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A new method to evaluate the sealing reliability of the flanged connections for Molten Salt Reactors

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HIGHLIGHTS

- We novelly valuate the sealing reliability of the flanged connections for MSRs.
- We focus on the passive decrease of the leak impetus in flanged connections.
- The modified flanged connections are acquired a sealing ability of self-adjustment.
- Effects of redesigned flange configurations on molten salt leakage are discussed.

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ABSTRACT

The Thorium based Molten Salt Reactor (TMSR) project is a future Generation IV nuclear reactor system proposed by the Chinese Academy of Sciences with the strategic goal of meeting the growing energy needs in the Chinese economic development and social progress. It is based on liquid salts served as both fuel and primary coolant and consequently great challenges are brought into the sealing of the flanged connections. In this study, an improved prototype flange assembly is performed on the strength of the Freeze-Flange initially developed by Oak Ridge National Laboratory (ORNL). The calculation results of the finite element model established to analyze the temperature profile of the Freeze-Flange agree well with the experimental data, which indicates that the numerical simulation method is credible. For further consideration, the ideal-gas thermodynamic model, together with the mathematical approximation, is novelly borrowed to theoretically evaluate the sealing performance of the modified Freeze-Flange and the traditional double gaskets bolted flange joint. This study focuses on the passive decrease of the leak driving force due to multiple gaskets introduced in flanged connections for MSR. The effects of the redesigned flange configuration on molten salt leakage resistance are discussed in detail.

1. Introduction

The Molten Salt Reactor (MSR) was selected by the Generation IV International Forum (GIF) as one of the six advanced nuclear reactors concepts for its favorable feature in inherent safety, economy, fuel cycle, and a lower pressure primary loop (GIF-IV, 2002; MacPherson, 1985; LeBlanc, 2010). In the recent decades, there has been a growing interest in MSRs. A Thorium based MSR (TMSR) development project was started by the Shanghai Institute of Applied Physics, Chinese Academy of Sciences (SINAP) in 2011. Several research and development (R&D) projects on MSRs' technologies were conducted by some countries and institutes benefiting from the past experience of molten salt technologies acquired at Oak Ridge National Laboratory (ORNL) (Guo et al., 2013). The MSRs use liquid salts as both fuel and primary coolant, therefore the technology is essentially different from the traditional solid fueled reactors. It has brought great challenges into the sealing of flanged connections which is very common in the pressure vessels and piping systems of nuclear reactors. Prevention against liquid salt leakage is the primary function for flange assemblies in MSRs, as the sealing performance is directly related to the overall system safety, hence the necessity of study in depth.

There are two factors causing the leakage of flange assemblies' face seal: The one, necessary condition for leakage occurring, i.e. tiny holes or cracks in the seal face caused by manufacturing or

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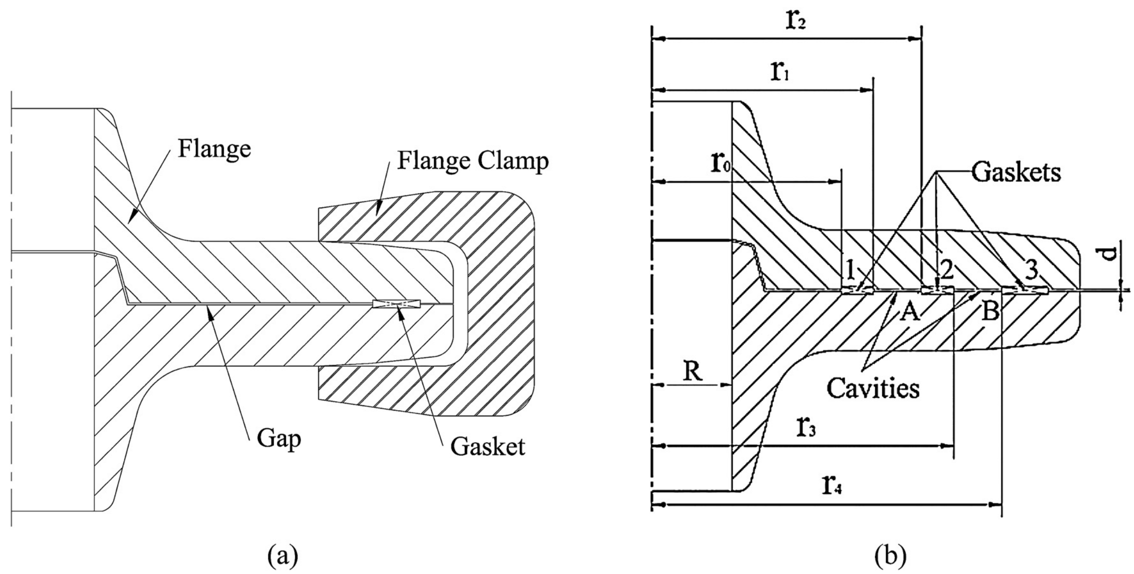

Fig. 1. Cross section of (a) the Freeze-Flange and clamp in MSRE and (b) the modified one, where the clamp is not marked out.

construction error etc. The other, the leaking driven force, i.e. the differential pressure between the two sides of the leak proof seal. In general, the fluid leakage may be stopped or suppressed by means of eliminating or reducing either factors above (Fu and Zhang, 2011). Since the seal structure is one of the key factors affecting the sealing behavior, many researchers have studied the seal structural optimization using finite element analysis (FEA). Izumi et al. (2009) investigated the double-nut tightening method and the spring washer to resist self-loosening with three dimensional FEA, while Choi and Seo (2011) conducted the shape optimization of a torus seal under multiple loading conditions with the linearized stress constrains on the basis of the stress categories in the AMSE code section III. The failure mode of mechanical seals and the various cause events to help in taking appropriate steps to improve sealing reliability are discussed by Singh et al. (2012). All these studies have basically regarded the traditional bolted flange joints. Nevertheless, mathematical design techniques concerning decreasing leak momentum have rarely been taken into account. Historically, an innovative flange assembly termed Freeze-Flange was firstly proposed and developed to undertake in an experimental MSR (MSRE) at the ORNL (Robertson, 1965). Since then, although many research and development in the molten salt related technologies are carried out, few studies on the Freeze-Flange were reported.

In this study, a modified prototype flange assembly was designed based on the finite element thermal analysis and verified by experimental results. The ideal-gas thermodynamic theory was used to analyze the influence of the flanged connections with more than one gasket on leakage prevention, and the passive reduction in the impulse of leakage owing to double or more gaskets introduced in the present study will be discussed.

2. Freeze-Flange assembly configuration

The Freeze-Flange designed in the MSRE is described in Fig. 1(a) (Robertson, 1965). It consists of a male flange, a female flange, clamps, a gasket and a salt screen. The flange is about 580 mm in outside diameter and roughly 38 mm thick when measured through the thickest portion of the flange face. Two semicircular clamps are compelled around the outer edge of the flanges to assemble the male and female flanges together. A 1 mm wide gap containing a salt screen is provided between the flanges. One groove with base diameter of about 527 mm in the face of both the male and female flanges is machined to accommodate the ring gasket. The salt screen primarily provides a convenient way to withdraw the frozen salt as a whole cake when the connection is disassembled.

A modified Freeze-Flange assembly selected as an example is shown in Fig. 1(b), where the clamp is not marked out. The following modifications are made for the new Freeze-Flange. Increasing the gasket groove number from one to two or more, accordingly more annulus chambers are created. The metal seals, the silicon carbide seals or the graphite gaskets etc., which can be used for high temperature wear and high corrosion resistance, are feasible candidate for the gaskets.

3. Analysis and discussion

In the process of sealing reliability evaluation, the steady heat transfer behavior analysis is firstly performed since the temperature profile plays a significant role in the sealing performance of the Freeze-Flange. Then theoretical analysis of the thermodynamic properties of the modified flange assembly is carried out by virtue of the formulation of ideal-gas and the mathematical methods. Based on the analytic solutions, the sealing performance of the structural redesigned flanged connection will be evaluated.

3.1. Temperature profile of the Freeze-Flange

Boundary conditions are described below. With the finite element commercial software of ANSYS 14.0 (ANSYS Inc., 2012), the uninsulated Freeze-Flange is modeled. It is cooled by loss of heat to the atmosphere with a natural convective heat transfer coefficient of 10.0 $W/m^2 K$ and a surface normal total emissivity of 0.7 (Bergman et al., 2011) accompanied by an ambient temperature of 22 °C without any other sources of forced cooling. Additionally, some conditions of constant temperature such as 873 K and 973 K are independently applied to the inner surface of pipe to simulate different typical steady thermal cycles. The Freeze-Flange is made of the Hastelloy® N alloy, of which the thermal conductivities varying with temperatures are given in Table 1 (Davis, 2000).

It is easy to know that, although the number of the gaskets is changed, the cooling conditions and the thermal conducting mechanism of the modified Freeze-Flange are the same as the one in the