to produce hydrogen from water by utilizing copper chloride cycle as shown in Reactions (1-4). ~~(R1-R4)~~. It thus provides a clean fuel for transportation and chemical industries.

$$2\ Cu + 2\ HCl_{(g)} \rightarrow 2\ CuCl_{(l)} + H_{2(g)} \tag{1}$$

$$2\ CuCl_2 + H_2O_{(g)} \rightarrow Cu_2OCl_2 + 2\ HCl_{(g)} \tag{2}$$

$$2Cu_2OCl_2 \rightarrow 4\ CuCl + O_{2(g)} \tag{3}$$

$$2\ CuCl \rightarrow CuCl_{2(aq)} + Cu \tag{4}$$

2. DESCRIPTION OF SMALL MODULAR REACTOR (SMR)

Small nuclear reactors can be installed at remote locations or at sites where large nuclear capacity plants are not feasible (Ingersoll, 2015). As, majority of construction work is carried out at factory rather than on site, this results in reduction in cost and refinement in quality. Another advantage of SMR over traditional nuclear power plant (>1000 MWe) is that, its onsite installation is easier and have less onsite construction possibility. Thereby, SMR have less onsite construction time. These factors result in shorter project implementation time and lower front end investment. Less power and use of passive concepts leads to reduced dependence on active safety system and other pumps (NuScale Power, 2016). Reduced size helps in ease of reactor deployment underground. These reactors can be utilized in countries having limited grid and comparatively lesser experience with nuclear power plants.

This paper discusses the design and safety features of fluidized bed SMR with helium as fluidizing medium as well as coolant. The reason for choosing gaseous coolant is that to overcome change in reactivity with boiling of coolant, corrosion and stress related difficulties (Abram & Ion, 2008). Also, the higher energy neutron spectrum by helium and its less cross sectional absorption (Abram & Ion, 2008) played important role on its selection. Many literatures are published on fluidized bed nuclear reactors (Rots et. al, 1996; Sefidvash, 1996; Sefidvash & Mohamad, 2002). Borges & Vilhena (1995) have reported that behaviour of fluidized bed reactor is like a conventional reactor.

The nuclear fuel is Tri-structural-isotropic (TRISO) coated particle consisting of 10% enriched U235. The overall particle size and kernel size of TRISO coated particle is 500 μm and 300 μm respectively, with its density being 3200 kg/m^3 and its sphericity is assumed to be 1. For generating 40 MW thermal power from nuclear reaction with 50% burn-up, an estimated inventory of 300 kg of TRISO particle will be required. The reactor module consists of reactor core and fuel chamber.

Reactor core has a number of fluidizing tube through which the TRISO particle is fluidized by helium particle (Figure 1). It also has graphite moderator of thickness 150 mm. The dimensions of fluidized bed were estimated based on the void fraction of 0.45, it was evaluated that estimated inner diameter of each fluidized bed will be 960 mm and bed height of 1184 mm. So, the outer diameter of the fluidized bed cell becomes 1260 mm. Here apart from fluidizing the fuel particle helium will be acting as coolant and thereby removing the fission energy. For the loss of coolant accident, the fluidization of the fuel particle will cease and the fuel will return to the fuel chamber. The temperature of reactor core is assumed to be maintained at 700-725°C.

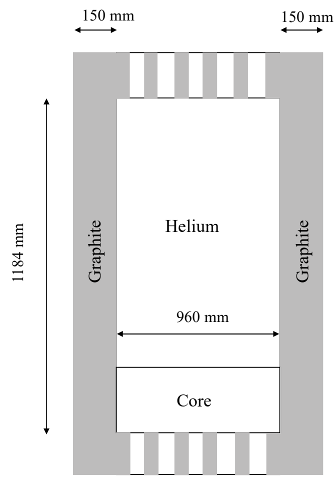

Figure 1: Fluidized bed nuclear reactor design (Adapted from Kloosterman et. al, 2001)

This reactor being self-regulating thermostatic reactor, thus active control devices for this reactor canbe avoided (Kloosterman *et. al*, 2001).

3. BASIC DESIGN OF FLUIDIZED BED NUCLEAR REACTOR

One gram mole (235 grams) of U-235 contains 6.023×10^{23} atoms (Avogadro's number). It is known that 190 amu (atomic mass unit) are converted to energy for every nucleus of U-235 that undergoes the fission process (Glasstone & Sesonske, 1986) and the energy released due to the fission of one U-235 atom, ΔE_1 may be calculated based on the theory of relativity ($\Delta E = mc^2$) as shown in Eq. (5).

$$\Delta E_1 = 190\ amu \times \frac{1.66056 \times 10^{-27}\ kg}{1\ amu} \times \left(\frac{3.0 \times 10^8 m}{s}\right)^2 = 2.84 \times 10^{-11}\ \text{J} \quad (5)$$

1 amu is equal to $1.66056\ x10^{-27}$ kg and velocity of light, c is 3.0×10^8 m/s. For the fission of 1 mole U-235, the amount of energy, ΔE released may be calculated according to Eq. (6)

$$\Delta E = \frac{2.84 \times 10^{-11}\ J}{1\ \text{atom of U235}} \times \frac{6.023 \times 10^{23}\ \text{atoms of U235}}{1\ mol\ \text{U235}} \times \frac{1\ mol\ \text{U235}}{0.235\ kg\ \text{U235}} = 3.785 \times 10^{13}\ \text{J/ kg U235} \quad (6)$$

We considered Tri-structural-isotropic (TRISO) coated particles of average particle size 500 μm with kernel size of 300 μm. The estimated density of TRISO particles is 3200 kg/m^3 (Lowe *et al.* 2015). The TRISO particles are spherical. So sphericity may be assumed as 0.92. Based on the assumptions of 10% enriched U235 and 50 % burn-up, we need 300 kg TRISO particles in the fluidized bed for a nuclear reactor of capacity 40MW (thermal).

The TRISO particles may be recirculated in the fluidized bed till be desired 50 % burn-up is achieved. On-line fueling of TRISO particles will be carried out to maintain constant neutron flux in the bed. Till date, no attempts were made to reprocess the spent TRISO fuels. Since the fission products are confined in three layers of coating, possibility of leakage of radioactivity is less. After sufficient cooling period, repossessing of the spent fuels may be carried out in conventional process after crushing.

3.1 Design of the fluidized bed reactor

TRISO particles are 500 micron in diameter and have mean density of 3203 kg/m3. It is being fluidized in helium at 6 MPA pressure. According to Geldart particle classification TRISO particles could fall under group – D particles. So, the nuclear reactor would be a set of aggragatively fluidized bubbling beds, where TRISO particles would be fluidized with helium.

Helium will fluidize the TRISO particles as well remove the fission energy. The fission energy removed will be transferred to the Rankin cycle's working medium, supercritical steam through a secondary cycle. Conceptually one could use supercritical water as the fluidizing medium to avoid the secondary heat exchange for simplicity and higher efficiency. But there could some material issue. For that reason the present work avoided supercritical water in the fluidized bed reactor

The temperature of the proposed fluidized bed nuclear reactor (FBNR) will be maintained at 700-725 °C, which is reasonable for its long life. The minimum fluidization velocity (u_{mf}) of TRISO particles is 0.12 m/s and the optimum operating helium has been considered eight times of u_{mf} i.e., 1.01 m/s. The helium enters the reactor at 350 °C and leaves at 700 °C. The total mass flow rate of the helium is 22 kg/s. Based on this we select 10 nos of fluidizing tubes, each module having diameter of 960 mm diameter.

With the thickness of graphite moderator of 150 mm thickness the overall diameter of the FBNR cell will be 1.26 m.

4. THERMODYNAMICS OF STEAM CYCLE

The layout of the fluidized bed SMR plant is shown in Figure 2. The steam cycle is indirect supercritical steam cycle with no reheat. The advantage of indirect cycle is that the hazards of transmission of the radioactive particles via coolant could be avoided and no reheat reduces the capital costs (Naidin *et. al*, 2009). Water at 350°C and 25.8 MPa enters the counter flow heat exchanger having a large heat transfer area. Heat gets transferred from coolant to water; it converts into supercritical steam and exit the heat exchanger at 25 MPa and 625°C. It is then led to HP turbine, which produces 7.41 MWe power. The supercritical steam at 6.6 MPa and 410°C from outlet of HP turbine goes to LP turbine. LP turbine generates 12.34 MWe power and saturated steam exit the LP turbine. The saturated steam at 38.4°C and 6.77 MPa from the outlet of turbine enters to condenser and waste heat is removed. The condensed water is pumped by condensate extraction pump. The water is then heated by steam bled from LP turbine at LP heater and then it is further heated at deaerator such that it becomes saturated water. Booster pump takes the suction from deaerator and discharges compressed water to HP heater, where ith is futher heated to make saturated water at that pressure. Then this water re-enters the heat exchanger and the cycle is repeated.

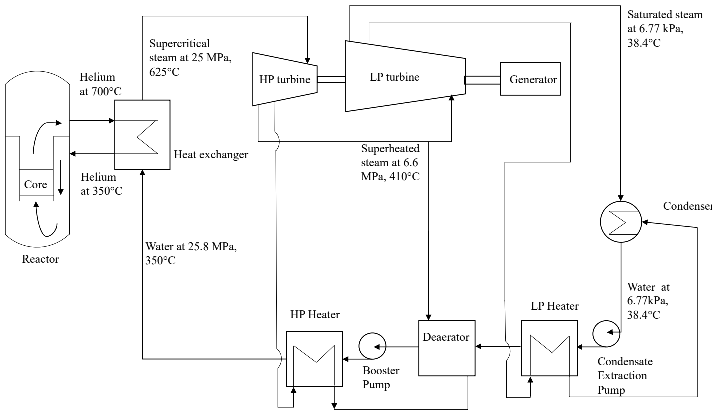

Figure 2: Layout of fluidized bed SMR plant

Following assumptions were made for carrying out the thermodynamic analysis of the steam cycle:
1) Gland Steam and auxiliary steam consumption was not taken into account (Naidin et. al, 2009).
2) Performance losses and drop in pressure in piping was not taken into account (Naidin et. al, 2009).

Based on the assumption thermodynamic analysis of the heat transfer was carried out. It was estimated that the 38.57 MW of thermal energy could be extracted from coolant at heat exchanger and it will produce 15.47 MW of electrical energy and rest 23.6 MW of energy will be removed at condenser. This waste heat can be utilized to produce hydrogen from water using copper chloride cycle. The thermal effiecincy of the plant will be 41.1%.

Table 1: Parameters of steam cycle

Nuclear reactor		
Helium inlet temperature at core	350	°C
Helium outlet temperature at core	700	°C
Helium specific heat	5.18	kJ/kg K
Thermal capacity of nuclear reactor	40	MW
Mass of helium circulated around core per sec	22	kg/s
Heat exchanger		
Water inlet temperature	350	°C
Water inlet pressure	25.8	MPa
Supercritical steam outlet pressure	25	MPa
Supercritical steam outlet temperature	625	°C
Water mass flow rate	19.83	kg/s
Enthalpy of water at 25.8 MPa and 350°C (inlet to heat exchanger)	1621.5	kJ/kg
Enthalpy of supercritical steam at 25 MPa and 625°C (outlet of heat exchanger)	3566.4	kJ/kg
Total heat required per sec	38573.9	kJ/s
Total heat required in MW	38.57	MW
Helium inlet temperature to heat exchanger	700	°C

Helium outlet temperature from heat exchanger	350	°C
Mass of helium circulated around heat exchanger per sec	22	kg/s
Thermal energy per sec released by helium from heat exchanger	40	MWth
HP Turbine		
Enthalpy of supercritical steam at 25 MPa and 625°C (outlet of heat exchanger)	3566.4	kJ/kg
Enthalpy of superheated steam at 6.6 MPa and 410°C (outlet of HP turbine)	3193	kJ/kg
Enthalpy of superheated steam at 14.9 MPa and 525°C (bled from HP turbine)	3385	kJ/kg
Fluid flow before bled	19.83	kg/s
Fluid flow after bled	19.77	kg/s
Total heat transferred from steam per sec	7394.34	kJ/s
Electricity produced by hp turbine	7.39	MWe
LP Turbine		
Enthalpy of superheated steam at 6.6 MPa and 410°C (inlet LP turbine)	3193	kJ/kg
Enthalpy of saturated steam at 6.77 kPa and 38.4°C (outlet of LP turbine)	2570.7	kJ/kg
Enthalpy of steam at 1.55 MPa and 200°C (bled from LP turbine)	2570.7	kJ/kg
Fluid flow before bled	12.97	kg/s
Fluid flow after bled	9.24	kg/s
Total heat transferred from steam per sec	8072.3	kJ/s
Electricity produced by turbine in MWe	8.07	MWe
Condenser		
Enthalpy of saturated steam at 6.77 kPa and 38.4°C (inlet of condenser)	2570.7	kJ/kg
Enthalpy of water at 6.77 kPa and 38.4°C (outlet of condenser)	160.6	kJ/kg
Fluid flow	9.78	kg/s
Heat removed at condenser	23.6	MWth
LP Heater		
Enthalpy of water at 14.9 MPa (outlet of condensate extraction pump)	175.63	kJ/kg
Enthalpy of water at 14.9 MPa and 180°C (outlet of LP heater)	770.4	kJ/kg
Flud flow	12.97	kg/s
Heat required	7.71	MWth
Deaerator		
Enthalpy of water at 14.9 MPa and 180°C (outlet of LP heater)	770.4	kJ/kg
Enthalpy of water at 14.9 MPa and 340°C (outlet of deaerator)	1222	kJ/kg
Fluid flow	19.83	kg/s
Heat required	8.97	MWth

HP Heater		
Enthalpy of water at 25.8 MPa (outlet of booster pump)	1618	kJ/kg
Enthalpy of water at 25.8 MPa (outlet of HP heater)	1624	kJ/kg
Fluid flow	19.83	kg/s
Heat required	0.1	MWth
Total electricity produced	15.47	MWe
Thermal efficiency	41.1	%

5. CONCLUSIONS

Utilization of nuclear power for generation of electricity and hydrogen production will help in achieving the goal of having carbon free sustainable society. Small modular reactor due to their sizes can be installed underground and will be particularly beneficial to places where it will be difficult to construct a power plant or feed a local community, installations from local power. Since majority of construction is done off site for SMR, it provides ease of installation and reduces installation time. Fluidized bed SMR helium cooled nuclear reactor provides a safer design as in case of loss of coolant accident (LOCA), the fuel can itself be removed from core by gravity and it will be back in fuel chamber. Having indirect steamcycle for power generation limits the hazards of transmission of radioactive particle from coolant.

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