Numerical-experimental analysis of contact interactions in main connector of reactor plant VVER-1000

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Abstract. Each connector has a gasket in his composition that allows obtaining tightness of this connection. Reliable tightness allows avoiding leakages of working substance into external environment. Problem of reliable tightness is actual for connectors of nuclear plant since to these connectors are presenting elevated requirements to safety. Those requirements are reaching by calculation for tightness and strength or experimental confirmation. Calculation of tightness and strength is performing by finite element method in this article. The results of numerical simulation are comparing with results of experiment which is performing by method of digital image correlation.

1. Introduction
Sealing devices are relating to main elements for industrial construction. The main purpose of those devices is elimination of leakages of working substance in external environment.

Sealing gaskets have a changing of shape during exploitation. This leads to contact area changing which gives a more reliable tightness. Such changing of shape is obtaining by using materials with high plasticity properties or hyperplastic properties. Those devices allow eliminating or decreasing leakages through connector edges.

The depressurization of connector is possible by following reasons: presence of roughness at surfaces of connector, waviness of sealing device, defects, temperature and load deformations during exploitation. This problem is especially urgent for tightness and strength of sealing devices in the first contour of reactor plant. These systems are important from the safety point of view.

The designing of connectors is allows to establish a necessary strength and tightness of sealing devices to eliminate the radioactive coolant leakages into external environment thereby ensuring of non-accident work of reactor plant and radioactive safety. The engineers are guided by simplicity and perfection in designing of the main connector. Thereby, the following factors are taking into account, which arising during exploitation: high temperature, high pressure, neutron- or gamma-radiation, mechanical properties changing and i.e. The additional factor in the connector designing is existence of large zones of connections and the loads application.

Flanged connectors are using for reactor plants type VVER. Those connectors are able to apply a whole load to gaskets from the power elements of connector. Also, this type of connectors is able to compressing gaskets until obtaining necessary shape, while remaining loadings are applying to the limiting ring [1].
Contact loadings in the connector are very important in tightness estimation. The depressurization may arise due low load application. Low load may be occurred as result of irregular crimping of gasket during installation, decreasing of crimping during stress relaxation under high temperature or displacements of flanges under inner pressure.

2. Methods
Tightness estimation is performed by numerical simulation. The goal of this stage was a performing simulation for installation and crimping of gaskets by flanges. The results of simulation were validated with digital image correlation method.

2.1. Finite element method
Computation part of this simulation was performed with using finite element method. The main principle of this method is dividing of whole domain for subregions (elements) and solution searching of differential equations as function for those subregions.

This function is approximated in specific subregions by polynomials of 1st, 2nd or 3rd order (form function). Values of function at nodes of subregions are unknowns and they are task solution. The searching of approximate coefficients is going between borders of element (equality of neighbor functions). Those coefficients are expressed through the values of function in nodes of elements. The linear algebraic system of equations are composing based on those coefficients, where number of equations is equals to number of unknowns values in nodes. Solution of initial system is finding at those nodes [2].

Two contact pairs were defined in connector:
- Flange – gasket (Figure 1), where the flange is defined as master surface and the gasket is defined as slave surface.
- Flange top – gasket (Figure 2), where the flange top is defined as master surface and the gasket defined as slave surface.

2.2. Digital image correlation method
Digital image correlation method (Figure 3) is intended for analyzing of deformable shape of object surfaces. The displacements of same points are fixing at surface before and after load application. Those points a chaotically are painting on research surface and them are called speckle-structure. This experimental method allows registering the fields of displacements and calculating deformations as for static loading to body, as for dynamic loading.

The procedure of method realization is includes following stages:
- Preparation of sample.
- Setting up, aiming and focusing of camera at sample.
- Cameras calibration.
- Execution of experiment and images registration.
- Correlation of images.
- Data analyzing.
All surfaces are dividing for subregions during the processing of obtained images. Displacements of speckle-structure are analyzing within of each subregion. Method postulates, that distribution of displacements within of current subregion could be approximate to simple and known form function, which has bounded series of defined numerical parameters. Total function of displacements of elastic strains appears to linear superposition for partial function data. Digital images are processed with using of correlation analysis method of accidental functions, that characterizing intensity (level of brightness) in each pixel of image. Fragments of image of loaded sample are comparing with reference image of non-deformable sample. Maximum value of correlation of two structures defines searching parameters of function within of each subregion. Condition of correlation will defines length and direction of average displacement vector of subregion in case of approximation of simple parallel translation of subregion with plane deforming. The partial derivatives are calculating from obtained function of displacements which allows obtaining components of the strain tensor [3].

**Figure 3.** The schematic diagram of installation for measuring of displacement vector by digital image correlation method (1 – sample, 2 – lighter, 3 – camera, 4 – computer).

### 3. Materials

Priority is given to the heat-resistant materials when choosing materials for flange. Those materials are allows to works with temperatures in range for 650 °C and pressures in range for 25 MPa. Usually, austenitic cladding is using for hardening of flange. Construction steel [4] with 0.15 % of carbon, 2 % of chrome, 1 % of molybdenum, 0.35 % of vanadium and clear pure impurities is using for this simulation (15CrMoVA) as flange of reactor plant.

Choosing materials for gaskets depends from working environment, temperature and pressures in connector. Necessary properties for these connectors:

- High plasticity.
- High elasticity.
- Heat-resistance.
- Resistance to aggressive environments.
- Resistance to radioactive radiation.
- Lack of adhesion.
- No corrosive effect for connector parts.
- Resistance to aging of material.
- Resistance to relaxation.
- Ecological cleanliness.
Usually copper and nickel are using for those purposes. Nickel gasket NP-2 was used for this simulation. Material properties (Figure 4) were obtained from experiment. The ten samples with 10 mm height and 5 mm diameter were prepared for experiment. Samples were tested for compression at testing machine INSTRON 5982. Results of experiment (the stress-strain diagram of NP-2 compressing) were processed by statistical processing methods.

![Figure 4. NP-2 stress-strain diagram.](image)

4. Results
The main connector of VVER-1000 (Figure 5) consists from flange, top flange and gaskets which are connecting by 54 pins. Summary loading of tightening of pins is equals to 379.8 MN [1].

![Figure 5. The main connector of nuclear plant VVER-1000. Finite element model.](image)

Sector with 0.1 degrees was built for simulation of contact interaction when the pins are tightened. Force of pins tightened was applied to flange top and equals to 105.5 kN. Model was built with using 8-edge hexahedron elements type C4D8. Minimal size of element was chosen from results mesh convergence investigation and it is equals to 0.1 mm. Total number of nodes equals to 208885, total number of elements equals to 103206.
Figure 6. Contact pressure in connector.

Figure 7. Mises intensity (a) and plastic strain (b).

Figure 8. FE model of linear part.

Figure 9. Experiment case with linear part.
Linear part of FE model (Figure 8) was created for comparison with experiment. Experimental cases were realized on test machine INSTRON 5982 (Figure 9) with using VIC-3D for obtaining fields of displacements and deformations. Samples were created from 15CrMoVA and NP-2 materials. The dimensions of the model were taken from recalculation of tightening forces of pins to maximal load of test machine 100 kN. Each step was registered and compared with reference image.

5. Conclusion
Numerical simulation shows that stresses (Figure 7a) in the connector are too high. Gaskets and flanges are reaching plasticity. Plasticity of gaskets allows obtaining tightness in the connector. Also, behavior of gaskets is confirmed by distribution of contact pressure along gaskets. This distribution (Figure 6) is showing that two peaks arising in contact area of gaskets that talking about more effective tightness in those zones.

But, in same time, plasticity in flanges leading to indentions and fractures at contact surfaces during exploitation. Plastic strain field (Figure 7b) shows location of indentions emerging on flanges. Indentions and fractures are grows during following cycles. Respectively, connector requires using gaskets with larger diameter or additional repairs after using old gaskets.

The fields of Mises strains are showing a good visual matching of strain distribution between simulation (Figure 10) and experiment (Figure 11) in range of 1%. This shows reliability of using numerical methods for estimation of tightness in main connector of reactor plant VVER-1000.

References
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