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THEORETICAL AND EXPERIMENTAL MODELING OF THE MULTIPLE PRESSURE TUBE RUPTURE FOR RBMK REACTOR. PART II

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ABSTRACT

Rupture of a single fuel channel (FC, pressure tube) or several FCs of the RBMK take place in service conditions on NPPs with a variety of initiating events. Justification of impossibility of the multiple pressure tube rupture (MPTR) under escaping coolant effect requires performing a series of theoretical and experimental studies of separate physical processes running in the RBMK reactor, as well as development of mathematical models and their physical equivalents.

The coolant discharge through the FC break and motion of steam along the stack gap were investigated on the TKR-F (graphite) test facility with the tested core being composed of two graphite blocks. The graphite blocks were in a position to move apart and turn under steam pressure action. Features of the performed tests were measurements of maximum forces at the blocks due to steam outflow through the gap between the blocks.

The thermohydraulic coolant/stack interaction, far from the emergency fuel channel under outflow conditions, close to stationary, was implemented on the TKR-F (graphite) tested core with fixed four graphite blocks. That enables to estimate effects of cooling, wetting and phase transfers on characteristics of steam and water-steam mix motion through narrow gaps of the stack.

Keywords: RBMK, fuel channel, rupture, coolant.

1. INTRODUCTION

As a result of a FC break the coolant outflows to the RBMK stack. Since in certain cases a basic cause of the RBMK FC rupture was superheating of the channel tube, superheated steam is in the channel at the time of breaking. At the initial time after breaking the steam volume is limited by the gap dimensions between stack elements. Therefore, initially a localized short-term pressure peak appears in the gaps between the blocks near the break spot. Peak height is significantly dependent on gap sizes between graphite columns, which are varied from 1 mm to 4-5 mm subject to conditions and operation life. Pressure in the gaps results in the deflection of columns. As increased in deflection, flow areas for coolant outflow increase. Pressure in the break location reduces and then stabilizes at some level.

Generally, the coolant outflowing can be divided into several phases as follows:

- very fast (short-term) shock phase including break, block displacement and filling of the cavity near the break;
- fast (short-term) phase of column displacement by contact forces, near-break pressure and pressure gradients along the gaps;
- slow phase (about a minute) of conditional stabilization of heat sink from graphite, separation, drain, water evaporation (which flows from the break after some time) and steam superheating with frontal advance of steam superheating to the stack periphery.

The very fast and fast phases were studied at the TKR-F (graphite) tested core, containing two movable graphite blocks. To investigate the slow phase, a tested core of TKR-F (graphite) rig with four fixed graphite blocks was developed.

2. BRIEF DESCRIPTION OF THE TKR-F (GRAPHITE) TEST FACILITY

2.1 Tested core with two blocks

For modeling of the FC break the TKR-F (graphite) tested core (Fig. 1-3) was equipped with bursting membranes. The membrane unit (Fig. 1) contained two flanges between which three rings were tied up with eight pins. The rings clamp two bursting disks. When the FC pressure was increased up to the half of the expected pressure of the break, compressed air with pressure a little bit lower than the FC pressure was supplied to the space between membranes through the gap in the middle ring. Then the FC pressure was increased up to the required level.

After reaching the appropriate regime, compressed air was released (by means of the electromagnetic valve), that resulted in the membrane break. The membrane break allowed sharp pressure increases before the gap (as it was after the FC break) and direction-controllable motion of the coolant. The break pressure was changed by means of membrane selection. To supply steam to the gap between the blocks a nozzle was used (Fig. 2). A cone-shaped filter (Fig. 2) with a triple open flow area, in comparison with the membrane section, was installed in front of the nozzle in order to prevent the ingress of the membrane debris into the nozzle. The nozzle was a tapered channel with outlet dimensions 90x2 mm or 90x4 mm.

The graphite blocks were fastened on the test facility as follows. To provide the motion under the steam pressure action along and across the gap, six through holes, four of which were used for installation of the lateral pins and 8 springs on them, were milled in every block (Fig. 1 and 2). The pins and springs allowed for blocks moving horizontally. Initial gap size between the graphite blocks was established with steel plates of the specified thickness. They were fixed horizontally in the top and bottom parts of the blocks. In the longitudinal direction every block was fastened on two pins by means of springs pressing the block to the steam supply flange.

Lead tubes with diameter 32 mm and wall thickness 1.0 mm were installed on pins under the springs in order to measure maximal longitudinal and lateral displacements of graphite blocks. Tube lengths before installation equaled the length of the springs (+1-2 mm) compressed up to the required length in each experiment. Maximal graphite block displacement was analyzed according to residual deformation of every tube.

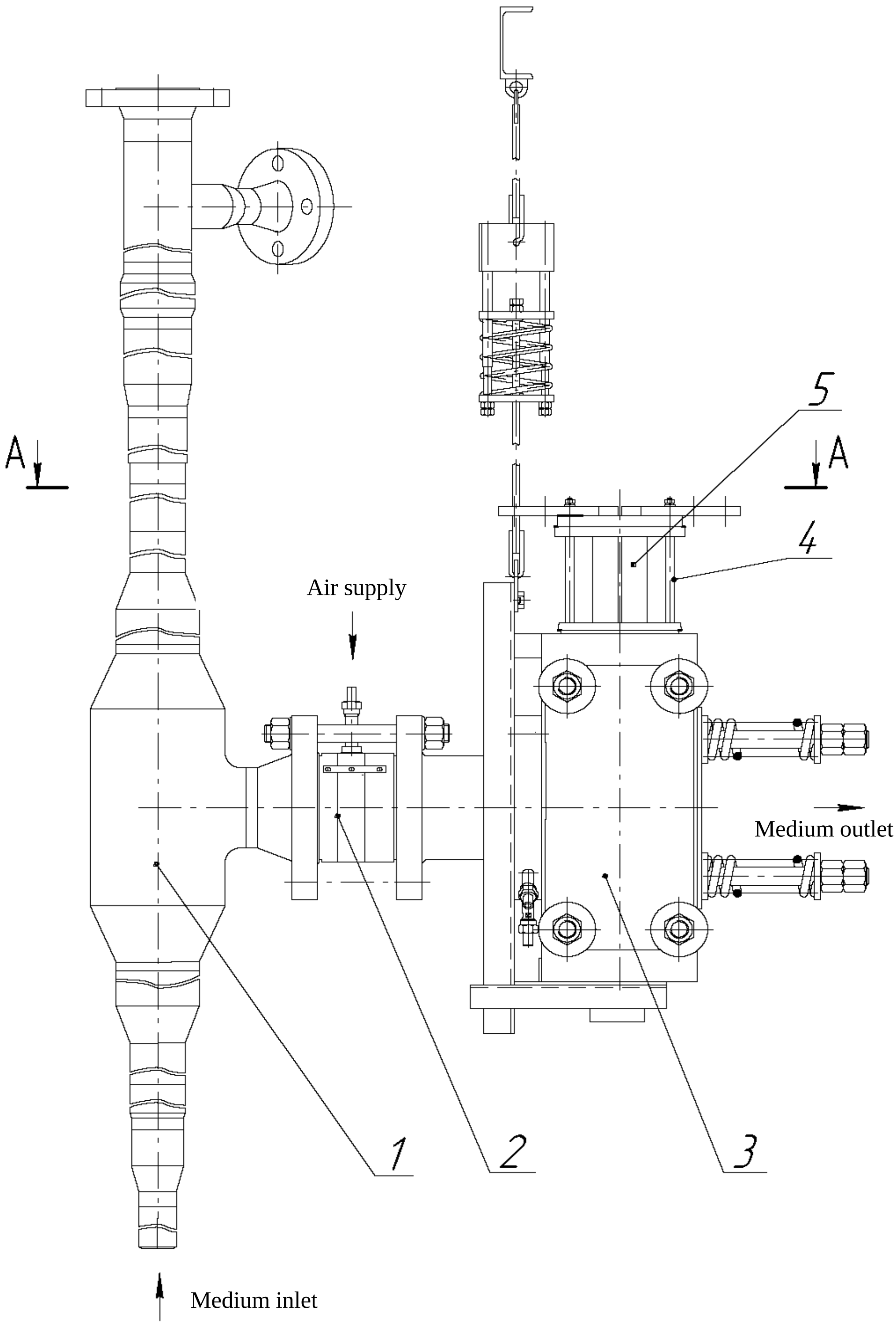
The steam supply flange put together with the outlet membrane unit flange make a united part in the form of a coil (Fig. 2), where the filter and nozzle were located. Owing to the fact that the holes under longitudinal pins were oval in the horizontal plane, the blocks are able to move aside for 24 mm under the steam pressure action and to turn within the gaps between pins and holes.

A direct heater was installed in the central holes of each block. The heater was a thin-wall tube of length 800 mm, diameter 88 mm and wall thickness 2.0 mm cut along a 700 mm length to provide electric power supply and removal on one side.

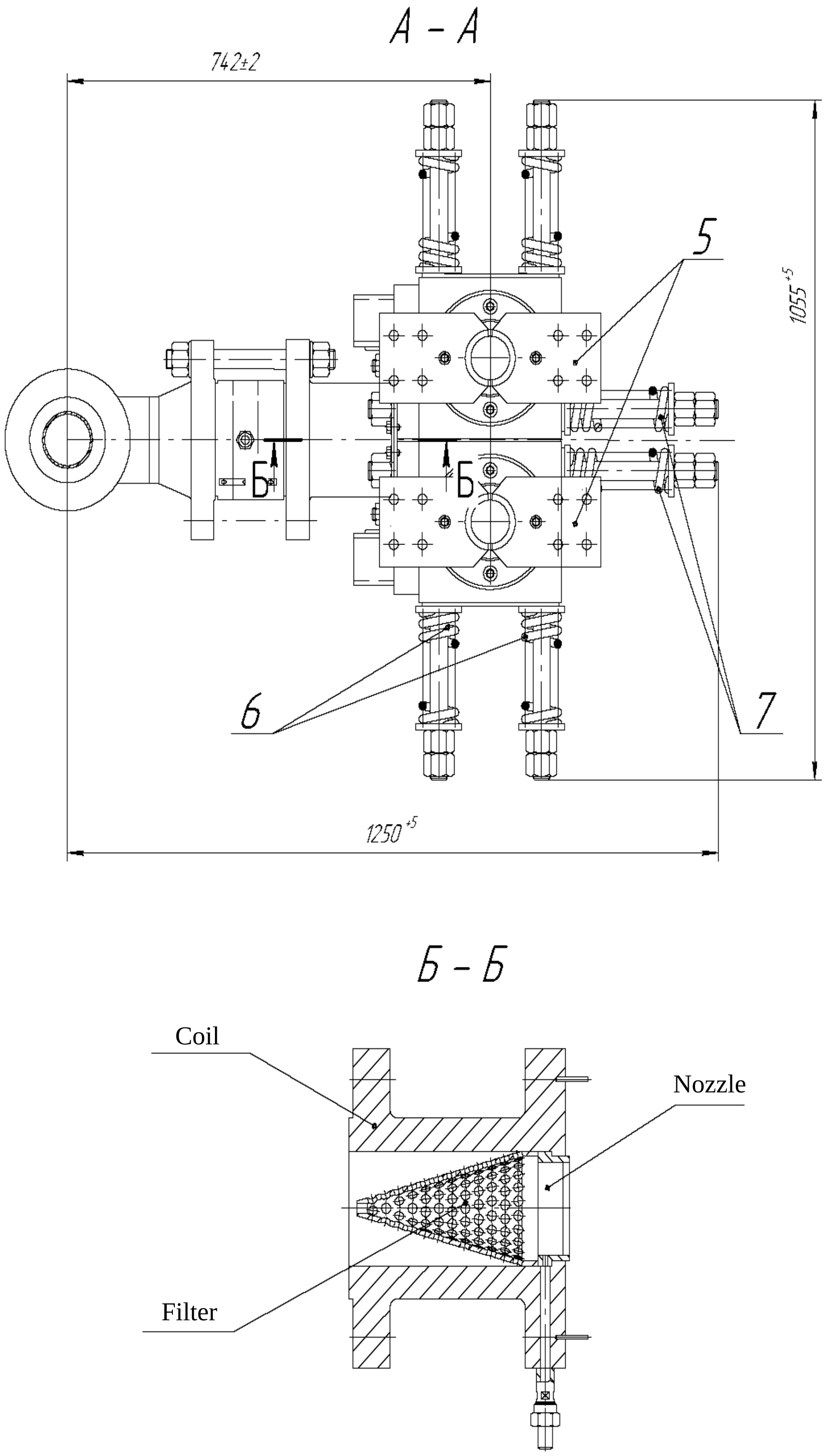
The system for measuring velocity, temperature and pressure of the coolant in gaps as well as the system for measuring maximal block displacement and turns was suitable for the process dynamics under investigation. The instrumentation type and measurement range are included in Table 1. Additionally to the parameters specified in the course of the experiment the following were measured:

– steam pressure at the tested core inlet and outlet;
– pressure in the protective housing;
– steam temperature at the tested core inlet and outlet;

– temperature in the protective housing.

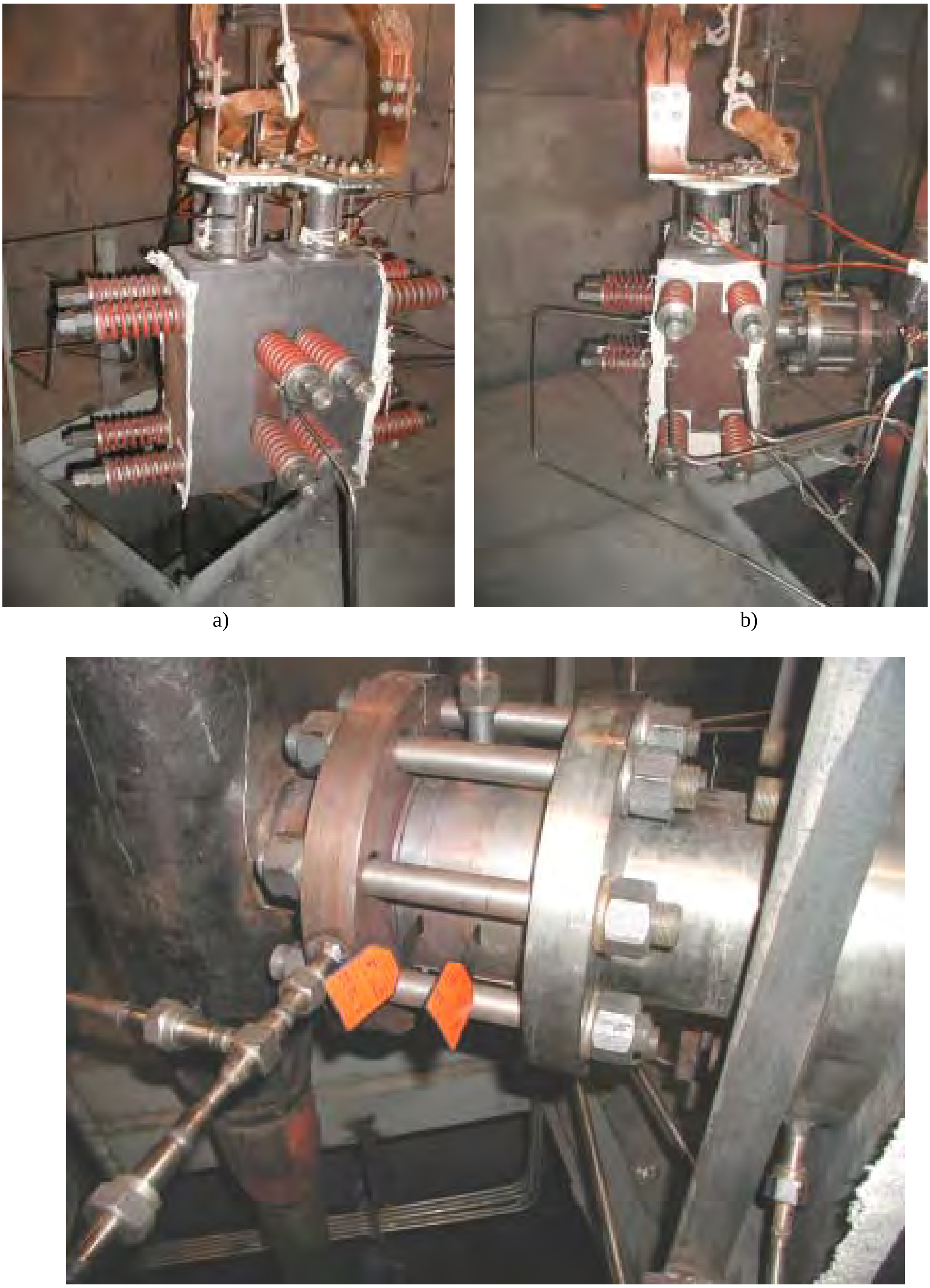


1 – T-bend; 2 – membrane unit; 3 – graphite block; 4 – fitting of the heater; 5 – heaters;
Figure 1 – Tested core of the TKR-F (graphite) rig with two graphite blocks (one side view)



5 – heaters; 6 – lateral spring; 7 – longitudinal springs

Figure 2 – Tested core of the TKR-F (graphite) rig with two graphite blocks (top view and coil with the filter and nozzle)



a) from the front; b) from one side; c) membrane unit
Figure 3 – General view of the TKR-F (graphite) rig tested core with two graphite blocks

Table 1 – Measurable values, instrumentations and measurement range at the TKR-F (graphite) rig with two graphite blocks

No.	Designation on the rig	Measurable value	Instrument - gauge	Unit	Measuring range	Accuracy class
1	P.01.01	Pressure of air in bursting disk	"Metran" DD 22	MPa	2-6	0.5
2	P.06.01	Steam pressure before graphite blocks	"Metran" DD 22	MPa	0-8	0.4
3	P.06.02	Steam pressure in the gap between the block and flange	"Metran" DD 22	MPa	0-8	0.4
4	P.07.01-P.07.03	Steam pressure along the graphite gaps	"Metran" DD 22	MPa	0-8	0.4
5	T.08.01-T.08.02	Temperature of graphite surface in the gap	Thermocouple XA	°C	0-1300	0.5
6	L.01.01-L.01.08	Linear displacement of blocks	Inductive gauge or leading tube	mm	0-50 1-100	0.5
7	V.01.01	Steam speed at the T-bend inlet	Tube of dynamic head	m/s	5-300	0.2
8	U	Voltage on the heater terminals		v	0-15	0.5
9	A	Heater current	Current transformer	A	0-1800	0.2
10	T.08.01-T.08.02	Temperature of the heater surface	Thermocouple XA	°C	0-1300	0.5

4.2 Tested core with four blocks

In this group of tests the TKR-F (graphite) rig was equipped with a water-steam mixture preparation system with a specified range of controlled values of void fraction, pressure and flow rate. The water-steam preparation system contains a superheated steam supply of pressure 9.8 MPa and temperature 540°C and a supply of feed water with pressure 1.6 MPa and temperature 170 °C. Flowmeters (Venturi tubes), temperature and pressure sensors as well as control and stop valves are installed in these areas. A steam mixer providing wet steam generation with different void fractions or superheated steam of different temperature is installed at the supply outlet. At the stage of system heating, after the mixer, the steam or water-steam mixture is supplied to the bypass pipeline or to the tested core during its heating. Then the steam or water-steam mixture passes through a separator and, after separation into steam and water, is discharged through the control valve system to the condenser. Use of a separator makes it possible to maintain smoothly and precisely needed pressure in the tested core on running of water-steam mixture.

Preliminary commissioning tests performed enabled the assessment of the mixture preparation system capability for pressure ranges 0.5-0.75 MPa typical for the coolant in graphite stack gaps. Fig. 4 presents the maximum possible flow rate of the water-steam mixture subject to void fraction. Within this range the system produces an equilibrium water-steam mixture and maintains stable specified parameters. At a pressure of about 1,0 MPa the mixture flow rate decreases significantly due to the large hydraulic resistance of the separator, and producing of mixture with void fraction under 0.4 at different pressures does not go beyond maximum possible flow rate of feed water.

The four graphite blocks were installed vertically generate the channels of required geometry for the flow of the water-steam mixture (Fig. 5-7). Coolant is supplied through the valve (Fig. 5) and flat nozzle 7×90 mm to the gap between graphite blocks. The blocks are heated up to a predetermined temperature by means of direct heaters installed in the block central orifices (Fig. 5). Graphite block attachment ensures setting of predetermined width of the gap and immobility of blocks in the course of coolant flow. Due to the presence of springs, the attachment system makes it possible to compensate thermal expansion of graphite blocks arising in the course of heating.

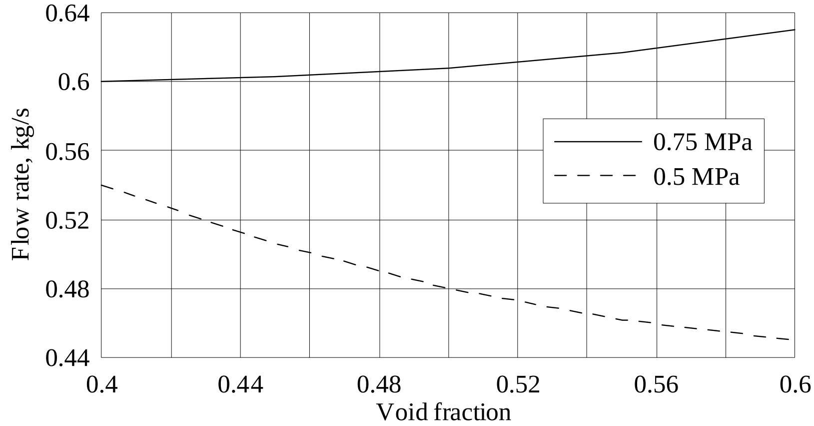
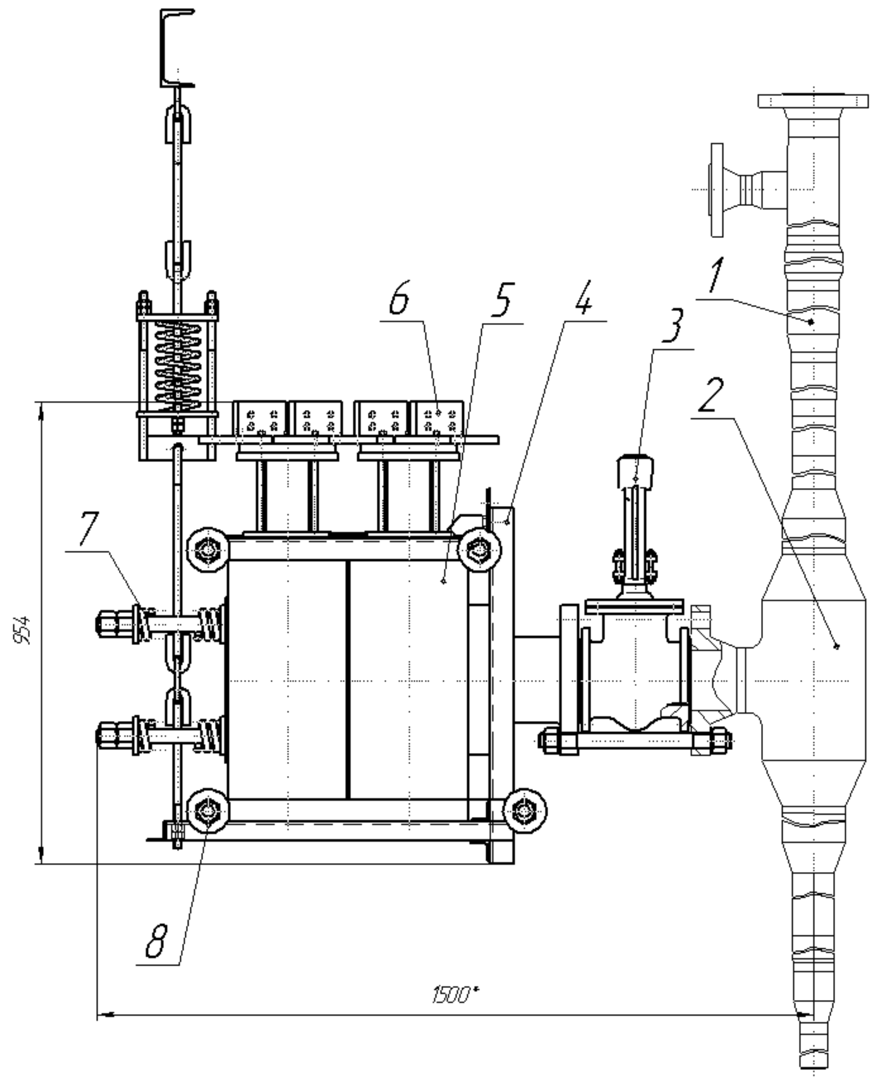


Figure 4 – Relation of maximum flow rate to void fraction at constant pressure 0.5 and 0.75 MPa



1 – steel tube; 2 – T-bent; 3 – valve; 4 – attachment point for blocks; 5 – graphite blocks; 6 – heater; 7 – longitudinal springs; 8 – lateral springs.
Figure 5 – Tested core of TKR-F (graphite) rig with four graphite blocks (side view)

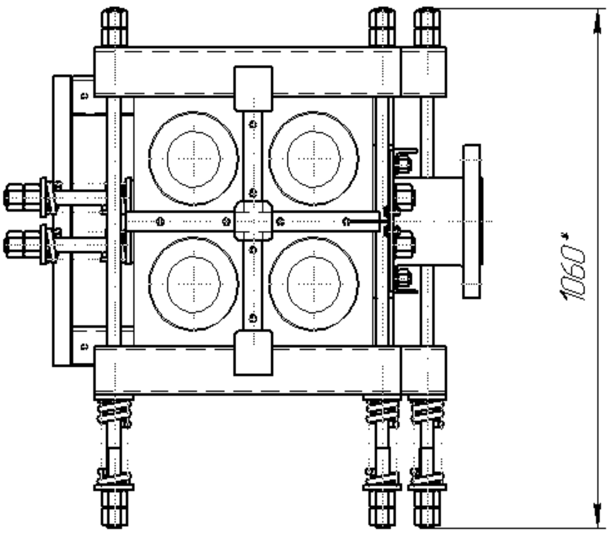
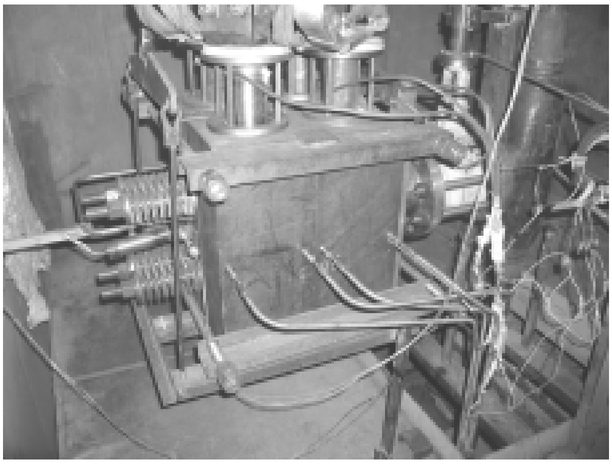


Figure 6 – Tested core of TKR-F (graphite) rig with four graphite blocks (top view)

a)



b)

a) one side view; b) back view

Figure 7 – General view of TKR-F (graphite) rig tested core with four graphite blocks

Table 2 includes the types and characteristics of sensors used on the TKR-F (graphite) rig with four blocks.

Table 2 – List of instrumentation of the TKR-F (graphite) rig with four graphite blocks

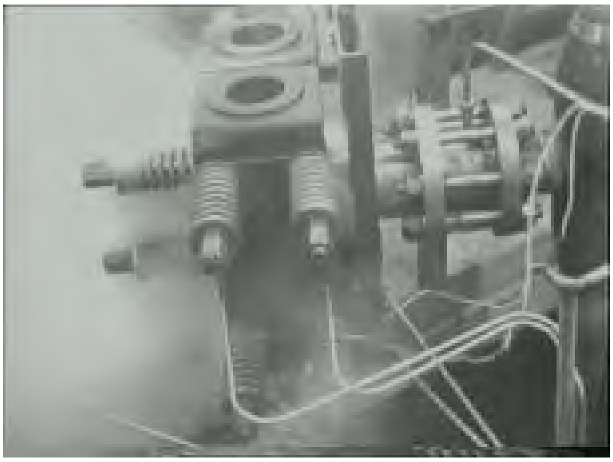
Identifier	**Name**	**$f_{sam.fr.}$**	**Sensor type**	**Boundary**	**Phys. unit**	**Error**
T.04.01–T.04.09	Temperature of housing wall	1(20)	XA	1200	^{0}C	1.5%
T.07.03-T.07.08	Temperature in the gap between graphite blocks	1(20)	XA	1200	^{0}C	1.5%
T.07.09-T.07.14	Temperature of graphite block surface	1(20)	XA	1200	^{0}C	1.5%
T.07.15-T.07.20	Temperature of graphite blocks	1(20)	XA	1200	^{0}C	1.5%
T.01.02	Temperature of feed water at area I-9	1(20)	XK	200	^{0}C	1.5%
T.02.04	Temperature of steam before the mixer	1(20)	XK	600	^{0}C	1.5%
T.01.03	Temperature of medium at the tested core inlet	1(20)	XK	400	^{0}C	1.5%
T.05.01	Temperature of medium at the tested core outlet	1(20)	XK	400	^{0}C	1.5%
F.02.03	Steam flow rate at area I-6	1(20)	22M-DD	100	kPa	2.5%
F.01.04	Feed water rate at measuring area I-9	1(20)	22M-DD	25	kPa	2.5%
F.01.05	Feed water rate at measuring area I-9	1(20)	22M-DD	250	kPa	2.5%
P.01.02	Pressure at measuring area I-9	1(20)	22M-DD	25	MPa	0.5%
P.01.03	Pressure of medium at the tested core inlet	1(20)	22M-DI	10	MPa	0.5%
P.05.01	Pressure of medium at the tested core outlet	1(20)	22M-DI	10	MPa	0.5%
P.05.02	Pressure of medium in the separator	1(20)	22M-DI	10	MPa	0.5%
P.04.01	Pressure under the housing	1(20)	22M-DI	100	kPa	2.5%
W.06.01	Velocity of medium at the gap inlet	1(20)	22M-DD	630	kPa	2.5%
P.07.04-P.07.07	Steam pressure along graphite gap	1(20)	22M-DI	1	MPa	0.5%
DP.07.01-DP.07.02	Pressure differential at graphite block	1(20)	22M-DD	250	MPa	0.5%
T.08.01-T.08.04	Temperature of heaters	1(20)	XA	1200	°C	1.5%

3. SOME TEST RESULTS

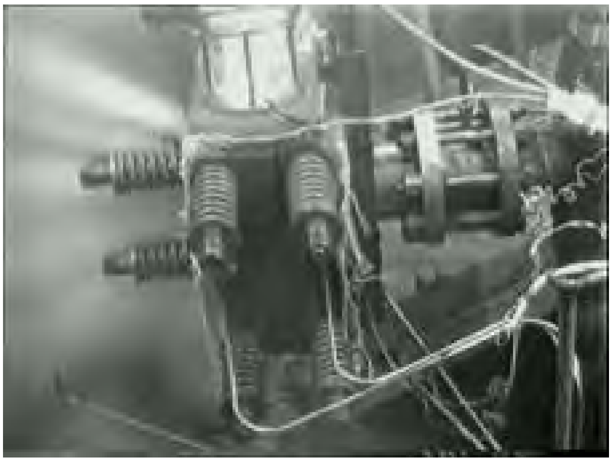
3.1 Tested core with two blocks

A series of pictures on the Fig. 8 represents the moment of the membranes breaking obtained by means of video observation in the different tests in the TKR-F (graphite) rig with two graphite blocks.

a)



b)



c)

a) and b) – "cold" graphite blocks; c) overheated graphite blocks

Figure 8 – Moment of diaphragm breaking in tests

The analysis of the experimental data received from investigations in the TKR-F (graphite) rig with two graphite blocks shows that factors, which have an influence on the average pressure and, hence, on the effective force on the blocks, can be listed in the following descending order:

- hydraulic resistance of gap;
- pressure in break zone;
- size of open flow area of nozzle (area of FC rupture);
- initial clearance between blocks
- heat exchange between steam and blocks.

3.2 Tested core with four blocks

Some experimental data on differential pressure along the gap received from investigations in the TKR-F (graphite) rig with four graphite blocks represented on Fig. 9 and 10.

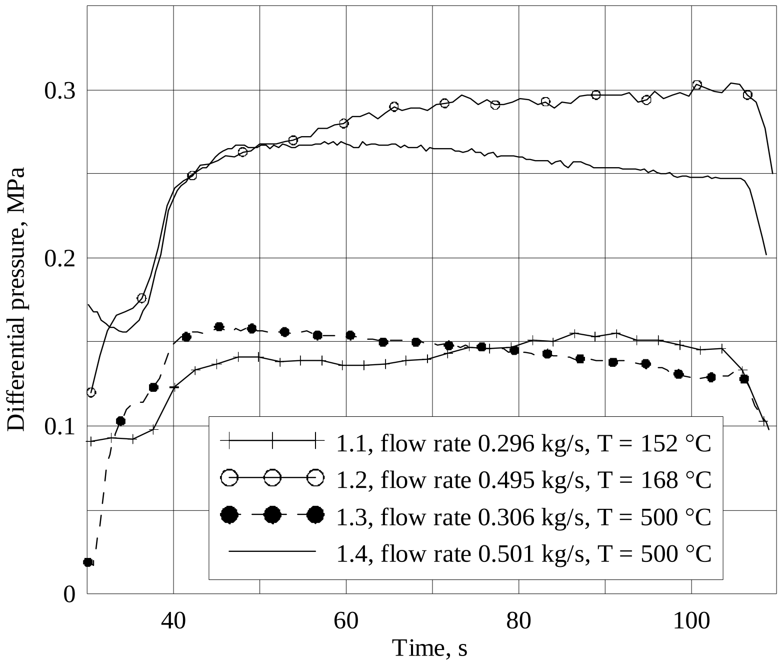


Figure 9 – Dependence of differential pressure along the gap on steam flow rate and graphite temperature

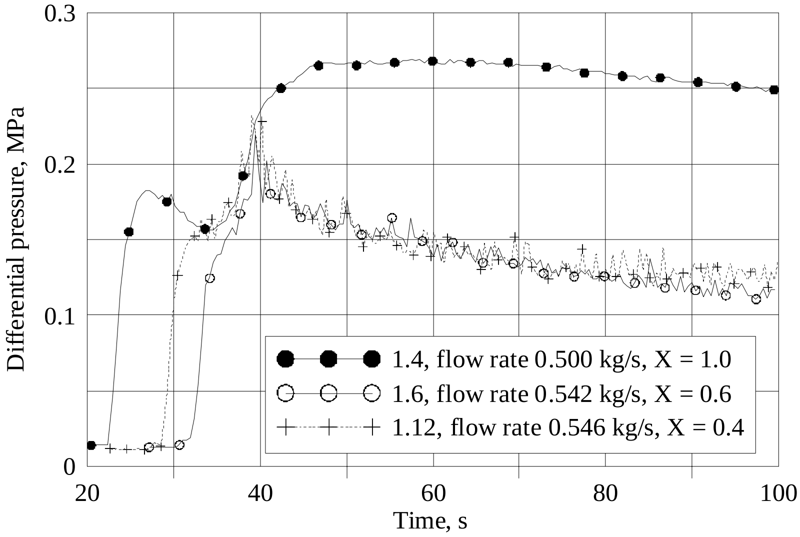


Figure 10 – Dependence of differential pressure along the gap on steam-water mixture flow rate and void fraction X

4. CONCLUSIONS

Processes of coolant discharge through the FC break and motion of steam along the stack gaps were investigated on the TKR-F (graphite) rig with the tested core being composed of two graphite blocks. The 8 tests performed have enabled us to estimate pressure in the gap between blocks under different parameters (pressure in the FC, gap size, block temperature) and maximum efforts moving apart and turning the blocks. The data obtained from the tests is a basis for the development of unlikely accident scenarios, the implementation of which is available in the RBMK type reactors.

A group of TKR-F (graphite) tests with a tested core with four fixed graphite blocks has been performed, processes of cooling, wetting and phase transfers on characteristics of steam and water-steam mix motion through narrow gaps of the stack has been studied. The data obtained from the experimental investigations run on the TKR-F (graphite) rig will be applied for the computation of the hydraulic resistance of the missing part of stack of the full scale TKR rig and for the development of techniques for its simulation.