

## Study on Flow-Accelerated Corrosion Behavior of Main Coolant Pump in Lead-Cooled Fast Reactors

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### Abstract

The advancement and deployment of lead-cooled fast reactors (LFRs) are significantly hindered by the corrosive nature of lead-bismuth eutectic (LBE) coolant, which adversely affects internal components, including the main coolant pump (MCP). This corrosion can lead to structural failures, posing serious risks to reactor operational safety. In this study, a computational fluid dynamics (CFD) based mathematical model of an axial flow pump in a lead-bismuth reactor was developed and validated using experimental data. Numerical simulations of the MCP were conducted under various operational conditions using the SST  $k-\omega$  turbulence model. The results revealed that the blade surface skin friction coefficient ( $C_f$ ) reaches its maximum at the blade inlet edge. Under standard operating conditions, the peak  $C_f$  at the blade leading edge is minimized; however, when under the operating conditions of 0.8Q0 and 1.2Q0, the peak value of  $C_f$  increased by approximately 36.3% and 72.7% respectively compared to the rated operating conditions. This will result in the MCP being unable to operate stably under eccentric working conditions. Deviations from these conditions cause a rapid increase in  $C_f$  at this location. Additionally,  $C_f$  at the blade leading edge exhibited a positive correlation with the velocity gradient of the LBE. This study provides valuable insights for optimizing the hydraulic design of MCP in LFRs and for further investigation into the structural aspects of reactor flow channels.

## Full Text

# Flow-Accelerated Corrosion Behavior of the Main Coolant Pump in Lead-Cooled Fast Reactors

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**Abstract:** The advancement and deployment of lead-cooled fast reactors (LFRs) are significantly hindered by the corrosive nature of lead-bismuth eutectic (LBE) coolant, which adversely affects internal components including the main coolant pump (MCP). This corrosion can lead to structural failures, posing serious risks to reactor operational safety. In this study, a computational fluid dynamics (CFD) based mathematical model of an axial flow pump in a lead-bismuth reactor was developed and validated using experimental data. Numerical simulations of the MCP were conducted under various operational conditions using the SST  $k-\omega$  turbulence model. The results revealed that the blade surface skin friction coefficient ( $C_f$ ) reaches its maximum at the blade inlet edge. Under standard operating conditions, the peak  $C_f$  at the blade leading edge is minimized; however, under operating conditions of  $0.8Q_0$  and  $1.2Q_0$ , the peak value of  $C_f$  increased by approximately 36.3% and 72.7% respectively compared to rated operating conditions. This will result in the MCP being unable to operate stably under eccentric working conditions. Deviations from these conditions cause a rapid increase in  $C_f$  at this location. Additionally,  $C_f$  at the blade leading edge exhibited a positive correlation with the velocity gradient of the LBE. This study provides valuable insights for optimizing the hydraulic design of MCPs in LFRs and for further investigation into the structural aspects of reactor flow channels.

**Keywords:** Lead-Cooled Fast Reactor; Axial Flow Main Coolant Pump; Flow-Accelerated Corrosion; Wall Shear Stress

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## Introduction

The lead-cooled fast reactor (LFR) is a leading reactor type in Generation IV nuclear power technology, distinguished by its potential for modular, miniaturized, and movable designs due to the unique physical properties of lead-bismuth eutectic (LBE) [1][2]. However, the development of LFRs has been hindered by numerous unresolved engineering challenges, keeping most LFR projects worldwide in the experimental stage. Among these challenges, the high corrosiveness of the LBE coolant toward internal structural materials remains a critical issue limiting the advancement and deployment of LFR technology. Within the internal components of the reactor, the primary corrosion mechanism is flow-accelerated corrosion (FAC), a complex phenomenon driven by the dissolution of the protective oxide film on material surfaces by the coolant. This process results in material thinning and accelerated corrosion rates. Extensive research has shown a strong correlation between the FAC rate and flow velocity as shown in Fig. 1, with the FAC rate increasing significantly at higher flow velocities [3].

The MCP is the only moving component in the reactor, where the high-speed rotation of the impeller transfers energy to the lead-bismuth eutectic (LBE) to overcome circulation resistance. Due to its compact design and ease of maintenance, the axial flow configuration has become the preferred choice for MCPs in lead-cooled fast reactors (LFRs) and is widely adopted in many countries [4]. As shown in Fig. 2a, which illustrates a comparison of the axial flow impeller before and after operation in an LBE test stand, the initial failure of the LBE impeller occurred at the rim of the inlet side, where significant crimping deformation was observed [5]. Furthermore, Fig. 2b presents the results of a lead-bismuth MCP durability test conducted in Russia, showcasing the impeller after complete erosion.

Current research on MCPs in lead-bismuth reactors primarily focuses on hydraulic performance. For example, Guo [6] compared the hydraulic performance of an MCP model in both lead-bismuth eutectic (LBE) and water media, revealing minimal differences in head, with marginally superior hydraulic performance observed in LBE. Similarly, Wang [7] investigated the pressure pulsation in the MCP of LBE and demonstrated that viscosity has negligible impact on the pulsation coefficient, while the medium density exhibits a linear positive correlation with the pulsation amplitude at the inlet of the impeller.

Si [8] investigated flow-accelerated corrosion (FAC) in mild steel 90° elbows through a combined experimental and computational fluid dynamics (CFD) approach. Their results demonstrated that the inner surface of the elbows exhibited the highest corrosion rates, aligning with the CFD-predicted velocity profiles. In particular, the local velocity component within the inner curvature of the elbow was identified as a dominant driver of FAC. Similarly, Ali [9] designed a rotating cage apparatus coupled with CFD simulations to replicate FAC under lead-cooled fast reactor (LFR) flow conditions. Their work highlighted that elevated frictional shear stresses directly accelerate material degradation,

with FAC rates showing a positive correlation with both shear stress magnitude and flow velocity. Matai [10] extended this understanding by analyzing FAC in high-pressure pipelines with progressive contraction/expansion geometries. In contraction sections, flow velocity, turbulence kinetic energy, and frictional shear stress intensified downstream, while expansion sections exhibited secondary vortices induced by flow separation under reverse pressure gradients, amplifying the severity of FAC. Complementing these findings, Su [11] simulated flow fields in butterfly valve pipelines via CFD, revealing that localized peaks in frictional shear stress—coinciding with high-velocity zones—directly correlated with valve failure hotspots, confirming FAC as the primary failure mechanism. Further supporting this hydrodynamic FAC linkage, Utanohara [12] quantified FAC erosion rates downstream of orifice plates using a high-temperature water loop. Their experiments showed that erosion rates scaled with flow velocity, while concurrent CFD simulations established wall shear stress as a quantifiable predictor of FAC erosion, enabling empirical modeling of the process [13][14].

Collectively, these studies underscore that the high-speed operation of lead-bismuth reactor MCPs exacerbates FAC within internal flow components. Hydrodynamic factors—particularly flow velocity, surface roughness, and geometric design [15][16]—play pivotal roles in governing FAC severity. For instance, corrosion rates in circulating high-temperature LBE solutions exceed static conditions by 10–25 times [17][18][19]. Despite this, current research on LBE corrosion remains largely confined to static or low-velocity scenarios, neglecting the dynamic flow regimes characteristic of operational MCPs. This gap limits the ability to correlate real-world flow dynamics with FAC progression in critical components such as impellers and rotor systems.

The complexity of FAC mechanisms in LBE MCPs is further compounded by impurities within the coolant and cavitation phenomena induced by reactor operation. While acknowledging these multifactorial interactions, this study specifically isolates the hydrodynamic contribution to FAC by analyzing frictional shear stress distribution patterns across MCP flow components under varying operational conditions. By mapping these distributions to flow states, this work aims to establish predictive correlations between hydrodynamic parameters and FAC susceptibility, providing a foundation for optimizing MCP design to mitigate corrosion risks.

## Establishment of the Mathematical Model

### Lead-Bismuth MCP Model and Parameters

The research object, depicted in Fig. 3, features the following basic parameters: impeller diameter ( $D = 440$  mm), specific speed ( $ns = 570$ ), rated speed ( $n = 750$  r/min), flow rate of  $2050$  m<sup>3</sup>/h, head of  $5.6$  m, five impeller blades, nine guide vane blades, and an axial clearance of  $26$  mm between the impeller and guide vane. The three-dimensional model of the MCP is illustrated in Fig. 3 and comprises the suction, impeller, guide vane, and press-out sections.

## Numerical Calculation Methods and Settings

The lead–bismuth coolant consists of 44.5% lead and 55.5% bismuth by weight, characterized by low melting and high boiling points. At atmospheric pressure, it melts around 125.6°C and can reach a boiling point as high as 1670°C [20][21], exhibiting significant thermal expansion properties. The density and dynamic viscosity of lead-bismuth are temperature-dependent and remain constant at specific temperatures. For the calculations, the average operational temperature of 400°C in the Russian SVBR lead-cooled fast reactor served as a reference. Table 1 presents a comparison of the physical parameters of lead-bismuth and room temperature water at this operating temperature.

The impeller and guide vane passages of the axial-flow MCP exhibit significant adverse pressure gradients, which can trigger boundary layer separation. To address this phenomenon, the shear-stress-transport (SST)  $k-\omega$  turbulence model—developed by Menter as an improvement of the baseline model (BSL)  $k-\omega$ —was adopted for the modeling of turbulence [22][23]. This turbulence model integrates the robustness of the  $k-\omega$  formulation with the free-stream accuracy of the  $k-$  approach, enabling precise prediction of the onset and extent of flow separation under adverse pressure gradients through improved treatment of eddy viscosity.

The SST  $k-\omega$  model imposes strict requirements on the resolution of the near-wall mesh, necessitating the placement of the first grid layer within the viscous sublayer. However, achieving this is complicated by two factors: (1) geometrically complex twisted blades of axial pumps, which challenge uniform mesh refinement across curved surfaces, and (2) the high-Reynolds-number ( $Re > 10^6$ ) flow regime of the lead-bismuth eutectic (LBE) coolant, amplifying sensitivity to irregularities of the wall mesh. Compromises in mesh quality risk computational instability and inflated resource demands. Previous studies suggest that viscous sublayer resolution remains feasible under controlled conditions. Given the focus of this study on the distributions of frictional shear stress coefficients, directly governed by near-wall velocity gradients, the explicit resolution of the viscous sublayer was prioritized. Consequently, a boundary layer mesh with a growth rate of 1.1 was implemented across the impeller and guide vane surfaces (Fig. 4), balancing numerical stability with boundary layer fidelity.

Table 2 provides mesh details for each domain, including inlet, impeller, guide vane, and outlet sections, with quantities in millions of cells.

The high-temperature operation of lead-bismuth eutectic (LBE) poses significant experimental challenges, including equipment durability constraints and risks of harmful gas release. Consequently, hydraulic performance tests for hazardous heavy metal coolants such as LBE often substitute water as a working fluid. This substitution is theoretically justified by the axial pump head equation (Eq. 1) [24]:

$$H = \frac{U_2 V_{u2} - U_1 V_{u1}}{g}$$

where  $U$  and  $V_u$  represent the peripheral speed and circumferential velocity component, respectively. Crucially, the theoretical head depends solely on kinematic parameters ( $U$ ,  $V_u$ ) and is independent of medium-specific properties such as density or viscosity.

For convenience of research and statistics, the data extraction method is shown in Fig. 5, and the radial coefficient method is adopted to describe the flow state between each flow surface. The MCP blades and guide vanes are respectively composed of the hub, flange, leading edge, and trailing edge.

To validate this principle, numerical simulations of the MCP model were performed in two distinct media, and the theoretical head curves at the impeller outlet were compared (Fig. 6). The nearly overlapping curves confirm that macroscopic hydraulic performance, specifically energy transfer from impeller to fluid, remains consistent between Newtonian fluids despite differences in physical properties. This invariance enables the use of water as a safe and practical surrogate for LBE in preliminary hydraulic performance tests, ensuring experimental feasibility without compromising model validation accuracy.

Model testing is considered a crucial method for validating the reliability of numerical simulation results, as demonstrated for the multifunctional hydraulic machinery test platform (Fig. 7). During MCP condition testing, the measurement points were appropriately distributed along the entire energy curve, ensuring adequate stabilization time between successive operating points. Upon achieving stable experimental data, the measurements encompass the flow rate, head, rotational speed, shaft power, and other pertinent test parameters. The external characteristic distribution was calculated at five operating points ( $0.8Q_0$ ,  $0.9Q_0$ ,  $1.0Q_0$ ,  $1.1Q_0$ ,  $1.2Q_0$ ).

Comparing the simulated external characteristic curves with the experimental values (Fig. 8) reveals that the error between the experimental and simulated values under rated conditions is less than 5%, indicating the accuracy and reliability of the simulation method.

Fig. 9 illustrates the Y+ distribution of grids near the wall, showing the surface distribution of the impeller and guide vane, which satisfies the turbulence model requirements for wall grid utilization. The model conducts transient numerical calculations, setting the inlet boundary condition as the velocity inlet and the outlet boundary condition as the free outflow. The outer wall of the impeller in the water body adopts the inversion mode in the relative coordinate system while maintaining stationarity in the absolute coordinate system. The convergence accuracy was maintained at  $10^{-5}$ , with the total calculation time set to six cycles. The impeller rotates by  $3^\circ$  per time step, resulting in a transient calculation interval of 0.000115 s, where every 120 time steps corresponds to one impeller rotation.

The flow-assisted corrosion (FAC) process in the LBE MCP is complex, resulting in a variety of corrosion products that are difficult to quantify. Relevant research indicates that the mechanism of LBE erosion on materials during the FAC process is shown in Fig. 10, which can be divided into three stages. In the first stage, impeller blades driven by high-speed rotation work on the LBE, leading to electrochemical dissolution and a reduction in the thickness of the oxide film on the surfaces of the flow components. In the second stage, once the oxide film is disrupted by the LBE, the metal ions on the surfaces of the flow components react with the limited oxygen atoms present in the coolant, thereby regenerating a porous oxide film structure. In the third stage, the unstable oxide film structure on the surfaces of the flow components was continually disrupted by the LBE, perpetuating this cycle until the eventual failure of the flow-component structures occurred.

According to the assumption that no relationship exists between the cylindrical layers, the axial flow within the fluid mass point at the axis of the cylindrical surface was considered, with the radial flow at the fluid mass point adjacent to the surface being negligible compared to the mainstream velocity [24]. Therefore, each cylindrical surface or flow surface can be regarded as a combination of flow surfaces, representing the media flow within the axial pump. To analyze the variation in the friction shear stress coefficient in the MCP impeller and guide vane, as illustrated in Fig. 5, three cylindrical sections with radial coefficients of 0.1, 0.5, and 0.9 are examined within the impeller and guide vane domains. The relationship between the friction stress coefficient and radial coefficient is described in Eq. (2), where a radial coefficient of 0 corresponds to the hub and 1 corresponds to the rim.

The radial velocity distribution from the inlet to the outlet within the impeller and guide vane channels is shown in Fig. 11 and Fig. 12. The maximum radial velocity within the impeller passages is measured at less than 0.1 m/s, while in the guide vane passages, it reaches 0.3 m/s. Both values were significantly lower than the average flow velocity in their respective passages.

### Distribution Patterns of Frictional Shear Stress

According to the cylindrical layer independence hypothesis for axial flow pumps, the complex motion within the MCP can be simplified as a flow on a cylindrical surface. Although significant differences may exist in the structure of the local flow field between individual flow surfaces, the overall variation pattern of the flow parameters within each surface remains consistent. Consequently, the variation pattern of the coefficient of friction ( $C_f$ ) across different flow surfaces within the MCP can be inferred by analyzing the changes in  $C_f$  on the impeller and guide vane surfaces within a specific fully developed flow surface. The distribution of  $C_f$  on the impeller (Fig. 13) and guide vane (Fig. 14) surfaces at a radial coefficient of  $R^* = 0.95$  shows that the  $C_f$  variation trends for both the impeller and guide vane are similar within the same flow surface. However, the  $C_f$  peak at the leading edge of the impeller was approximately three times

greater than that of the guide vane. This disparity is attributed to the distinct operational principles of the impeller and guide vane. In axial flow pump design theory, the impeller, as the rotor component, rotates at a high speed to drive fluid flow, with the relative velocity at the impeller inlet resulting from the combination of axial and circumferential velocities. In contrast, the guide vane, as a stationary component, experiences an inlet velocity equal to the outlet velocity of the impeller, resulting in a similar  $C_f$  peak magnitude at the guide vane inlet and impeller outlet.

When the LBE comes into contact with the surfaces of the impeller and guide vane, the  $C_f$  at the leading edge (LE) experiences a sharp increase, rapidly reaching a peak before undergoing a steep decline. As the fluid flows across the pressure surface (PS) and suction surface (SS),  $C_f$  gradually decreases. At the trailing edge (TE), a slight increase in  $C_f$  was observed. The flow near the inlet edge induces acceleration, thinning the boundary layer and resulting in a rapid increase in the frictional shear stress coefficient. After the fluid passes through the edge of the blade inlet, the frictional shear stress coefficient decreased sharply, followed by a more stable downward trend. The shear stress on the suction surface was higher than that on the pressure surface. At the trailing edge, the frictional shear stress shows a slight increase, although it remains significantly lower than at the inlet edge. This increase in the frictional shear stress coefficient accelerated the erosion rate of the structural material, increasing the risk of erosion failure at the inlet edge.

### **Distribution Patterns of High-Velocity Regions within the Flow Passage**

The relative velocity at the leading edge within the impeller passage is determined by two components: the inflow velocity at the impeller inlet ( $V_m$ ) and the circumferential velocity generated by the impeller's high-speed rotation. These velocities were combined in accordance with the velocity-triangle principle, and the relative velocity at the impeller inlet is shown in Fig. 15. Although the inlet velocity of the MCP remains constant within the primary flow region, the circumferential velocity increases with the radius as a result of the impeller rotation. Consequently, the region of the highest relative velocity within the impeller passage is concentrated near the shroud.

The distribution of the high-velocity regions within the impeller passage of the MCP under the three operating conditions is shown in Fig. 16. The volume of the high-velocity LBE increased as the flow rate increased. It can be observed that these high-velocity regions are primarily distributed along the suction surface near the rim of the impeller. The backside of the blades induced a flow-acceleration effect on the LBE, leading to an increase in velocity. Consequently, high-velocity regions within the passage were concentrated on the suction surface near the shroud. However, when comparing the  $C_f$  distribution on the impeller surface, the  $C_f$  peak was observed at the leading edge of the impeller, whereas a steady decline was noted along the suction surface. By contrasting

the distribution of high-velocity regions within the passage with the actual Cf distribution, it can be concluded that for the MCP impeller structure, the highest risk of Flow-Accelerated Corrosion (FAC) failure occurs at the leading edge near the rim, rather than on the suction surface of the rim where the velocity is greatest. Therefore, for complex geometrical surfaces, the magnitude of Cf is influenced by factors beyond the surface velocity of the LBE.

### Mechanisms of Boundary Conditions Affecting the Cf on the Impeller Surface

To ascertain the distribution pattern of the frictional shear stress coefficient under various operating conditions, the coefficient was extracted at the impeller rim for three distinct scenarios, as illustrated in Fig. 17. The Cf at the impeller rim for  $1.2Q_0$  is slightly higher than that for  $0.8Q_0$ , whereas the Cf for  $1.0Q_0$  is significantly lower than that observed in the other conditions. The contour map of the Cf at the leading edge of the impeller demonstrates that peak Cf values under all three operating conditions occur at the leading edge position, where Cf is significantly greater than at other locations. An increase in the frictional shear stress coefficient accelerates the corrosion rate of structural materials, indicating that the risk of structural failure is highest at the leading edge of the MCP impeller.

Although peak Cf is consistently located at the leading edge, the specific position of this peak and its variation trend differ across the operating conditions. To facilitate the description of these positions, the transitional area between the leading edge and pressure surface was designated as  $\alpha$ , while the transitional area between the leading edge and suction surface was designated as  $\beta$ , as shown in Fig. ?? . At  $1.2Q_0$ , the Cf peak value of the leading edge of the impeller was 0.019, which was 26.6% higher than the Cf peak value of 0.015 under the  $0.8Q_0$  working condition. Under the working condition of  $1.0Q_0$ , the peak Cf of the leading edge of the impeller is only 0.011, which is much lower than  $0.8Q_0$  and  $1.2Q_0$  working conditions. At this stage, the Cf values at positions  $\alpha$  and  $\beta$  exhibit minimal discrepancy. However, when comparing with the  $0.8Q_0$  and  $1.2Q_0$  conditions (Fig. 17), a pronounced divergence in Cf distribution emerges between the  $\alpha$  and  $\beta$  locations. This contrast demonstrates that the distribution pattern of leading-edge Cf displays significant sensitivity to inflow conditions.

Under the  $1.0Q_0$  operating condition, the relative flow angle of the coolant matches the blade stagger angle exactly, resulting in zero incidence flow (Fig. 18). When LBE contacts the impeller leading edge, a distinct stagnation point forms near the central region. As the impeller rotates, the LBE undergoes flow acceleration around both sides of the stagnation point, causing a sharp increase in Cf. Under  $0.8Q_0$  operating conditions, the maximum Cf values are simultaneously achieved at both  $\alpha$  and  $\beta$  monitoring positions during this acceleration phase, followed by rapid downstream decay. While the relative inlet velocity of the impeller is lower than that under  $1.0Q_0$  conditions, the peak Cf value is approximately 36.3% higher. This clearly indicates that the magnitude

of inflow velocity is not the decisive factor determining the peak Cf value. The incidence is shown in Fig. 18; in the  $0.8Q_0$  condition, the incidence  $> 0$  and the stagnation point is located near position  $\alpha$ . The LBE flows around both  $\alpha$  and  $\beta$  positions from the stagnation point, but due to differences in the degree of flow deflection, significant variations occur in their peak Cf values.

Specifically, the peak Cf at position  $\beta$  reaches 0.015, while at position  $\alpha$  it is only 0.006—representing a 150% higher Cf value at  $\beta$  compared to  $\alpha$ . This conclusively demonstrates that multiple factors including inflow angle, stagnation point location, and geometric configuration all significantly influence the distribution of peak Cf values. In the  $0.8Q_0$  condition, the deflection angle through which the LBE flows around position  $\beta$  is significantly larger than that around position  $\alpha$ . Consequently, the flow deflection effect toward position  $\beta$  is stronger, the acceleration phenomenon at  $\beta$  is more pronounced, and thus the peak Cf value occurs at position  $\beta$ .

For the  $1.2Q_0$  operating condition, the incidence  $< 0$  and the stagnation point is located near position  $\beta$  (Fig. 18). With the LBE flowing around both  $\alpha$  and  $\beta$  positions, the peak Cf value at position  $\alpha$  reaches 0.019, while at position  $\beta$  it is only 0.003. The closer proximity of the stagnation point to position  $\beta$  results in weaker flow acceleration around  $\beta$ , leading to lower Cf peaks at this location. Conversely, the greater distance between the stagnation point and position  $\alpha$  produces stronger flow acceleration effects, explaining why the LBE exhibits significantly higher Cf peaks at  $\alpha$  compared to  $\beta$ . These observations thoroughly validate the aforementioned analysis.

To better visualize the Cf distribution pattern along the impeller leading edge, Fig. 20 presents the extracted Cf distributions for all three operating conditions according to the measurement positions indicated in Fig. 19. The horizontal axis represents radial distance while the vertical axis shows normalized region length. The plot clearly demonstrates that all Cf peaks consistently occur at either  $\alpha$  or  $\beta$  positions. The distribution of Cf shows a clear relationship with velocity. However, according to the aforementioned research observations, Cf depends more on the local velocity near the solid surface rather than the macroscopic velocity away from the solid surface. This phenomenon is also verified by the theoretical formula for Cf calculation. For this purpose, the velocity gradient vector distribution at the impeller leading edge is extracted, as shown in Fig. 21. It can be observed that the velocity gradient at the stagnation point is the smallest. As the LBE moves relatively toward both sides of the impeller leading edge, the velocity gradient gradually increases and reaches its maximum value at either the  $\alpha$  or  $\beta$  position. This figure more intuitively demonstrates that when operating conditions change, the stagnation point position at the impeller leading edge also shifts accordingly. The peak positions of the velocity gradient completely coincide with the peak positions of Cf, indicating that the peak Cf value of the impeller is determined by the magnitude of the velocity gradient at the leading edge. When the MCP of a lead-cooled fast reactor operates under rated conditions, the leading-edge Cf peak is minimized, which

can effectively reduce the risk of FAC failure. Therefore, the zero-incidence design criterion should be adopted during the hydraulic design process, and efforts should be made to ensure the MCP operates under rated conditions during actual operation.

## Conclusion

In this study, a computational model suitable for a lead-cooled fast reactor MCP was developed using computational fluid dynamics (CFD) methods, and the model's accuracy was validated through comparisons with experimental data. Based on this foundation, calculations were performed for the LBE MCP under various operating conditions, followed by a comparative analysis of the distribution patterns of the frictional shear stress coefficient on the impeller surface. The following conclusions were drawn:

1. The peak value of  $C_f$  in the MCP flow components occurs at the leading edge, with the  $C_f$  at the impeller leading edge being significantly higher than that at the guide vane leading edge. When LBE contacts the impeller surface, the  $C_f$  at the impeller leading edge rapidly rises to its peak value before sharply decreasing. As LBE flows toward either the pressure surface or suction surface, the  $C_f$  on the impeller surface gradually decreases, showing a slight increase at the trailing edge position.
2. The peak values of the  $C_f$  at the impeller leading edge were measured as 0.015, 0.011, and 0.019 under the three operating conditions of  $0.8Q_0$ ,  $1.0Q_0$ , and  $1.2Q_0$  respectively. At the  $1.0Q_0$  operating condition where the incidence angle approached zero, the minimum  $C_f$  peak value was observed. In contrast, when the MCP deviated from the designated operating conditions, the  $C_f$  peak value at the impeller leading edge demonstrated a rapid increase.
3. The  $C_f$  magnitude exhibits a strong positive correlation with the local fluid velocity gradient. This steep gradient rise at the leading edge is directly driven by flow acceleration governed by the leading edge geometry during fluid impingement. When the incidence angle between LBE and the MCP impeller approaches  $0^\circ$ , the FAC effect at the MCP leading edge will be significantly weakened.

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*Note: Figure translations are in progress. See original paper for figures.*

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