Experimental Study on Friction Force and Control Rod Drop Performance of CF2 Fuel Assembly Under Multiple Misalignment Conditions

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Date: 2024-05-29T00:00:00+00:00

Abstract

The CF series fuel assembly is a core component of the advanced third-generation nuclear power reactor independently developed by China National Nuclear Corporation (CNNC). To analyze the friction characteristics and rod drop performance of drive line moving components of the CF2 fuel assembly under multiple misalignment conditions in water and air environments, a 1:1 scale CF2 simulated fuel assembly combined with an independently designed and developed adjustable rotary top head was utilized to achieve, for the first time, the integration of multiple misalignment values, enabling scientific and accurate adjustment thereof. This methodology optimization for drive mechanism performance research yielded comprehensive data on friction forces and rod drop performance across the full stroke range under multiple misalignment conditions in both water and air media. The total rod drop time and rod-to-buffer time both increase with increasing misalignment value, whereas the buffer time remains essentially constant. The fuel assembly and control rods demonstrated satisfactory operation under maximum misalignment conditions, with friction forces remaining within allowable limits and no rod jamming phenomenon occurring under large misalignment conditions. These research results provide important experimental basis for the design finalization, safety assessment, and software development of the CF series fuel assemblies, and the methodology can be extended to subsequent research projects on fuel assemblies such as CF3.

Full Text

Abstract

CF series fuel assemblies are core components of advanced third-generation nuclear power reactors independently developed by China National Nuclear Corporation (CNNC). To analyze the friction force and rod drop performance of CF2 fuel assembly drive line moving parts in both water and air under multiple eccentricity conditions, a 1:1 simulated CF2 fuel assembly was used in conjunction with a self-developed adjustable rotating top cap. This integration of multiple eccentricity values was achieved for the first time, enabling scientific and accurate adjustment of various eccentric conditions. The methodology for studying drive mechanism performance was optimized, and comprehensive friction and rod drop performance data were obtained for the full stroke under multiple eccentricity conditions in both water and air media. The results show that total rod drop time and time to reach the buffer port increase with eccentricity, while buffer time remains essentially constant. The fuel assembly and control rod operated properly under maximum eccentricity conditions, with friction forces not exceeding allowable limits and no rod jamming occurring under large eccentricity conditions. These findings provide important experimental evidence for the design finalization, safety evaluation, and software development of CF series fuel assemblies, and the methodology can be extended to subsequent research projects on CF3 and other fuel assembly types.

Keywords: CF2 fuel assembly, rod drop performance, friction

Introduction

CF series fuel assemblies are core nuclear power components independently developed by CNNC[1]. Together with the drive mechanism, they constitute a critical part of the reactor in large pressurized water reactor nuclear power plants, directly affecting reactor operational stability and safety. The drive line has extremely strict alignment requirements to prevent excessive friction during operation that could lead to rod jamming. Therefore, any fuel assembly and related equipment development must undergo friction and rod drop testing to verify structural integrity and performance[2].

Traditional friction and rod drop performance tests are conducted only under small eccentricity conditions to obtain friction forces, rod drop curves, and other experimental data, making it impossible to analyze performance under multiple eccentricity conditions, particularly large eccentricities. Furthermore, comprehensive mechanical comparative analysis of drive mechanism friction forces throughout the full stroke in both water and air media has not been extensively studied.

This experimental study obtained CF2 fuel assembly mechanical and operational performance data under multiple eccentricity conditions in both air and static water. A specially designed test top cap was developed for friction and rod drop performance testing, enabling rapid continuous adjustment of eccentricity and solving the challenge of completing multiple eccentricity tests with a single top cap. This significantly improved drive line performance testing efficiency and yielded multiple sets of comparative performance data in air versus static water under different eccentricity conditions. The top cap design has been granted one authorized invention patent[3]. The comparative performance results provide important evidence for subsequent design improvements, safety evaluation, and software development of CF3 and other fuel assembly series.

1.1 CF2 Fuel Assembly

The CF2 fuel assembly consists of an upper nozzle component, lower nozzle component, and 264 fuel rods arranged in a 17$×$17 configuration. The fuel rod cladding material uses recrystallized Zr-4 alloy, offering excellent corrosion resistance and irradiation performance. The guide tube buffer structure was improved with added grid anti-hooking features, and particularly the leaf spring structure was optimized[4].

This test used a simulated component with identical structural dimensions and fluid characteristics to the actual assembly, with equivalent weight simulated using metal materials. The fuel assembly is installed in the square hole of the reactor internals' barrel, with the lower nozzle located at the lower core plate and positioned by two locating pins. The upper nozzle connects to the guide tube through locating pins, and sufficient compression force is provided by four sets of compression plate springs fixed at the top plate's four sides to ensure axial compression of the fuel assembly. A simplified diagram of the installed CF2 fuel assembly is shown in [Figure 1: see original paper].

1.2 Adjustable Rotating Top Cap

The adjustable rotating test top cap is a critical component for fuel assembly and drive line testing, with its structural schematic shown in [Figure 2: see original paper]. The drive line passes through the test top cap, connecting to the control rod below and the drive shaft above. When lifting or releasing the control rod, its movement speed directly determines nuclear reactor control sensitivity, while friction resistance caused by misalignment between the drive line and fuel assembly is the primary factor affecting this sensitivity. Eccentricity is achieved through the drive mechanism housing and upper support plate[5]. The main components of the newly developed rotating top cap include: sealed rotating parts, eccentric flange, rotating bolts, limit baffles, and scale rulers. The upper and lower flanges of the sealed rotating part connect the drive line to the pressure vessel. The key difference from conventional test top caps is the ability to achieve continuous adjustment of eccentricity between the drive line and fuel assembly through continuous flange rotation. The special sealing structure and high-precision scale ruler ensure accurate eccentricity results and stable test pressure on a single test top cap. This structural design enables rapid continuous eccentricity adjustment, significantly improving drive line performance testing efficiency and providing assurance for drive line and nuclear power software development. This test method can be widely applied to various eccentricity tests, offering significant importance for achieving precise alignment, shortening test cycles, and improving test efficiency.

1.3 Internal Components

The test internal components mainly consist of bellows assemblies, flow distribution tube assemblies, 吊篮 (core barrel) assemblies, and compression barrel assemblies. Both the 吊篮 and compression barrel assemblies are suspended on the internal table surface of the test pressure vessel and positioned and fixed with limit blocks. The primary functions of the internal components are to support and fix guide columns and fuel assemblies, maintain the relative positional relationship between guide columns, fuel assemblies, and drive mechanisms on the reactor, provide flow channels, and simulate environmental conditions of the drive line in the reactor. This approach achieves the purpose of simulating a set of drive lines in the reactor and conducting friction and rod drop tests out-of-pile.

1.4 Drive Mechanism

The control rod drive mechanism is a vertically stepping magnetic lifting mechanism assembled from components including the drive shaft, travel tube, gripper assembly, rod position indicator, and thermal sleeve. Installed on the reactor pressure vessel top cap and connected to the control rod assembly, its main functions are to lift or insert the control rod assembly within the fuel assembly, hold it at a certain height, or release it to allow rapid insertion under its own weight. This enables reactor startup, power regulation, power maintenance, and safe shutdown functions. This test used a domestically produced Type B drive mechanism with 225 steps set for the full stroke.

2 Test Apparatus

The test apparatus includes the loop system, instrumentation and measurement/control system, rod power cabinet and rod control/position system, and electrical system. The loop flow diagram is shown in [Figure 3: see original paper]. The loop system provides the required test environment and uses a vertical lifting device to conduct friction tests.

The instrumentation and measurement/control system monitors and controls test apparatus operating parameters and rapidly acquires test data. The measured parameters are listed in . The rod power cabinet provides regulated and rectified cyclic operating current to the three working coils of the drive mechanism. The rod control/position system enables automatic and manual reciprocating operation and rod drop actions of the drive mechanism, and automatically records the number of steps traveled.

3 Test Conditions

Based on the control rod's operating trajectory in the fuel assembly guide tube and the CF2 fuel assembly structure, the internal components were assembled with certain test margins. Eleven nominal values were selected within the 0–10 mm range as the eccentricity δ between the control rod drive mechanism centerline and the fuel assembly guide tube centerline. Through analysis and summary of actual reactor operating conditions, and to study friction characteristics at different control rod heights, eccentricity friction and rod drop performance tests were conducted at different axial heights under both static water and dry conditions. The total control rod height is 3571 mm, with 12 points selected within this height. hmax represents the control rod dropping to the bottom of the fuel assembly guide tube, i.e., the total length of the control rod. The specific parameter values are shown in .

To obtain accurate test data, friction forces in both air and static water were measured using the averaging method. Each measurement point was measured at least 10 times during drive shaft lifting, and the drive shaft movement speed was recorded. Similarly, full-height rod drop times under different eccentricity conditions in static water (treated deionized water) were measured, with at least 10 rod drop tests conducted for each condition. After each test, wear and deformation of test components were inspected and compared with pre-test conditions.

4 Test Results and Analysis

Using the above rotatable test top cap and test apparatus components, and simulating the actual reactor internals positioning method, alignment and re-alignment work was first completed under conditions of 5°C–40°C temperature, 0.1 MPa–3 MPa pressure, and air/deionized water (static water) media. After the re-alignment results met test requirements, 110 friction tests at 11 eccentricity values and different heights in both air and static water were completed, along with 11 full-height rod drop tests at 11 eccentricity values in static water.

4.1 Friction and Rod Drop Performance Research

Using a vertical lifting device to raise the drive shaft from the lowest to the highest position at approximately 0.9 m/min, data were collected and recorded throughout the process via electronic dynamometer. In air, the control rod is primarily subjected to gravity and mechanical friction. In water, it is additionally subjected to viscous drag and buoyancy. After system debugging, friction tests under different eccentricity conditions were completed in both air and static water.

Water was injected into the test loop and apparatus, submerging the control rod and fuel assembly completely. Using the rod control power cabinet, the control rod was raised to the 225-step height at a certain frequency, then the power was cut off for free-fall motion. The rod passed through the guide tube assembly and fuel assembly guide tube, finally dropping to the reduced-diameter section below the buffer segment. During this process, important parameters including rod drop speed, time, and height were collected.

4.1.1 Effect of Different Alignment Conditions on Friction [Figure 4: see original paper] shows comparative full-height friction data when raising the control rod from position 0 (lowest) to 225 steps (highest) at eccentricity values of 4.67 mm, 6.0 mm, and 9.4 mm in 22°C air. The results indicate that friction values gradually decrease as the rod position increases, then slowly rise, with a significant increase near the highest position. At the start of lifting, the control rod bullet tip is below the buffer segment. Since this area has a reduced diameter design with smaller clearance, metal-to-metal friction is relatively large. As lifting height increases and the control rod enters the larger-clearance area above the buffer segment, friction decreases rapidly. However, as control rod height continues to increase, the inclination angle of the portion remaining in the guide tube gradually increases, and the influence of the C-shaped groove inside the upper guide tube assembly causes friction to gradually increase.

Comparing data from the three different eccentricity conditions shows similar curve trends, with larger eccentricity values corresponding to relatively larger friction forces. At 4.67 mm eccentricity, friction at the lowest and highest positions was 26.5 N and 32.1 N, respectively. At 9.4 mm eccentricity, friction at the lowest and highest positions was 37.1 N and 39.2 N, respectively.

[Figure 5: see original paper] shows comparative full-height friction data in 18°C static water at eccentricity values of 4.67 mm, 6.0 mm, and 9.4 mm. The results show that friction values in static water gradually decrease as rod position increases, then stabilize, with a slight increase near the highest position. Similar to air tests, friction is relatively large at the start of lifting due to the same reasons. As lifting height increases, friction decreases rapidly. As control rod height continues to increase, water forms a liquid film in the narrow space between the control rod and guide tube, reducing the influence of the portion remaining in the guide tube and the C-shaped groove inside the upper guide tube assembly on friction, resulting in relatively stable friction magnitude. Near the highest position, the relative water effect diminishes, causing a slight friction increase.

Comparing static water data from the three eccentricity conditions shows similar curve trends, with larger eccentricity values corresponding to larger friction forces at both lowest and highest positions. At intermediate heights, larger eccentricity conditions show greater offset and thus larger friction, while smaller eccentricity conditions show little difference in friction magnitude, indicating that in such conditions, water effects and eccentricity offset effects are essentially equivalent. In static water at 4.67 mm eccentricity, friction at the lowest and highest positions was 54.8 N and 39.5 N, respectively. At 9.4 mm eccentricity, friction at the lowest and highest positions was 62.8 N and 44.1 N, respectively.

According to fluid kinematics stress principles, shear stress τ equals the product of velocity gradient and dynamic viscosity coefficient . Comparing friction results in static water and air shows that due to water's higher dynamic viscosity coefficient, friction values in static water are generally larger than in air throughout the full height range. However, as the control rod gradually lifts, friction increase in air is much greater than in static water. The maximum friction in air occurs at the highest position, while in static water it occurs at the lowest position.

4.1.2 Effect of Different Alignment Conditions on Rod Drop Performance [Figure 6: see original paper] shows the full-height rod drop curve under conditions of 16°C temperature, 0.3 MPa pressure, and 4.67 mm eccentricity in static water. Observing the vibration and displacement curves reveals that when the armature opens, the absolute vibration value changes significantly while displacement decreases rapidly, indicating the control rod is in an accelerated descent phase with continuously increasing speed until control rod gravity balances the upward resultant force, after which speed gradually stabilizes. Near the buffer segment, speed decreases rapidly. When dropping to the guide tube bottom, the control rod impacts the bottom surface causing large vibration changes, which eventually stabilize after repeated oscillations.

Comparing rod drop performance, velocity, displacement, and vibration curves from the other 10 eccentricity conditions shows consistent patterns with [Figure 6: see original paper]. Four nominal values were selected to study full-height rod drop parameters, as shown in . The results indicate that as eccentricity increases, friction during rod operation increases correspondingly (see Figures 4 and 5), causing maximum rod drop speed to gradually decrease while total rod drop time and time to reach the buffer port increase accordingly. The data shows minimal influence of eccentricity on buffer time, which remains essentially constant, indicating that the buffer segment structure can generate large frictional resistance to rapidly reduce rod speed. This corroborates the test results in Figure 5 and validates the rationality of CF2 fuel assembly design. The minimum rod drop time occurred at the smallest eccentricity condition (nominal 0 mm), with time to buffer port of 1.049 s and time to bottom of 1.477 s. The maximum rod drop time occurred at the largest eccentricity condition (nominal 9.4 mm), with buffer time of 1.183 s and time to bottom of 1.589 s.

Conclusions

Using the self-developed sealed rotating test top cap, rapid alignment between the drive line and reactor internals was achieved, significantly improving test efficiency and reducing test costs. Friction and rod drop performance tests were conducted under different eccentricity conditions, expanding research scope in this field, obtaining multiple sets of friction data and rod drop performance curves for comparative study. The main conclusions are:

1. Using the self-developed test top cap for alignment work innovatively

changed traditional drive mechanism alignment methods, achieving innovation in rapid multi-eccentricity alignment.

2. Comparative research on friction values in air versus static water was conducted under full-stroke, multi-eccentricity conditions. Friction in static water is generally larger than in air throughout the full stroke range, but as the control rod gradually lifts, friction increase in air is much greater than in static water.
3. As eccentricity increases, friction during control rod operation increases correspondingly, causing total rod drop time and time to reach the buffer port to increase, while buffer time remains essentially constant.
4. Through multiple friction and rod drop performance tests, the fuel assembly and control rod operated properly, friction magnitude did not exceed limit values, and no rod jamming occurred under maximum eccentricity conditions, validating the rationality of CF2 fuel assembly design.

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