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Passive Cooling Characteristics of the Fluidized Bed Nuclear Reactor

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Abstract

In this paper the passive cooling characteristic of a new nuclear reactor is analyzed. The reactor design is based on the fluidized bed concept and utilizes the pressurized water reactor technology. Any reactor incident or accident, causes the small spherical nuclear fuel elements fall into the cylindrical fuel chamber by gravity. The system was treated as a porous medium. The calculations made on the cooling of the fuel elements through natural convection. They demonstrate the passive cooling characteristics of this reactor concept.

Introduction

None of the energy resources alone is a panacea. The solution to the ever increasing demand for energy to satisfy the needs of growing world population and improving its standard of living lies in the combined utilization of all forms of energy. Nuclear energy produced safely will have an important role in solving the world energy problem. The public objections to nuclear energy most often expressed are reactor safety, cost and nuclear waste disposal

At the end of 2000, 438 nuclear power reactors were in operation in 31 countries around the world, generating electricity for nearly 1 billion people. They account for approximately 17 percent of worldwide installed base load capacity for electricity generation and provide half or more of the electricity in a number of countries. These reactors are generating electricity in a reliable, environmentally safe and affordable manner without emitting noxious gases into the atmosphere.

Concerns over energy resource availability, climate change, air quality, and energy security suggest an important role for nuclear power in future energy supplies. While the current Generation II and III nuclear power plant designs provide an economically, technically, and publicly acceptable electricity supply in many markets, further advances in nuclear energy system design can broaden the opportunities for the use of nuclear energy.

To explore these opportunities, the U.S. Department of Energy's Office of Nuclear Energy, Science and Technology has engaged governments, industry, and the research community worldwide in a wide-ranging discussion on the development of next-generation nuclear energy systems known as "Generation IV". This has resulted in the formation of the Generation-IV International Forum (GIF), a group whose member countries are interested in jointly defining the future of nuclear energy research and development. In short, "Generation IV" refers to the development and demonstration of one or more Generation IV nuclear energy systems that offer advantages in the areas of economics, safety and reliability, sustainability, and could be deployed commercially by 2030.

A new small inherently safe nuclear reactor concept has been proposed by Sefidvash. This reactor is truly modular in design such that any size reactor, rather than the plant, can be constructed from the basic module. The reactor uses the light water reactor technology and promises to fulfill the objectives of design simplicity, inherent and passive safety, economy, standardization, shop fabrication, easy transportability and high availability. The inherent safety characteristic of the reactor dispenses with the need for containment; however, a simple underground containment is envisaged for the reactor in order to reduce any adverse visual impact.

The Dynamics of Technology and Nuclear Reactor

The history of technology development has shown that the substitution of a component of a system has drastically changed the trend of the success of that particular technology. For example, at the turn of this century, the railway industry began to replace steam locomotives by diesel-electric ones. This component substitution having a minor influence on the rest of the system, had a great effect on the railway industry. Another example is the commercial air transport industry which in the middle of this century replaced piston-driven motors by jet engines causing a revolution in that industry.

The potential growth for nuclear industry and nuclear power plants may depend on the substitution of the traditional reactor core with a new concept. This is only a component of the nuclear power plant. The nuclear industry is a complex of integrated components such as hardware component supplies, fuel fabrication, heat exchangers, transmission networks, design engineers, regulatory agencies, reactor operators, etc. A new nuclear reactor concept can be a relatively a minor change that may result in a turning point to the future success of nuclear industry

The fission nuclear reactors may be classified as three categories: Evolutionary Systems, Innovative Designs, and Emerging Concepts. The safety history of Evolutionary Systems is based on the accumulated experience of more than 6000 reactor-years of operation. One common measure of assessing the safety of an individual nuclear power plant is to estimate the expected frequency for a severe core damage. This parameter has decreased from one-in-thousand years before the TMI accident to well below one-in-ten-thousand years today. The prediction for the next generation of the evolutionary nuclear reactors is another decrease by at least a factor of ten. Most designers strive for a figure of one-in-million years.

Inherent and Passive Safety

The nuclear industry does not accept the concept and wording of the inherent safety as considers it to be unattainable, but in the academic world the consideration of ideal conditions is a common practice, such as analyzing power plants with ideal thermodynamic cycles. Therefore, ideally it should be very desirable to develop concepts of inherently safe nuclear reactors whose safety features are easily demonstrable without depending on the interference of active safety devices which have some probability of failing, or on operator skills and good judgment, which could vary considerably. True inherent safety exists when no mechanical or human intervention is required to shut down the reactor safely. But it is clear too that passive safety features do not lead to avoid failure always: a good example is the case of a leak in a tube which occurs without any mechanical action. Under these conditions, it must be clear that the inherent safety is an intellectual concept which is considered in order to help the nuclear technologies to advance.

All current reactors need to include safety systems to remove decay or residual heat produced after the chain reaction in a reactor has ceased. It is this decay heat that threatens to produce the most serious of nuclear accidents namely the core melt. The inherently safe reactors are transparently incapable of producing a core melt. They are "forgiving" reactors, able to tolerate human and mechanical malfunctions without endangering public health. Also they are called "walk away" reactors as the key feature of these reactors is their reliance upon passive or non-mechanical, safety systems.

There are only four significant sources of energy in a reactor accident: nuclear power excursion, thermal reactions (steam explosion), chemical reactions (zirconium/water and core/concrete), and radioactive decay heat. The first three can be limited or controlled by proper selection of materials - a form of inherent safety. The fourth energy source, decay heat, is a slow and inherently restricted form of energy release.

There are many ways to reach the goal of a relatively simple reactor design whose safety depends on passive, rather than active features. Many believe that the nuclear reactors of the future will be of the inherently safe and passively cooled types of reactors.

Description of the Reactor

A detailed description of the reactor is presented elsewhere (Sefidvash, 1985).Here a brief description of the main features of the reactor is given. The reactor is modular in design; therefore, any size of reactor can be made from the basic module. The total number of modules of the reactor is equal to [3N(N+1)+1], where N is the number of rings of modules surrounding the central module. The basic module has in its upper part the reactor core and a steam generator and in its lower part the fuel chamber .The core consists of a 25 cm diameter fluidizing tube in which, during reactor operation, the spherical fuel elements are fluidized. The fuel chamber is a 10 cm diameter tube which is directly connected underneath the fluidizing tube. A steam generator of the shell and tube type is integrated into the upper part of the module. A neutron absorber shell slides inside the fluidizing tube, acting similarly to a control rod, for the purposes of long term reactivity control.

The pump circulates the water coolant inside the module moving up through the fuel chamber, the core, and the steam generator and thereafter flows back down to the pump through the concentric annular passage. At the maximum or terminal fluidizing velocity, the coolant carries up the fuel elements into the core and fluidizes them .The increase in flow velocity causes higher porosity of the bed. In the shut down condition, the fuel elements leave the core and fall back into the fuel chamber by the force of gravity.

The 8 mm diameter spherical fuel elements are made of slightly enriched uranium dioxide, clad in by zircaloy for normal design, and stainless steel for modified design concept using supercritical steam. The cladding surface temperature limit in the modified design therefore is 450º Cand fuel center temperature limit is 2000º C. Alternatively a ceramic cladding may be used in order to increase the cladding temperature limit.

The fresh fuel elements are fed into the reactor core from the top of the module. The spent fuel leaves the module through a valve provided at the bottom of the fuel chamber. The valve is operated by a hydraulic system allowing the spent fuel to be discharged from the fuel chamber into a permanently cooled storage tank. The module is provided with a pressurizer system to keep the pressure a constant, and a depressurizer valve which leads the steam to the condenser for reducing pressure to allow opening of the valve for refueling. A simple new concept of the pressurizer may be used in order to utilize the saturation pressure of the steam as the regulating factor.

Any hypothetical accident will cut-off power from the pump causing the fuel leave the core and fall back into the fuel chamber by its weight where remain in a highly subcritical and passively cooled condition. The fuel chambers are cooled by natural convection transferring heat to the surrounding air or water pool.

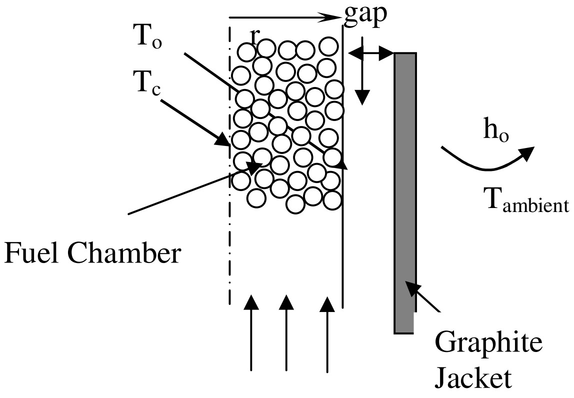
Passive Cooling Characteristics of the Fuel Chamber

Analysis:

The system can be modeled as a two co-axial cylinders with a gap between them. At the accident condition the gap may be filled with water vapor. For the simplification it is assumed that water vapor is non-participating medium for thermal radiation and stagnant. Therefore, it is assumed that the heat exchange between two walls of the gap is solely by radiation, i.e.,

$$q''_{r,g} = \frac{\sigma (T_{in}^4 - T_{out}^4)}{\frac{1}{\varepsilon_{in}} + \frac{1}{\varepsilon_{out}} - 1},$$

Heat transfer through graphite jacket is by condition. Since, the thickness of the jacket is small, then thermal resistance and thermal capacitance of the jacket is neglected. Heat transfer form the outer wall of the jacket to the ambient is considered as convective heat transfer. Furthermore, the fuel container wall thermal resistance and capacitance is assumed to be negligible compared with the thermal capacity of the fuel.



The fuel chamber is filled with spherical fuel pellets of 8 mm in diameter. In an accident condition the water vapor forms between pellets, hence heat generated in the fuel dissipates mainly by diffusion and radiation to the outer layer of the chamber.
The energy equation for fuel chamber is

$$(\phi \rho_f c_f + (1-\phi)\rho_s c_s)\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(k_{eff}\frac{\partial T}{\partial r}\right) + q_g$$

$$q_g / q_o = 0.095 t^{-\beta}$$

where k_{eff} is the effective thermal conductivity of the medium. The spherical fuel can be treated as a porous media. The heat diffusion through porous layer saturated with gas or steam can modelled as heat diffusion through porous medium with effective thermal conductivity. The radiation effect should be considered in the heat diffusion through porous medium. The effect thermal conductivity of the saturated porous can be expressed as sum of the two components; effective conductivity and radiative conductivity:

$k_{eff} = k_c + k_r$

$$k_c = \frac{2k_f}{1-(k_f/k_s)}\left[\frac{\ln(k_s/k_f)}{1-(k_f/k_s)} - 1\right]$$

$$k_r = 0.707\,k_f\,(k_s/k_f)^{1.11}\left[\frac{4\sigma T^3}{2(\frac{1}{\varepsilon}-1)+\frac{1}{F_{12}}}\frac{d_p}{k_s}\right]^{0.96}$$

The following values are used in the analysis unless otherwise stated.
k_f=0.03 W/mK, k_s= 4.0 W/mK
$\varepsilon = \varepsilon_{in} = \varepsilon_{out}$ =0.9, F_{12}=0.5, which shape factor between spherical pellets.
$\sigma=5.87\text{x}10^{-8}$, Stefan-Boltzmann constant
ϕ=0.38, porosity of the fuel pellets
ρ_f=1.0 Kg/m^3, c_f=1009 J/Kg.K, ρs=10500.0 Kg/m^3, c_s=402 J/Kg.K,
q_o= The heat generated within the UO2 region is 10^8 Watts/m3.
T_{amb}=300 K, $T_{initial}$=590 K
β=0.26 exponential factor for heat generation
Outer diameter of fuel chamber=10 cm, the gap =2 cm.

Method of solution:

The model equation is solved using control volume approach with central differencing in space. The solution up dated in time explicitly. Grid and time step sizes independent results are ensured by using 100 control volumes and 0.025 second time step.

Results

The results were produced for certain critical parameters. Figure 2 shows the time history for temperatures at the core of the system, at the mid layer of the fuel chamber and at the outer layer of the fuel chamber, for different values of β.

As it is expected, a higher value of β dissipates heat much faster than the lower values of β. The important conclusion can be said about the results presented in Fig. 2, is that the peak value of the temperature is below the melting temperature of the system components.

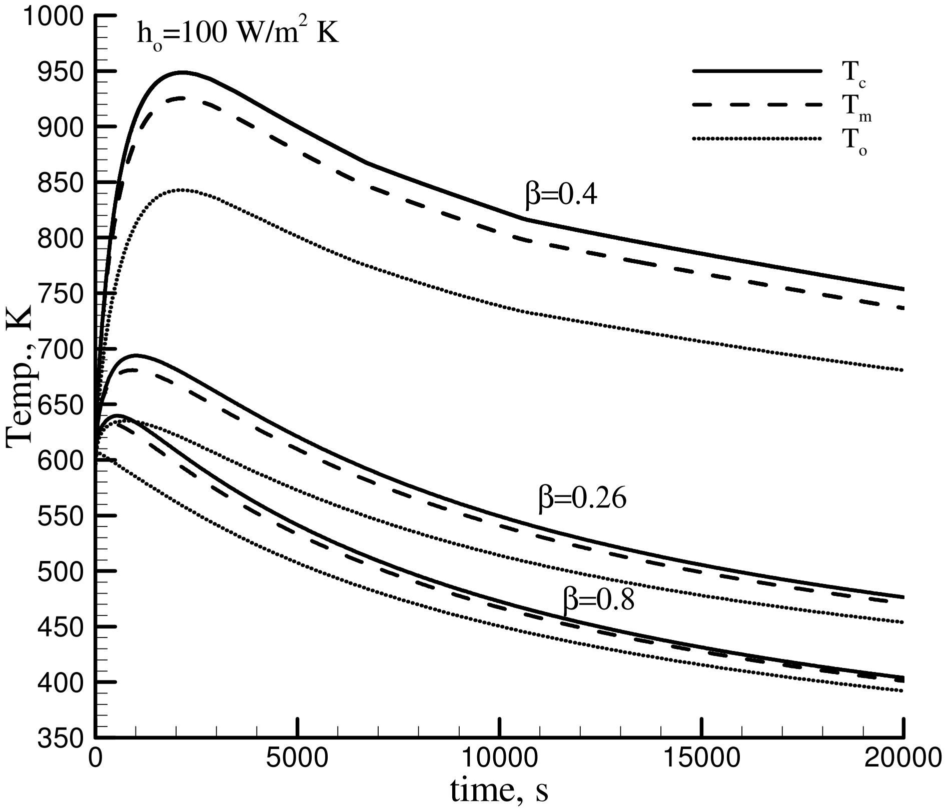


Figure 2. Effect of time exponential factor (B) on the temperature history at three locations (Tc, r=0, center of the system), T_m at the middle of the system (r=ro/2) and at the outer boundary of the system (r=ro)

Another parameter that may have effect on the peak temperature of the system is the overall heat transfer coefficient from the system to the ambient, h_o. For natural convection environment, the value can be order of 10 W/m^2K and for forced convection can be order of 100 W/m^2K. Figure 3 shows the effect of h_o value on the temperature history at three critical locations as for Fig. 2. The β is set to 0.26, which is a typical value of β. The results indicate that the peak temperature is below 750 K, which is below the melting temperature of the material used in the system.

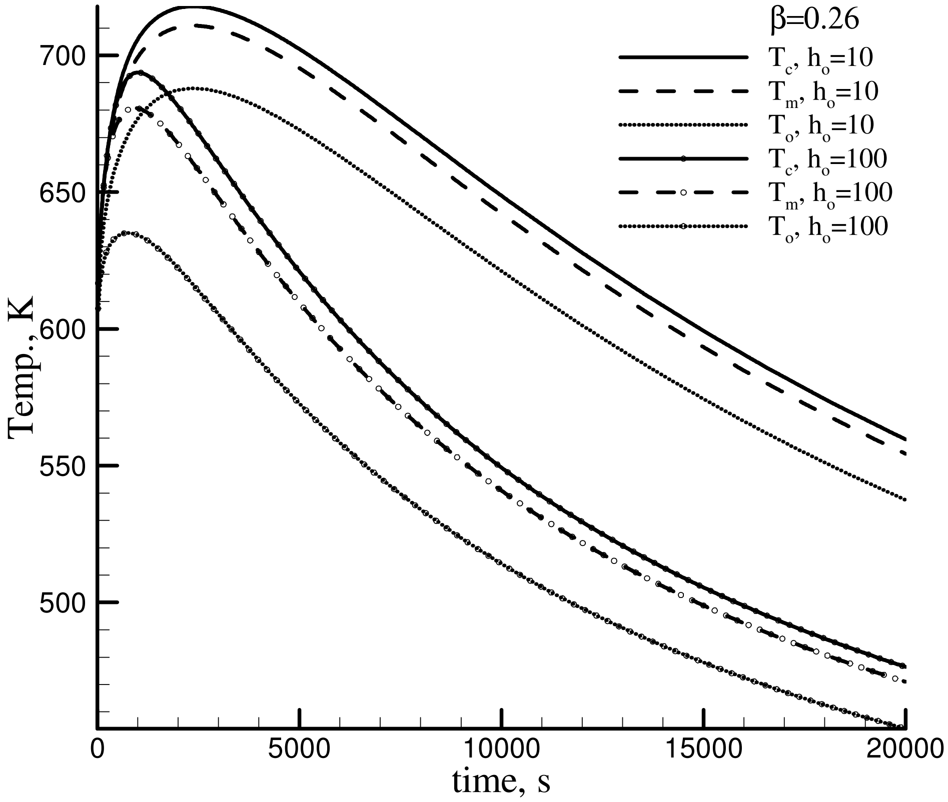


Fig 3. Effect of h_o on the temperature history.

For certain applications, the size of the modules may be designed to be larger than the typical size; therefore, effect of enlarging modules on the temperature is depicted in Fig. 4. The peak temperature increased by about 80 K compared with a typical size of modules (Fig. 3). Yet, the peak temperature is below the melting temperature of system components.

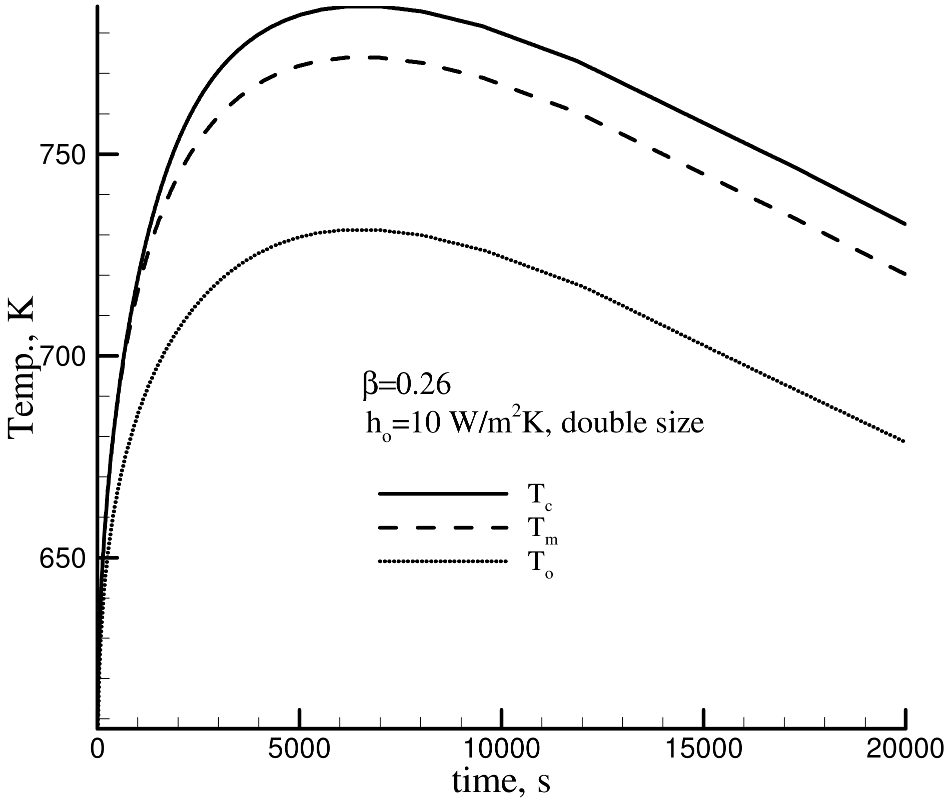


Fig. 4, Effect of double sizing the system from r_o=10 cm to 20 cm.

Conclusions

From all the above studies, one can conclude that the heat transfer through natural convection is sufficient to cool down the nuclear fuel deposited in the fuel chamber after whatever form of incident or accident that should occur. The peak temperatures are below the design limits and thus the passive cooling of the system is demonstrated.

References

1. F. Sefidvash, F. "A Fluidized Bed Nuclear Reactor Concept" , *Nuclear Technology*, 71 (1985) 527-534 .

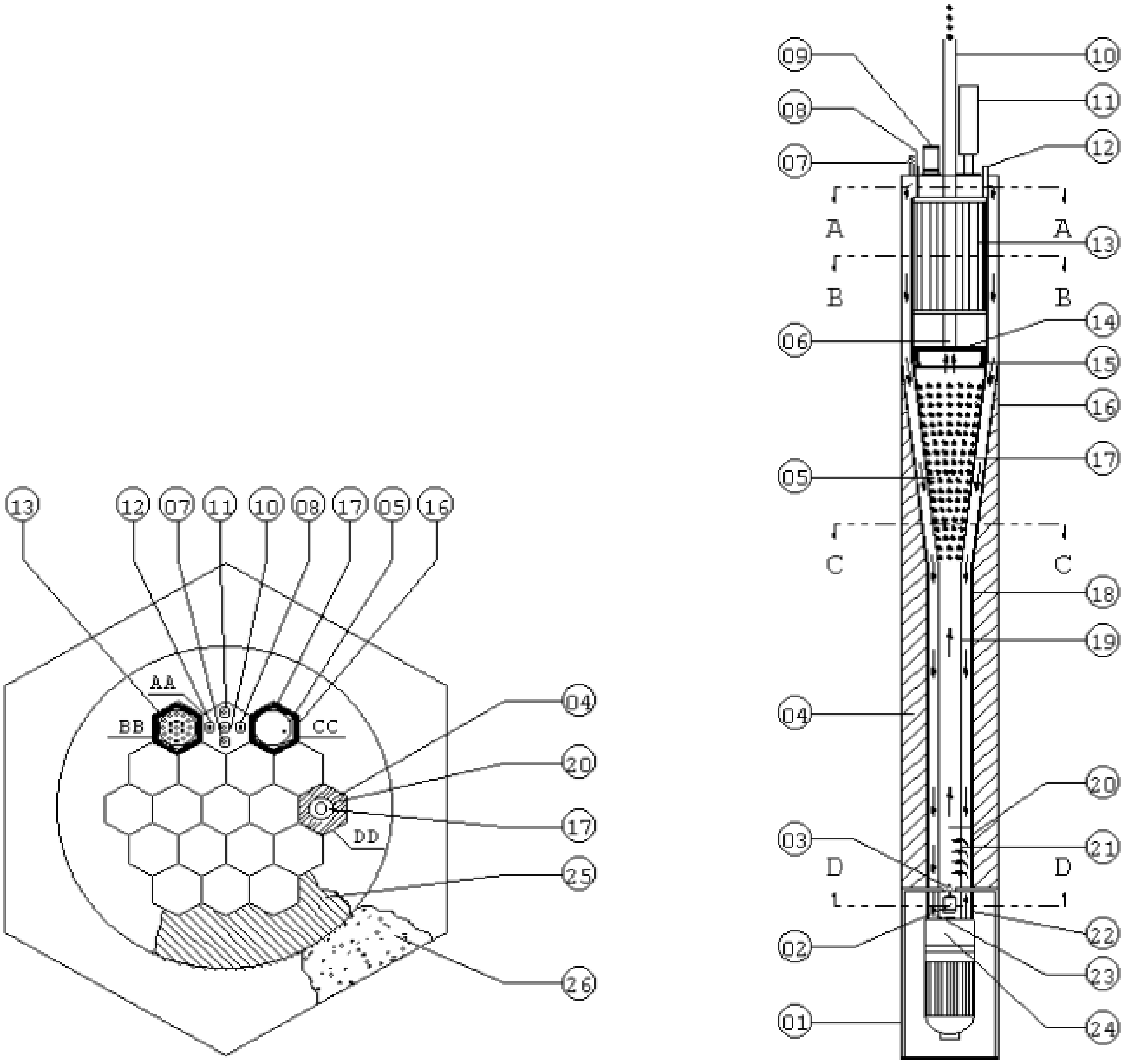


Fig 1.Schematic diagram of the fluidized bed nuclear reactor:

1) structural support; (2) hydraulic valve opener;(3) fuel discharge valve;(4) graphite jacket; (5) reactor core; (6) level limiter shaft; (7) depressurizer; (8) steam exit; (9) level limiter drive; (10) fuel feed; (11)pressurizer; (12) water entrance; (13) steam generator; (14) level limiter; (15) absorber shell; (16) hexagonal channel; (17) fluidization tube; (18) circular channel; (19) fuel chamber; (20) distributor (21) entrance perfurations; (22) coolant entrance; (23) coolant exit; (24) primary pump; (25) reflector; (26) biological shield.