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Study of functional characteristics for safety system check valve using scaled model

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Abstract

The paper provides results of experimental scale model studies of functional characteristics of a check valve used in the safety system of a liquid metal cooled reactor. The proposed check valve design with a hollow ball as a blocking element has a number of substantial advantages compared with the most widely spread valves with disc type flaps used as blocking elements. The advantages are valve operation independent of functioning of other safety systems and absence of friction pairs. The need to conduct experimental studies is determined both by the novelty of the proposed check valve design and by absence of verified computational validation methods for functioning of this type of valves. In this connection, the paper presents a computational validation method for hydrodynamic parameters of the proposed check valve design and similitude parameters describing hydrodynamic characteristics of the check valve – numeric values of the similitude parameters were obtained through calculations made by the ANSYSCFX commercial hydrodynamic code. The paper describes the experimental model of the check valve with two alternative options for the blocking element – one in the form of a hollow ball in a support bowl; and another one, in the form of a semi sphere on a guide rod going through the support sleeve on the valve spindle. Provided is a brief description of the test facility. Hydrodynamic characteristics of the check valve model obtained in experimental studies are shown in diagrams as functions of some design and operation parameters of the model.

Keywords: Liquid metal cooled reactor; Safety system; Check valve; Hydrodynamic force; Similarity criteria; Check valve model; Test facility.

Introduction

In the development of prospective NPPs with liquid metal coolant (LMC) [1] special attention is paid to the design and computational validation of the safety systems [2].

Check valve (CV) is one of the elements of the safety system of a LMC reactor (Picture 1), blocking the coolant flow in the system during regular operation of the reactor and opening the coolant flow in the modes demanding the safety system operation. The check valve of a liquid metal cooled reactor descried in [3] served as prototype for the design shown in the picture.

A substantial advantage of the CV design as compared with the most widely spread valves with disc type flaps used as blocking elements is, on the one hand, valve operation independent of functioning of other systems important for reactor safety and, on the other hand, absence of interrelated design elements and friction pairs. The blocking element moves in the valve chamber solely due to coolant acting on it.

At the moment there are neither proven CV designs of this type nor verified computational methods for them.

In view of the above a set of experimental studies was developed the first stage of which required the hydrodynamic characteristics of the check valve to be obtained on a scaled model. These studies were performed on the testing facility located at the JSC «Afrikantov OKBM».

Problem definition

The main difficulty for computational validation of the check valve design lies in the calculation of the coolant flow rate at

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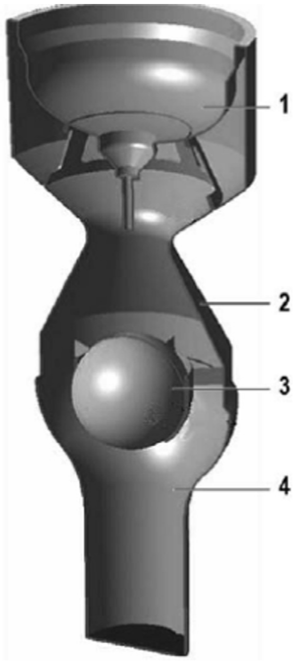

Picture 1. Check valve (sectional view): 1 – bottom of the heat exchanger; 2 – flow part of the valve; 3 – blocking element; 4 – supply pipe.

which the CV closes. This functional characteristic of the general CV design working efficiency can be found from the balance equation for forces acting on the valve blocking element:

$$m\frac{dw_m}{d\tau} = F_y + (m_o - m)g, \tag{1}$$

where m_o, m – masses of the blocking element and coolant forced out by it, respectively, kg; w_m – velocity of the blocking element, m/s; τ – time, s; $g = 9.81$ m/s^2– free-fall acceleration; F_y – hydrodynamic force, N, acting on the blocking element from the coolant,

$$F_y = \int_s (p + \tau_W)dS, \tag{2}$$

where p – coolant pressure on the surface of the blocking element, Pa; $\tau_W = \mu_o dw_o/d\tau$ – shearing stress on the surface of the blocking element, N/m^2; w_o – coolant velocity, m/s; S – surface of the blocking element, m^2; μ_o – dynamic viscosity coefficient of the coolant, Pa s.

In studying the movement of the check valve blocking element under the action of hydrodynamic force [4] postulates as proven fact resulting from tests that once it started moving in the same direction as the coolant, the blocking element does not stop until it blocks the flow through the valve.

In view of the above for the calculation of the flow rate at which the CV closes Eq. (1) can be viewed in the stationary position determining the force created by the flow of coolant on the surface of the blocking element at which the element starts moving:

$$F_y = (m_o - m)g, \tag{3}$$

In order to select the scale for the check valve model in view of the capacity of the available experimental base the system consisting of Eqs. (2) and (3) was analyzed in order to choose the similarity criteria with the help of dimensional analysis [5,6].

The following four criteria were obtained as a result:

- Reynolds $Re = w_o \cdot l/v_o$;
- Euler $Eu = \Delta p/(\rho \cdot w_o^2)$;
- Froude $Fr = w_o^2/(g \cdot l)$;
- buoyancy $Bu = m_o/m$,

where l is a specific size equivalent to the radius of the outer surface of the CV blocking element.

Experimental model and testing facility

Computational analysis of the CV full-scale structure with the help of CFD ANSYSCFX code [7] (using the SST turbulence model) resulted in flow rates for liquid metal coolant required for check valve shutdown and pressure difference on CV at reactor safety system operation.

Based on the calculated hydrodynamic parameters for CV operation similarity criteria were as follows: $Re = 2.1 \times 10^6$; $Eu = 0.323$; $Fr = 0.458$; $Bu = 1.61$.

In view of the experimental results and similarity criteria obtained a model was created in the scale of 1:5 of the full-scale check valve. Fluid dynamic characteristics of the model with the blocking element in the form of a hollow ball (water-filled water-tight) initially placed in the support bowl (Picture 2a) or on thin-wall edges (Picture 2b) as well as a semi-sphere connected to the guide rod (Picture 2c) were studied in tests.

During preliminary testing the design with the blocking element in the form of a semi sphere connected to the guide rod was rejected based on the comparative analysis of hydrodynamic parameters obtained for the model and on the structural specifics. The model with the blocking element in the form of a hollow sphere initially located on thin-wall edges proved unworkable.

Therefore, the model with the blocking element in the form of a hollow ball initially located in a support bowl with a gap between its surface and the surface of the blocking element was taken as the “base” option. The gap size was chosen based on structural specifics.

When studying the function of hydrodynamic parameters on the position of the blocking element in the support bowl the ball was moved with the help of positioning screws in such a way that the gap increased in the direction of water movement and remained unchanged in the equatorial plane of the ball. In the extreme position of the blocking element in the support bowl its equatorial plane coincided with the edge of the support ball.

To obtain the function of LMC flow rate of the mass of the blocking element at model shutdown the hollow ball was filled with water for 50% and 100%.

To study the hydrodynamic properties of the CV model a testing facility was made (Picture 3) containing the model, circulation pump, hydrodynamic channel, connecting pipes, water flow rate and pressure difference measurement devices on the blocking element of the model.

Check valve model was tested at water flow rates from 0 to 50 m^3/h and water temperature of 33 °C. Testing error for flow