The further development of WWER-440 fuel design performance

Authors: V.B.Lushin, I.N.Vasilchenko, J.A.Ananjev, G.V.Abashina
OKB "GIDROPRESS".

1 Introduction

VVER fuel development is determined by two main factors:

- fuel reliability enhancement;
- fuel market requirements.

Thereof VVER fuel design is continuously improved within full service life of these type reactors.

The most distinguished stages in VVER-440 fuel development of the latest ten years are:

- designing of second generation FA complex;
- designing of sheathless working fuel assembly of the third generation (RK-3).

Designing of fuel assemblies of the second generation and RK-3 is characterized by the tendency to power increase of VVER-440 operating units with V-213-type reactor, that, in turn, has given a stimulus to further design enhancement of fuel assemblies specified.

2 Design of the complex of second generation fuel assemblies VVER-440

2.1 Main purpose of the second generation fuel designing for VVER-440 power units of V-213 type is fuel burn-up efficiency increase. This purpose is achieved by such technical solutions as increase of fuel charge (Figures 1, 2), decrease of hazardous neutron absorption (due to decrease of hafnium content in zirconium materials from 0,05 % to 0,01 % and decrease of zirconium amount as a result of transition to the cask width of scram/control/shim fuel assembly (FA) – 1,5 mm) and increase of fuel rod pitch in bundles (to 12,3 mm).

The following engineering solutions are concurrently applied in the design of secondary generation fuel assemblies aimed at the increase of fuel rod bundles vibration-resistance (redistribution of spacing grids (SG) along the fuel rod bundle axis and height increase of the first three grids in the direction of coolant flow, implementation of fuel rod improved elastic tip, stiffening crossbar under working assembly (WA) supporting grid and central tube fixing in the supporting grid by welding, introduction of special sleeve in the protective grid for bundle fixing from radial displacements in the upper part, introduction of various-level slots in the central tube to prevent spacing grid distortion and failure as a result of fuel rod temperature increase).

Fuel assemblies with the profiled fuel of average enrichment 4,25 % (with gadolinium absorber) are used for WA and 3,82 % for FA to provide five-year fuel cycle with some WA operation during the sixth year in NPP units with VVER-440.

Specified design is developed for RP of nominal power 1375 MW for NPP Kola-3 with subsequent adaptation for a number of other NPP with VVER-440 in Russia and abroad (Kola-4, Dukovany, Mochovce , Bohunice B-2).

Comparison of main design neutron-physical parameters of the core with second generation fuel for various power units is presented in Table 1.

Table 1

Parameter	Value				
	Kola-3, 4	Rovno-1, 2	Dukovany	Mochovce	Bohunice

Parameter		Value				
		Kola-3, 4	Rovno-1, 2	Dukovany	Mochovce	Bohunice
Power peaking factor of fuel assemblies		1,42	1,39 1,47	1,44	1,44	1,44
Power peaking factor of fuel rods		1,61 1,58	1,55 1,668	1,61	1,66	1,66
Power peaking factor of fuel pellets		2,21 2,27	2,06 2,30	2,27	2,21	2,21
FA maximum power, MW		6,17	6,48 6,15	6,25	6,11	6,11
Fuel rod maximum, kW		56,6 55,5	58,6 56,6	56,6	56,6	56,6
Average linear power of fuel rods, W/cm		126,1 125,1	140,4 125,8	125,1	126,1	126,1
Time of fuel cycle, eff.days		308,55 305,95	322,6 312,4	331,4	313,0	313,65
Make-up FA (number (pcs.)/ enrichment, (%))	WA	57/4,25	63/4,38 57/4,38	63/4,25	69/4,25	69/4,25
	FA	9/3,82	9/4,25	9/3,82	9/3,84	9/3,84
Burn-up in maximum burnt assembly, MW day/kg U		54,3 53,2	55,9 55,3	55,7	53,6	53,8
Average burnup of unloaded fuel MW day/kg U	WA	53,05 52,00	49,4 53,2	51,83	51,11	51,26
	FA	42,56 40,07	46,3 43,2	43,18	43,24	43,34

Besides Kola-3, second generation fuel for VVER-440 is put into operation to 2010 practically in all NPP units with VVER-440 of V-213 type in Russia and abroad (Table 2).
Table 2

NPP	Unit No	Year of implementation
Kola	4	2005
Dukovany	3	2005
Dukovany	1; 2; 4	2006
Mochovce	1; 2	2006
B-2 Bohunice	3; 4	2006
Paks	3, 4	2009
Loviisa	1; 2	2010

Maximum operating experience is obtained in Kola-3 in which pilot-commercial operation of second generation fuel assemblies was initiated in 2001. Unit core is fully completed with second generation fuel assemblies since 23-th fuel cycle. After completion of the 23-th fuel cycle, burn-up fraction of FA kept for the sixth year reached 1720 eff. days and burnup fraction in maximum burnt fuel assembly was 51,5 MW day/kg U.To achieve the aim (power increase) by request of the Customers the second generation assemblies are used. They are distinguished by U_{235} average enrichment of the bundle (Table 3) as well as by profiling the bundle.
Table 3

NPP	Planned Unit power, % N_{nom}	WA average enrichment , % by U-235	ERC FA average enrichment, % by U-235	Planned term for the end of calculation- and- experimental work (the year since which the Unit has been operating at the increased power
Kola	107	4,25 (with U-Gd fuel)	3,82	2009 - Unit 4 (since 2009) 2010 - Unit 3 (since 2010)
Dukovany	105	4,38 (with U-Gd fuel)	4,25 (with U-Gd fuel)	2008 (since 2009 – Unit 3)
Mochovce	107	4,25 (with U-Gd fuel)	3,84 (with U-Gd fuel)	2007 (since 2008)
B-2 Bohunice	107	4,25 (with U-Gd fuel)	3,84 (with U-Gd fuel)	
Paks	108	4,20 (with U-Gd fuel)	4,20 (with U-Gd fuel)	2009 (in 2009 - Unit 4)
Loviisa	109	4,37 (with U-Gd fuel)	4,0	2009 (since 2010)

Neutronic characteristics of the core during operation of Units at the increased power level are presented in Table 4.

Table 4

Characteristic		Value					
		Kola NPP, Units 3 & 4	Dukovany NPP	Mochovce NPP	Bohunice NPP	Paks NPP	Loviisa NPP
Unit power, % Nnom		107	105	107	107	108	109
Power peaking factor in fuel assemblies		1,46 1,42	1,45	1,44	1,45	1,37	1,32
Power peaking factor in fuel rods		1,55	1,55	1,546	1,54	1,44	1,47
Power peaking factor in fuel pellets		2,127 2,126	2,21	2,21	2,21	2,11	1,87
Maximum power of fuel assembly, MW		6,62 6,17	6,58	6,525	6,62	6,27	6,84
Maximum power of fuel rod, kW		56,6	56,6	56,6	56,6	53,2	61,54
Average linear heat rate of fuel rods, W/cm		134,94 135,05	126,1	126,1	126,1	136,1	152,14
Duration of loading, eff.days		302,45 307,85	324,5	330	323,5	324,8	333,5
Nomenclature of make-up fuel assemblies (number (pcs.)/ enrichment , (%))	WA	72/4,25 69/4,25	63/4,38	75/4,25	72/4,25	75/4,2	75/4,37
	FA	6/3,82 9/3,82	9/4,25	9/3,84	9/3,84	9/4,2	9/4,0

Characteristic		Value					
		Kola NPP, Units 3 & 4	Dukovany NPP	Mochovce NPP	Bohunice NPP	Paks NPP	Loviisa NPP
Burn-up in maximum burnt fuel assembly, MW.day/kg U		58,2 51,7	55,5	51,3	51,9	48,5	53,3
Average burn-up fraction of fuel unloaded, MW.day/kg U	WA	44,15 46,9	52,43	47,95	49,35	45,59	47,05
	FA	58,1 46,66	46,64	44,15	44,55	43,81	48,35

2.3 First, the second generation WAs with average enrichment of 4,25 % by U - 235 and the second generation ECR FAs with average enrichment of 3,82 % by U - 235 were designed for operation in the five-year fuel cycle (leaving some WAs for the sixth year) when the core operates at power of 1375 MW (100 %).

An increase in thermal power of the Unit on the basis of these second generation fuel assemblies leads to reduction of life time or to an increase in the number of make-up fuel assemblies (as a comparison of Tables 1 and 4 shows).

It is obvious that, when the reactor core operates at the increased power level, an increase in average fuel enrichment in WA and ERC FA is required (Czech and Finnish Customers have already asked for it). And, it is not the last stage connected with the increase in the initial enrichment of fuel assemblies at VVER-440.

Thus, in 2009-2010 there was fulfilled a complex of work on introduction of the second generation assemblies with average enrichment of 4,87 % by U-235 into the experimental-industrial operation at Kola NPP, Unit 4. The first set of test second generation fuel assemblies with average enrichment of 4,87 % was loaded into the core of Unit 4 at Kola NPP in PM - 2010. Design neutronic characteristics of the core of Unit 4 at Kola NPP are presented in Table 5.

Table 5

Parameters		Value
Unit power, % N_{nom}		107
Power peaking factor in fuel assemblies power		1,49
Power peaking factor in fuel rods power		1,58
Power peaking factor in fuel pellets power		2,08
Maximum power of fuel assembly, MW		6,75
Maximum power of fuel rod, kW		59,84
Average linear heat rate of fuel rods, W/cm		134,94
Duration of loading, eff. days		298,8
Nomenclature of make-up fuel assemblies (number (pcs.)/ enrichment , (%))	WA	54/4,87
	FA	6/4,25
Burn-up in maximum burnt fuel assembly, MW·day/kg U		67,3
Average burn-up fraction of fuel unloaded, MW.day/kg U	WA	58,0
	FA	61,15

2.4 The coolant mixing intensity increase in the problem areas of the fuel bundle is an important factor of raising the reactor power.

So, the introduction of mixing elements in both spacing grids (figure 3) into the design of the second generation WA is considered for improving the conditions of peripheral fuel rods cooling under the Contract with Loviisa NPP. Four spacing grids, placed in the middle part of the fuel bundle, are planned to be equipped with such mixing elements.

For substantiation of the SG with the mixing elements a complex of experimental work (bench hydraulic tests and operational-life proof) was planned to be performed in 2011. The hydraulic tests were performed using the mock-up simulating the WA geometry. To ensure the better reliability the tests were carried out on two test benches. Comparison of the results showed that the obtained PLC values are within the possible interval of deviations of PLC of the commercial fuel assemblies with a throttle washer of 50 mm in diameter caused by their measuring error and the technological causes. Operational-life proof was performed on the hot run-in test bench simulating the VVER-440 primary circuit parameters (pressure, temperature, flowrate) within 1000 hours. The test results showed reliability of the design developed.

2.5 One of the design restrictions is an average coolant temperature at the fuel assembly outlet. Fulfillment of this restriction at the NPP is checked by the temperature control at the outlet of the WA being in the cells with the temperature control sensors.

The better mixing the coolant at the WA outlet, the better adequacy of the output data as concerns the average coolant temperature, and, hence, the wider possibilities on increasing the reactor power.

To solve the problem set we carry out the work on changing a design of the protective grid in the WA top nozzle by arranging along the slots of the grid the inclined guides (plates) made by unbending the "cutting-out" part of the slot (Figure 4).

To analyze reliability and efficiency of the made change the OKB "GIDROPRESS" and JSC"MSZ" carried out the respective calculated and experimental work.

The further development of the second generation fuel assemblies is substantiation and implementation of the fuel rods with pellets without a central hole into the fuel assembly design. The comparative characteristics of the standard fuel rods and suggested ones are given in Table 6.

Table 6

Parameter	Value	
	Fuel rod of the second generation standard fuel assembly	Fuel rods with the pellets without the central hole
Diameter of the pellet central hole, mm	1,2	0
Outer diameter of the pellet, mm	7,6	7,8
Cladding thickness, mm	from 0,63 to 0,71	from 0,535 to 0,605

3 Design of the third generation sheathless working assembly

3.1 Elaboration of basic design for RK-3 of VVER-440 reactor is directed at further (in relation to the second generation fuel assemblies) improving the fuel utilization with keeping a safe operation, to this end the following structural decisions are introduced into design RK-3 (figure 5):

- increase in fuel rod pitch in the bundle;

- application of sheathless design with a skeleton from 6 angle pieces and three load-bearing tubes;

- increase in the internal diameter of the fuel rod cladding and the diameter of fuel pellet;

- usage of fuel rods without a central hole in the fuel pellets ;

- introduction of the optimized arrangement and quantity of the SG;

- increase in a stroke of the spring-loaded fingers of the top nozzle.

According the design the RK-3 is intended for operation in the V-213-type VVER-440 reactors in a six-year fuel cycle with the possibility to keep the part of the fuel assemblies in the reactor for the seventh year of operation.

To confirm safety of operation of the assumed RK-3 design the experimental studies and calculational analysis were made.

During PM-2010 at Kola NPP, Unit 4 the first batch consisting of 12 RK- 3 with an average enrichment of 4,87 % was placed for pilot-commercial operation The further development of the design is focused on a planned increase in uranium capacity of RK-3 due to application of skeleton with one load-bearing tube, as the latter a central tube is proposed to be used. As a consequence the number of the fuel rods in the bundles increases by 3.

Conclusion

The further development of the second generation fuel assembly design and the change-over to the third generation working assemblies will allow for fuel unitlization to be considerably increased under the conditions of application the more long-term fuel cycles for VVER-440 reactors and operation of the Units at the increased power.

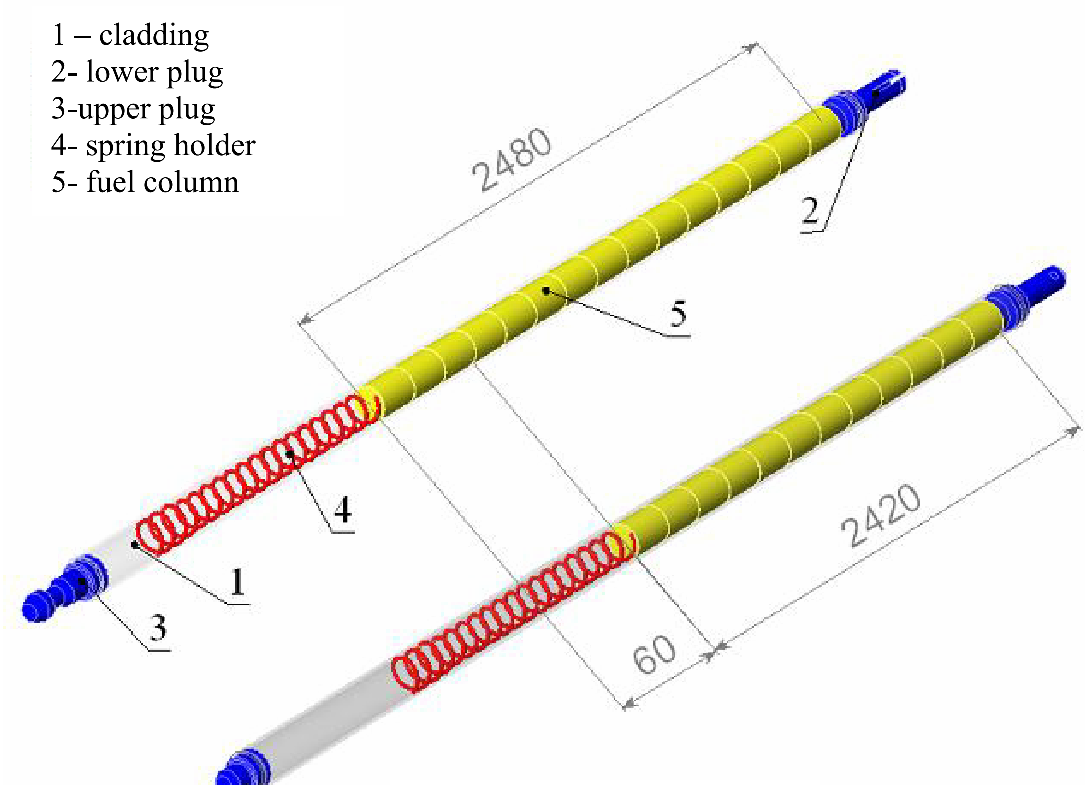

Figure 1 WA fuel rods

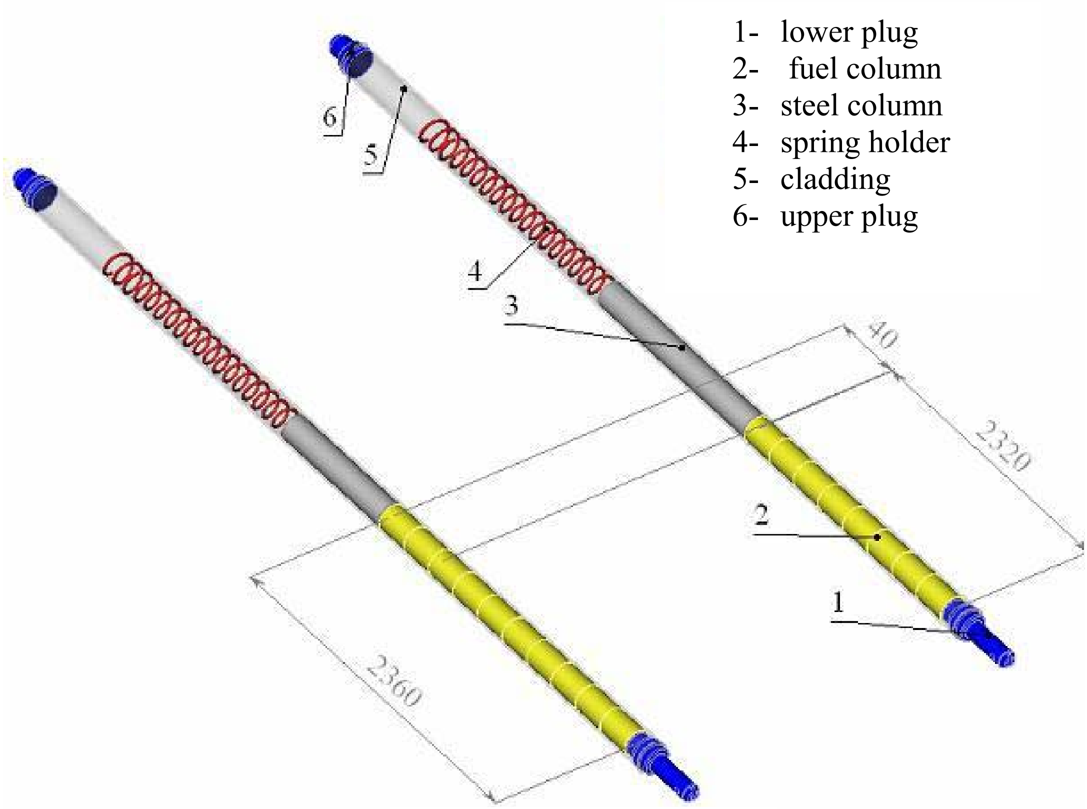

Figure 2 FA fuel rods

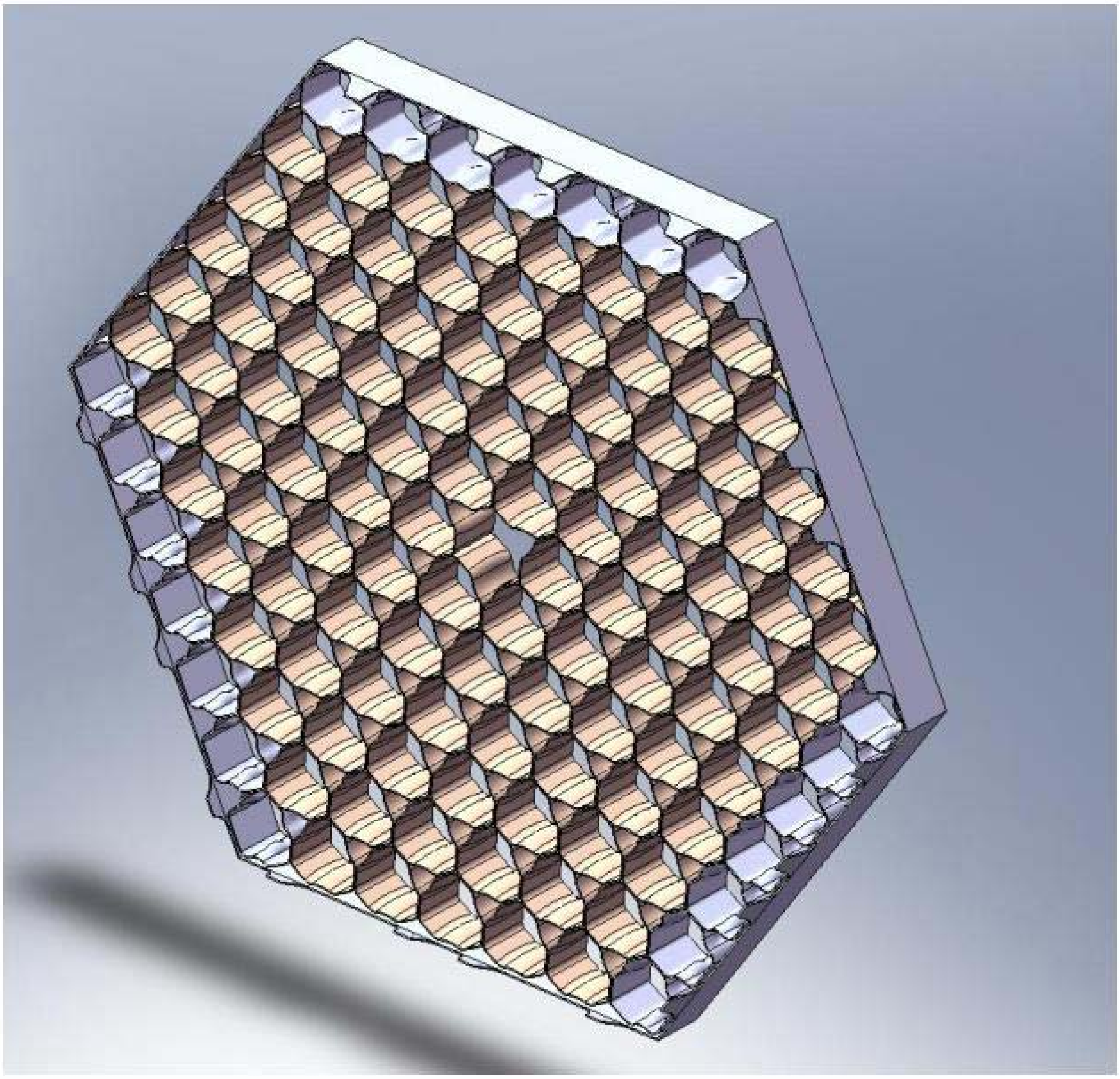

Figure 3 Spacing grid with mixing elements on the rim

Figure 4 Protective grid

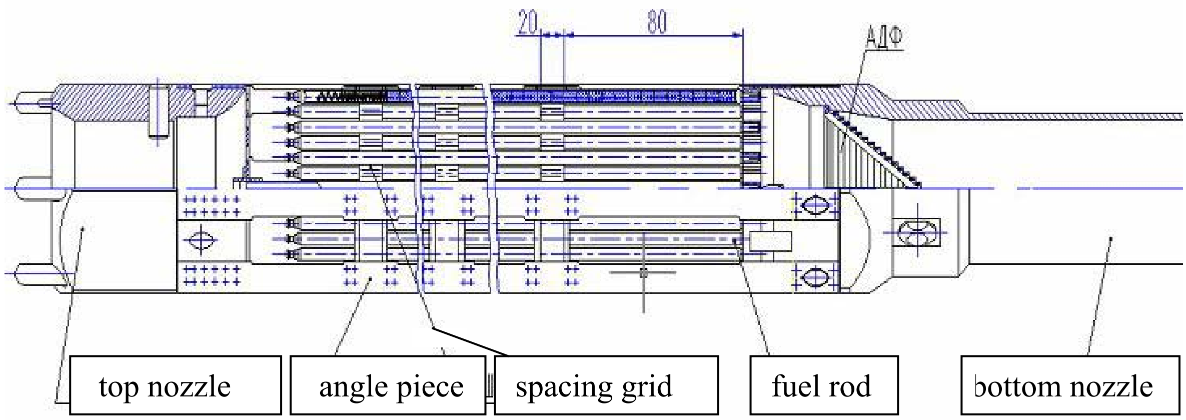

Figure 5 RK-3