THEORETICAL AND EXPERIMENTAL MODELING OF THE THERMOMECHANICAL RUPTURE OF PRESSURE TUBE FOR RBMK REACTOR

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ABSTRACT

The rupture of single fuel channel (pressure tube) of the RBMK reactor has occurred at a number of NPPs with a variety of initiating events. It is assumed in RBMK Safety Cases that the force of the escaping fluid will not cause neighboring channels to break. This assumption has not been justified. Hence, an analysis of the multiple pressure tube rupture (MPTR) possibility is needed. This analysis 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 experimental rigs concerned the MPTR problem have been designed and constructed at Electrogorsk Research & Engineering Center, Russia.

Investigation of the circumstances and mechanisms of a single channel rupture at the various conditions and scenarios is one of the main stages of the MPTR problem analysis. Test facility TKR-F (Fuel Channel - Rupture - Fragment) represents a fragment of RBMK fuel channel (FC) and is designed to study conditions of deformation and rupture of a single FC under normal operating conditions and in emergency conditions. The internal heater based on self-propagating high temperature synthesis was designed for simulating a mechanism of thermomechanical rupture of a FC on accident overheating. The experimental studies on the TKR-F rig aimed at searching of thermal and mechanical effects in FC rupture were performed.

Experimental examinations make possible the development and verification of theoretical models and make more exact the conditions and mechanism of a single channel rupture. Theoretical models of the single channel rupture under thermal and mechanical loading have been developed including a channel constrained by the graphite block. Deformation of the channel under internal pressure and localized thermal action is modeled within the framework of the nonlinear shells theory taking into account physically nonlinear material behavior. Computer program based on these models enables to describe the thermomechanical deformation of a single channel and to predict rupture moment.

Mathematical models of heat transfer from the source to a tube, heating, deformation and breaking of a tube have been developed, implemented numerically as a computer program. The numerical results fit good to the experimental data obtained on the TKR-F rig.

The developed mathematical models can serve as a basis for creation of the integrated computer code, which should serve as the computing tool for an analysis of processes in the RBMK reactor.

1 INTRODUCTION

Test Facility TKR-F (Fuel Channel - Rupture – Fragment, Figure 1) represents a fragment of RBMK fuel channel (FC). It was designed to study conditions of deformation and rupture of a single FC in emergency overheating conditions. The objectives of experimental studies to be performed in the TKR-F rig are to test the technique for simulation of emergency thermomechanical rupture of a fuel channel with the specified breaking parameters and to study the channel rupture and interaction of discharge and rupture products with the model graphite stack.

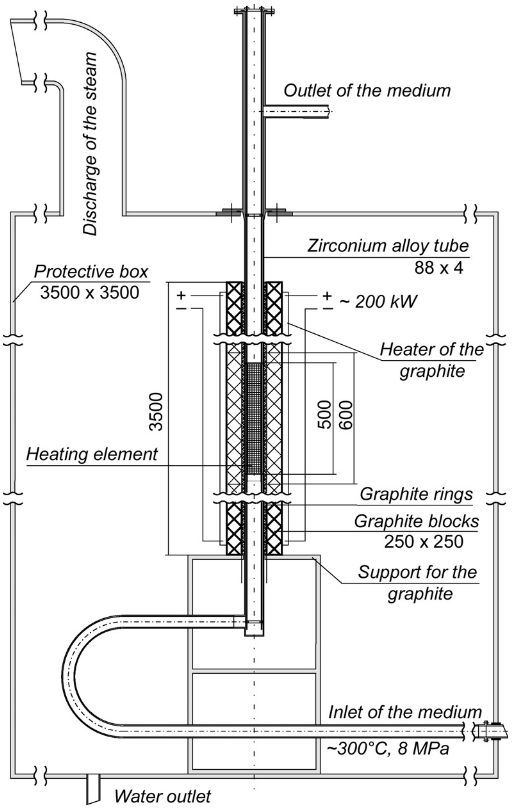

Figure 1: TKR-F rig.

The tested core is a ~ 2.8 m fuel channel (FC) section made of stainless steel or zirconium-niobium alloy (Zr + 2.5%Nb), of internal diameter 80 mm and wall thickness 4 mm. Steel adaptors connecting the tube with the pipeline, supplying steam from the state district power station, are placed on the zirconium tube ends. Inside the tube, in its central area, a thermite heater of external diameter 60 mm is hung axisymmetrically. The heater based on self-propagating high temperature synthesis is a sealed cylinder with a lateral brass foil or stainless steel wall, filled and vibration compacted with a thermite mixture power. Temperature of the heater surface after mix burning (failing steel layer) was predicted at the level 1600 - 1800 °C.

MATHEMATICAL MODELS OF FC HEATING, DEFORMATION AND RUPTURE

The following mathematical models of the physical phenomena and processes were developed:

1) Thermophysical model of a heating source (thermite blocks);
2) Model of heat transfer from the internal source of heating to the tube surface;
3) Model of temperature fields retiming in the tube wall;

4) Model of deformation and breaking of a tube under local thermal action and internal pressure which defines the mode of tube deformation during thermomechanical effect up to its rupture.

The mathematical model of heat transfer from the thermal source to the tube and transient redistribution of temperature field in the tube wall is based on the following on the following assumption:

1) Heat radiation (radiant heat exchange) is a mechanism for heat transfer from the heat source to the tube surface;

2) Convective heat transfer between tube surfaces and air/steam is essential;

3) Heat radiation from the tube surface during its heating is essential;

4) Processes of heat transfer due to heat conductivity can only be considered on the median surface of the tube, and heat-balance equations are entered for the entire tube wall;

5) The calculated heating temperature of the tube surface corresponds to average temperature through the thickness of the tube wall;

6) The reference tube wall temperature is determined on the basis of the experiment conditions;

The formulated assumptions of the mathematical model are based:

- on the analysis of experimental data about heating source;
- on comparison of characteristic heat transfer times through the steam and typical times for tube wall heating.

The thermophysical source model is based on the assumption that initially its temperature has a prescribed value (“instantaneous firing”), determined by physical and chemical parameters of a thermite block, and the external surface temperature decreases by the exponential law. As it is shown below, such simple (two-parametric) model of a source allows to modeling tube heating with acceptable accuracy.

The problem on searching for the distribution of temperature in the tube was reformulated as a 2D one on the basis of a linear approximation of a heat flow in radial (across the wall) direction. This transformation enables to simplify essentially the solution and to calculate rather precisely (square-law approximation) temperature gradient in the radial direction.

Further, the model of a piecewise-homogeneous tube is used along its generatrix consisting of separate elements of constant Young’s modulus complying with average temperature within the tube fragmentation element (Goldstein at al. [1]). The given model is similar to a finite-elemental model. Note, that the advanced approach is based on using the exact solution of equations describing the mode of tube deformation within the framework of the shell theory. That makes possible big elements (in comparison with linear or quadratic approximation in the method of finite elements) and reduces the computing time and required computer resources.

On thermal exposure and internal pressure the model of tube deformation and rupture is based on the following assumptions:

1) Temperature distribution is specified by maximal temperature in the central (vertically) part of the tube and by the gradients directed along the tube generatrix and its perimeter;

2) Temperature gradients along the tube perimeter are small (only first term of an asymptotic expansion is accounted for);

3) The temperature dependence on the Young moduli induces heterogeneity of deformation properties;

4) Deformation of a tube material can be described by the generalized Hook law for physically nonlinear, isotropic medium with the Young moduli depending on temperature;

5) Deformation of a tube can be described within the framework of the shell theory;

6) The tube deformation mode is dependent on the induced heterogeneity along the tube generatrix at its heating by a local source;

7) Average longitudinal pressure is absent;

8) The limit tube state is determined by attaining a principal tensile stresses the value related to ultimate strength in view of it temperature dependence.

The developed mathematical models were implemented numerically as a computer program for computing temperature and temperature dependence of the critical pressure through the tube section, and also to define the time from the heating source initiation up to its rupture at various geometric, thermophysical and mechanical parameters of experiment.

NUMERICAL MODELING OF FC HEATING, DEFORMATION AND RUPTURE

Let us proceed to the analysis and comparison of the estimated tube rupture time and temperature dynamics with experimental data (Medvedeva at al. [2]). Figure 2 represents experimental temperature data (symbols) according to indications of thermocouples T.03.09 and T.03.10, registered in research experiment performed at December 04, 2001 on TKR-F rig. The thermocouples were located in the most heated tube section, and, as a consequence, the tube was broken just in this section. Note, that zero in displaying the experimental data corresponds to "initiation" of the specified thermocouples indications.

Let us calculate the dynamics of the tube wall temperature before tube rupture and critical pressure at this moment, on the parameters given below:

- Reference source temperature – 1800 °C;
- Representative source time (time of reduction of surface temperature by e = 2.718 times) - 600 sec;
- Tube material - Zr + 2.5%Nb alloy;
- Initial tube temperature - 290 °C;
- Pressure – 7.8 MPa;
- Factor of convective heat exchange with steam - 200 W / (m^2K);
- Factor of convective heat exchange with air - 10 W / (m^2K);
- Factor of block emitting/absorption - 0.9;
- Factor of tube emitting/absorption - 0.5.

The computed time dependence of the average (through the wall thickness) temperature is given in Figure 2 (the curve). Note, that the presented data correspond to the axisymmetric placing of the heating source.

Evidently, at the initial stage the numerical temperature values exceed experimental data that result from the delay of thermocouple indications, fixed at the external tube surface, in relation to the average wall temperature. In six seconds of the process the calculated values are within the limits determined by the experimental data. Note, that azimuthal (circular) temperature differential registered by thermocouples in the section studied resulted from radial displacement of the heating source about the tube axis or with heterogeneity of optical properties of its internal surface.

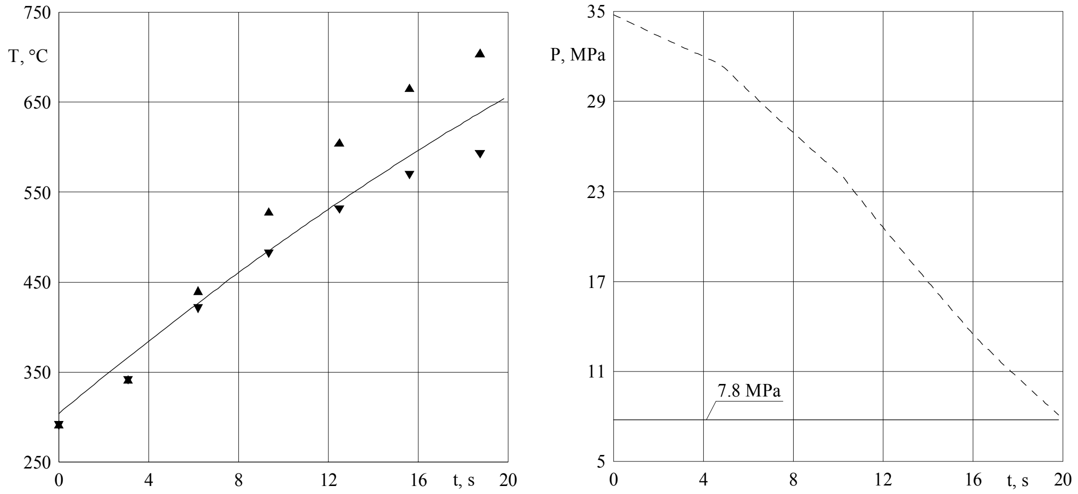

Figure 2: The dynamics of temperature and critical pressure

Figure 2 also represents numerical values of critical pressure change (dotted curve) according to the aforementioned solution of the problem. The internal pressure of tube rupture decreases with the tube temperature growth and the calculated pressure values determine the tube rupture time. Apparently, by twentieth second of the process critical pressure becomes equal to internal pressure in the tube that completely agrees with the experimental data (the horizontal line in Figure 3, right).

Figure 3 represents similar numerical and experimental data obtained within the framework of an analysis of research experiment on TKR-F rig carried out on March 23, 2002. As before, experimental data on temperature are given according to thermocouples indications located in the most heated tube section (thermocouples T.03.15 and T.03.16). The reference temperature of the tube and internal pressure in calculation were specified according to conditions of the experiment carried out (300 °C and 7.9 MPa). In this case, the characteristic cooling time of the source was equal to 100 sec. Other calculated parameters remained the same.

One can see (Figure 3) that the nature of a qualitative relation between the experimental and numerical data on temperature dynamics is similar to the aforementioned case - at initial heating stage the numerical values exceed thermocouples indications, and then (by the sixteenth second of the process) appear in the observed range. As it was presented above, the effect is caused by the lag of thermocouples indications from the average (through the thickness) tube wall temperatures. Computed temperature dynamics provides critical pressure by the twenty-eighth second of the heating process that completely agrees with the experimental data.

Comparison of the numerical and experimental data for test carried out on June 24, 2002 on TKR-F rig with a zirconium tube, is rather difficult since the maximal temperature fixed by thermocouples during the test equals 553°C. This temperature is much less than one related to tube rupture (about 700°C) at the pressure 8 MPa. Consequently, in the course of tube heating the zones of its local overheating were formed out of the thermocouples location that confirmed by visual examination.

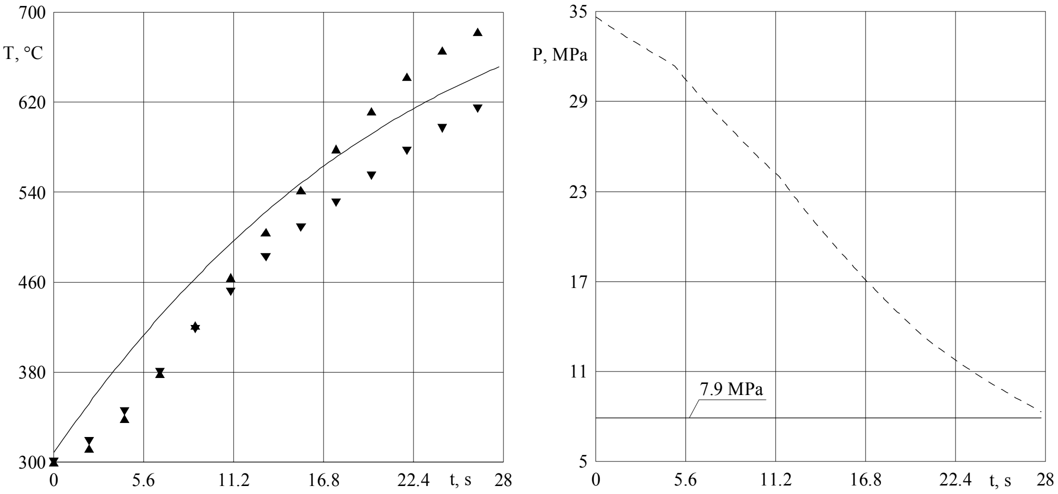

Figure 3: The dynamics of temperature and critical pressure

An analysis of the heating process, deformation and rupture of zirconium tube in the structure of a graphite column is the next stage of the experimental studies on TKR-F rig. Mathematical models of tube heating and deformation, which enable to analyze the tube heating and deformation processes with regard to graphite stack influence, have been developed in order to perform the numerical modeling of the above processes. Test calculations of temperature fields distribution in the tube and graphite were performed depending on thermophysical characteristics of the tube, graphite and thermite block at specified geometric parameters. The calculations demonstrated that the characteristic time of the tube heating in a graphite column prior to attaining maximal temperature is essentially higher (5-6 times), than for the tube without graphite. This fact requires using more powerful source with shorter time for heat emission.

4 CONCLUSION

Mathematical models of heat transfer from the source to a tube, heating, deformation and rupture of a tube have been developed and implemented numerically as a computer program. The numerical values and the experimental data fit good. The developed mathematical models could serve as a basis for creation of the integrated code, which should serve as the computing tool during an analysis of processes in the RBMK reactor.

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