Available Online: 20 June 2025 DOI: 10.54254/2977-3903/2025.24334

Key manufacturing process technologies of fluid connectors in liquid cooling systems

Yikang Sun

Suzhou Aerospace Electric Co., Ltd., Suzhou, China

15051789189@163.com

Abstract. With the rapid development of industries such as artificial intelligence and big data, the demand for liquid cooling in data centers is continuously increasing. Among various technologies, cold plate liquid cooling has become one of the most widely applied methods. The performance and quality of components in the cooling system directly affect its operational and maintenance costs. This paper focuses on fluid connectors in liquid cooling systems, exploring key technical factors influencing their performance. It introduces process methods covering the entire production cycle from part machining to assembly and testing, and elaborates on critical control points at each manufacturing stage. The aim is to improve the technological level of fluid connectors. Finally, the paper briefly introduces new materials and technologies applied to fluid connectors and presents prospects for the future development of the liquid cooling industry.

Keywords: Liquid cooling technology, fluid connector, machining process, assembly and testing, process control

1. Introduction

In recent years, the explosive growth in the demand for information technology has fueled the rapid development of industries such as artificial intelligence, big data, and cloud computing. As a result, the scale of data centers has been expanding, along with increasing energy consumption due to the massive volume of information transmission, processing, and storage within them. Statistics show that energy consumption by data centers has risen from 2.7% of total national electricity usage in 2020 to 4.7% currently, and is projected to increase by 1.5 to 2 times by 2030 compared to a decade earlier [1,2]. During operation, data centers generate a substantial amount of heat. The supporting cooling system is responsible for dissipating up to 70% of this heat, which is critical to maintaining the stable operation of equipment. However, cooling devices account for over 30% of total energy consumption in data centers, making the reduction of their energy use a key solution to the high energy consumption problem.

Air cooling remains a commonly used heat dissipation method in data centers. However, its power usage effectiveness (PUE) has a relatively low lower bound, typically only 1.5 to 1.6, making it suitable only for cabinets with low power density. When heat flux density rises to 5–10 W/cm², air cooling approaches its performance limit [3–6], making it ineffective for medium- to high-power-density cabinets. This results in a continuous rise in the temperature of electronic devices, leading to performance degradation or even damage. In contrast, liquid cooling is far superior: the thermal conductivity of liquid mediums is roughly 20 times that of air, and their specific heat capacity is 1,000 to 3,500 times higher [7,8], making liquid cooling a more advantageous option than air cooling.

Depending on whether the heat-generating components are in direct contact with the coolant, liquid cooling technologies are categorized into direct-contact and indirect-contact types. Direct liquid cooling can further be divided into immersion cooling and spray cooling. Immersion cooling works by submerging the heat-generating equipment completely in the cooling medium, allowing for circulation-based heat dissipation. It features a relatively simple system structure and good heat transfer uniformity. However, this method requires significant modifications to existing data center infrastructure, which increases structural strength requirements due to the heavier weight of the immersion equipment and coolant, thereby raising construction costs. Spray cooling, on the other hand, involves placing cooling sources and nozzles above heat-generating components. Through the atomization of the coolant, fine droplets are sprayed onto the component surface for heat exchange. This method offers strong heat transfer capability, small temperature differentials, and minimal temperature fluctuation during operation, while using relatively small amounts of coolant. However, spray cooling is still in its early stages of development with few practical applications, and has not yet been widely adopted. Additionally, due to coolant dispersal when contacting high-temperature sources, it may affect the server room environment and other equipment. Therefore, this method requires high sealing performance of the cabinet.

Indirect liquid cooling avoids direct contact between the coolant and heat-generating components. Instead, heat is transferred via thermal conductors, with cold plate cooling currently being the most mainstream solution. This approach is widely adopted, technologically mature, and requires minimal structural changes to existing data centers during retrofitting. A typical cold plate cooling system consists of liquid cold plates in contact with heat sources, manifolds, tubing, quick connectors (fluid connectors), cooling distribution units (CDUs), and leak detection lines. Its working principle is to utilize highly thermally conductive materials like copper or aluminum in the cold plate, which contacts the heat-generating components. The coolant flowing through the channels inside the cold plate transfers heat through the manifold to the external tubing, and ultimately to the CDU outside the server cabinet, which then dissipates the heat externally to the data center environment. To facilitate routine maintenance, it is necessary to isolate the coolant pathway of specific modules without affecting others. Thus, each module in the liquid pathway must be connected through quick connectors (fluid connectors). These connectors function similarly to clutches in mechanical systems, allowing for quick connection and disconnection of the liquid pathway. They are self-sealing to prevent coolant leakage and ensure stable, continuous system operation. Notably, fluid connectors are the most frequently used components in the entire system. Depending on the liquid flow rate in the cabinet, a dual-row manifold may be equipped with dozens of quick connectors. If these connectors malfunction—whether due to failed connections or coolant leakage—they can disrupt the entire system's operation and significantly increase maintenance costs. Therefore, effective process control during the manufacturing of fluid connectors is essential for ensuring their performance. This paper provides a brief discussion of the key manufacturing technologies involved in fluid connector production.

2. Categories and Types of Fluid Connectors

Fluid connectors, also known as liquid cooling connectors, are used in a wide range of scenarios. In addition to their application in data center liquid cooling systems, they are also extensively employed in sonar and radar detection equipment, as well as in vehicle-mounted and shipborne systems. In practice, fluid connectors typically function in matched pairs of plugs (male) and sockets (female), serving as interconnection components between cooling modules. According to whether manual operation is required to connect or disconnect the male and female ends, fluid connectors can be categorized into manual plug connectors and blind-mate connectors. Based on different structural designs, manual plug connectors can be further classified into bayonet-lock type, steel ball push-pull lock type, and steel ball quick-push lock type. The characteristics of these fluid connector types are summarized in Table 1 below.

Table 1. Structural Characteristics of Different Types of Fluid Connectors

Type		Locking Mechanism	Characteristics
Blind-mate		No internal locking structure; requires external force to mate the connectors	Male and female ends can achieve guided alignment through external housing design or floating alignment using elastic rubber rings in the mounting base
Manual Plug/Unplug Type	Bayonet Locking Mechanism	The plug and socket respectively have a sleeve and a protrusion. Locking and unlocking are realized through push-pull and rotation.	The sleeve's groove is curved, requiring relative axial rotation between male and female ends to engage or disengage the protrusion, ensuring high locking reliability.
	Ball-Push Locking Mechanism	The socket contains steel balls and an unlocking sleeve structure. The locking mechanism is formed by the steel balls and the contoured structure of the plug's outer shell.	Unlocking and plugging/unplugging require two-handed operation. This design supports diverse installation forms with pipelines and cold plates.
	Ball Direct Push Quick Locking	Includes steel balls and an unlocking sleeve structure, with the balls and contoured structure forming the locking mechanism. The unlocking sleeve resets via a spring.	This design is user-friendly, allowing one-handed locking and separation of the connector head.

In addition to the above common structures, fluid connectors may feature many other types derived to meet specific design needs and connection modes of liquid cooling components. Regardless of variations in locking mechanisms or interface forms, the core functions of all fluid connectors remain consistent: enabling and interrupting the flow of coolant under internal pressure while ensuring leak-free sealing. The primary components of a fluid connector include: Housing components for structural support and coolant containment; Valve core components for flow regulation (open/close); Spring components for resetting movable parts; Seal rings for static and dynamic sealing at the interface. For manual plug-type connectors, additional parts such as steel balls, unlocking sleeves, springs, sleeves, and bosses are also included as part of the unlocking mechanism. The machining precision and assembly quality of these key components directly determine the final performance of the fluid connector.

3. Key Manufacturing Technologies for Fluid Connectors

3.1. Component Machining Technologies

As previously mentioned, the main components of fluid connectors include housings, springs, sealing rings, and others. Their production involves a variety of processes such as mechanical machining, surface treatment, and molding. The following section outlines the process control methods related to their manufacture.

3.1.1. Housing Component Machining

The housing of a fluid connector is typically a rotary-type machined part that must maintain long-term contact with the coolant and withstand internal fluid pressures ranging from 0.3 MPa to 2.5 MPa. Therefore, the material must be corrosion-resistant to endure the effects of the coolant and external environments, possess sufficient mechanical strength to handle frequent plug-unplug operations or long-term exposure, and offer good machinability. Common materials include 6000-series aluminum alloys and 316 stainless steel. To ensure consistent and reliable machining quality, attention must be paid to several key aspects during process planning: production environment, machinery, machining methods, and protective requirements.

Environment: The mechanical processing area must adhere to strict 6S management standards to maintain a clean and orderly production site. A centralized air conditioning system is necessary to keep the ambient temperature between 20°C and 30°C year-round, providing a stable environment for precision machining.

Equipment: Due to the high precision requirements of fluid connector components—typically with tolerances in the 0.04 mm to 0.08 mm range—five-axis or higher-level CNC machines are required. Parts such as housings and unlocking sleeves can be processed using fixed-head lathes, while valve cores, which feature internal flow channels or holes for coolant, are better suited for sliding-head (Swiss-type) lathes. Table 2 compares the characteristics of these two types of CNC machines.

Machining Methods: For housing and unlocking sleeve parts, standard procedures like face turning, external cylindrical turning, internal boring, and external thread cutting are typically sufficient to complete the machining in one clamping cycle. However, valve core components, which feature specially shaped flow channels, often require repositioning, boring, and drilling operations. To ensure dimensional accuracy, errors caused by secondary clamping must be minimized. During thread cutting, groove machining, or inner bore processing, fine wire-like chips may adhere to the surface due to factors such as tool wear, large rake angles, and elevated temperatures. If not removed, these chips can interfere with the assembly of sealing rings and housings, leading to reduced or failed sealing performance. Furthermore, in real-world use, especially in high-frequency plug-unplug scenarios or under prolonged coolant exposure, such defects can damage the dynamic components and sealing parts of the connector, reduce lifespan and reliability, and even cause coolant leakage. Therefore, it is essential to: Strictly monitor tool life and coolant/lubrication conditions to maintain stable machining performance; Perform deburring and inspection after forming operations to ensure quality; Design custom-fitted transfer trays for various part shapes to protect components from collision or stacking damage during transport. Each part should be placed individually.

Table 2. Characteristics of Fixed-Head and Sliding-Head CNC Lathes

Type	Name	Characteristics	Comparison Summary
Fixed-Head	Fixed-Head CNC Lathe	Operates with a fixed clamping position; does not support multiple feeding cycles. Machining is done via spindle rotation (C-axis) and tool post movement in Z, X, and Y axes. Long parts require additional support such as tailstocks or custom tool holders.	During Swiss-type lathe turning, the bar stock is fed axially through a central guide bushing, with the cutting tool positioned close to the guide bushing's port. This setup provides high rigidity and enables high part accuracy. The Swiss-type lathe is equipped with a bar feeder designed for processing large batches of small bar-stock parts, with a maximum bar length of 2500 mm. It is suitable for parts with diameters below 32 mm and can achieve machining tolerances within 0.01 mm, making it ideal for valve core components.
Sliding-Head	Sliding-Head (Swiss-Type) Lathe	Tooling is fixed; the spindle box moves in the Z-axis and rotates via C-axis. Supports multiple feeding cycles; max part length depends on bar feeder.	The conventional turning machine covers a machining range of 300 × 1000 mm, capable of processing parts with an outer diameter larger than φ32. It is suitable for manufacturing components such as connector housings and other related parts.

3.1.2. Surface Treatment of Components

Stainless steel fluid connector components typically require only passivation after machining before they can be assembled. In contrast, aluminum alloy parts—due to their softness, insufficient hardness, and relatively poor wear and corrosion resistance—must undergo anodizing before use. The anodizing process generally includes the following stages: Pretreatment: inspection, degreasing and cleaning of parts, partial insulation treatment if needed, and surface deblackening and polishing. Anodizing: using electrolyte to perform anodization and subsequent rinsing. Post-treatment: sealing, cleaning, and removal of insulation materials from the component surfaces.

Some fluid connectors are used as fittings for various types of hoses at the terminal interface. In these cases, barbed ends with alternating diameters form a seal against the hose's inner wall. However, due to the multiple diameter transitions and sharp edges on the barbs, micro-cracks may appear at smaller outer diameters and transition areas during anodizing. These cracks expose the base material to the external environment. When paired with soft hoses made of PTFE or PFA, such micro-cracks may not allow for a complete fit, leading to gaps that can result in corrosion or leakage over time under prolonged coolant exposure. These micro-cracks are typically related to the growth rate, oxygen content, and film thickness of the anodic oxide layer. When the growth rate is too fast or oxygen concentration is high, the resulting oxide layer tends to be loose and porous, increasing the likelihood of cracking—especially on small-diameter surfaces. Additionally, the thicker the oxide film, the deeper the cracks. Even under identical electrolyte and current parameters, different structural features of a single part may have varying film growth rates, leading to inconsistent oxide layer thicknesses across the component. Therefore, during anodizing: The position of the hanging point and electrolytic parameters must be tailored to the specific part structure to ensure film uniformity within the post-treatment dimensional range. In batch anodizing, changes in electrolyte bath temperature and ion concentration between the upper and lower layers can result in color and thickness differences in parts depending on their mounting positions. This necessitates strict control over the working environment temperature and stability of process parameters throughout the anodizing operation.

3.1.3. Molding of Sealing Rings

In cold-plate liquid cooling systems, the coolant does not come into direct contact with electronic components. For cost-effectiveness and thermal performance, coolants with high specific heat capacity, such as deionized water, ethylene glycol, or their mixtures, are commonly used. Under these conditions, the internal sealing rings of fluid connectors are generally made from EPDM (Ethylene Propylene Diene Monomer) or fluorosilicone rubber.

Table 3. Surface Defects in Sealing Ring Molding

Defect Type	Appearance/Description	Cause
Flash Shrinkage Cracks	Flash or tearing on outer surface; U- or W-shaped cross-section	Forming temperature or other parameters lead to shrinkage of flash
Underfilling	Surface depressions, rough texture	Inadequate material fill or air entrapment
Surface Contamination	Black spots or raised particles on surface	Dust or contaminants entered mold before forming
Pits	Irregular surface dents or impressions	Residuals removed post-forming or foreign matter on mold cavity
Parting Line Indentation	Indentations along parting line	Mold edge deformation
Parting Line Protrusion	Continuous material bulge along inner or outer diameter parting line	Mold edge wear or excessive rounding
Flash	Thin film of rubber along parting surfaces	Gaps in mold clamping
Flow Marks	Shallow linear depressions or curls on surface	Poor flow or fusion of rubber material
Cracks	Surface cracks under natural or compressed states	Poor material fill or weak bonding in joint areas

These rubber sealing rings are typically manufactured by heating and compressing rubber material in molds. Their forming quality directly affects both dynamic and static sealing performance of fluid connectors, and therefore strict defect control is essential. In addition to the defect types listed above, other severe defects—such as misalignment, displacement, eccentricity, and excessive flash trimming—can also significantly degrade or completely disable sealing performance. Thus, the molding process must ensure: Precise control of forming parameters; Ongoing monitoring and maintenance of mold condition. After forming, sealing rings must undergo standardized dimensional inspections (cross-sectional and sealing dimensions) and sampling-based testing of critical properties such as hardness, tensile strength at break, and media compatibility. Once testing is complete, the sealing rings should be packed in inflatable protective bags to prevent deformation due to prolonged compression during transportation or storage.

3.2. Assembly and Testing Techniques

3.2.1. Component Assembly

The primary assembly procedures for fluid connectors include O-ring installation and the integration of housing components.

Environmental Requirements: A cleanroom environment is essential for the assembly and testing of products. The assembly area must be free from dust, lint, and other contaminants that may adhere to component surfaces and compromise sealing performance. The cleanroom should be equipped with an air circulation and filtration system, anti-static flooring, air shower passageways for material and personnel entry and exit, and an air-conditioning system to regulate temperature and humidity.

Component Cleaning: Prior to assembly, all components must undergo thorough cleaning—typically by ultrasonic cleaning followed by drying—to eliminate dust, grease, and impurities accumulated during machining and handling. Different types of components, such as metal housings, springs, and O-rings, should be cleaned separately to prevent cross-contamination.

Assembly Procedures: O-rings must be correctly installed in the corresponding grooves of housing and valve core components. Before installation, a uniform layer of lubricant should be applied to ensure smooth operation and prevent sticking or jamming. Installed O-rings must not exhibit lifting or twisting. To ensure consistency in installation, dedicated fixtures or customized equipment may be used in place of manual assembly to expand and compress the O-rings during installation. For different types of fluid connectors, the methods used to assemble housing components vary. Based on the types commonly used in data centers and by various manufacturers, the main assembly techniques include threaded locking, retaining ring fixation, and press riveting. The key points for each method are as follows:

1. For threaded locking-type fluid connectors, it is necessary during design to reserve force-bearing surfaces (flat areas) on the parts, with an area and quantity sufficient to withstand the corresponding locking torque without damaging the part structure. To ensure the joint strength between housing parts, thread adhesive is usually applied between the mating threads to fill the thread gaps, thereby increasing torque resistance and preventing loosening.

2. Snap ring connectors rely on the two end faces of the snap ring to clamp and fix against the housing parts. In different products, snap rings include compression rings used with fitting holes and tension rings used with shafts; attention should be paid to selecting the appropriate type. If the product structure allows the use of standard snap rings with clamping holes, they should be preferred to reduce manufacturing costs. If non-standard snap rings need to be designed according to structural requirements, a C-shaped opening should be reserved to ensure the assemblability of the parts.

3. For press-riveted fluid connectors, the initial design should consider the alignment structures between shaft hole mating parts to prevent skewing or misalignment during housing assembly. If dimensional constraints prevent reserving guiding structures, the press-riveting tooling must be improved to ensure concentricity during the assembly of the shaft hole and housing. Additionally, the press-riveting stroke and force must be controlled to guarantee consistency.

3.2.2. Performance Testing

The fundamental function of fluid connectors is to enable the flow and cut-off of coolant while ensuring self-sealing. Therefore, it is essential to test their sealing performance, interchangeability, and dynamic characteristics. Sealing performance tests cover both the flow and cut-off states of the fluid connector. Commonly used methods include hydrostatic pressure testing, pneumatic pressure retention testing, and helium leak detection. Care must be taken to ensure that the applied medium pressure does not exceed the structural strength of the connector itself, in order to avoid damage to elastic and sealing components. During testing, the connector should first be evaluated in the mated (flow-through) state with male and female ends engaged, followed by testing in the self-sealed (cut-off) state. This sequence helps determine the current sealing performance in cases where the status of the moving parts may change after the male and female components are mated.

In interchangeability testing, male and female ends of the fluid connector should be paired with their corresponding counterparts for complete mating and separation. The insertion and extraction process should be smooth and free of jamming, with full engagement and complete elastic rebound to the proper position. If further insight into the rebound behavior throughout the entire insertion process is required, instruments can be used to separately record the variation of insertion force and extraction force with displacement. Comparing the two force-displacement curves at identical positions allows assessment of localized resistance or sticking. All of the above performance tests should be conducted on every unit (full inspection) to characterize the stability of the assembly process. This enables timely monitoring and interception of anomalies.

4. Conclusion

This paper compares the application and development of various liquid cooling solutions in data centers, analyzes the characteristics of cold plate-based liquid cooling technology, introduces the types of fluid connectors used in liquid cooling systems, and explores their key manufacturing processes and control methods. The main topics include machining of components, anodizing treatment for aluminum alloy parts, molding of sealing rings, and assembly and testing techniques, all aimed at enhancing the technical level of fluid connector components in liquid cooling systems.

Due to space limitations, this paper only discusses selected aspects and does not cover emerging fluid connector designs and manufacturing technologies. For example, in terms of materials and component forming methods, some manufacturers have begun developing engineering plastic housings for fluid connectors. Additionally, the manufacturing of certain metal valve cores has evolved from traditional machining to powder metallurgy, demonstrating strong potential for low-cost production. On the assembly side, some companies are experimenting with coated sealing rings to replace lubricants, aiming to reduce both material and labor costs.

As a relatively mature solution, cold plate liquid cooling technology has evolved over several decades. However, new processes, materials, and methods continue to emerge. With further research and the accumulation of engineering experience, liquid cooling technologies and their industrial models are expected to advance toward higher performance, lower cost, and greater standardization. Looking ahead, it is essential to establish industry norms based on the general-purpose technologies developed by manufacturers at all levels, integrate upstream and downstream supply chains, and optimize operation and maintenance systems. These efforts will provide stronger momentum for the continued evolution and innovation of data center models.

References

[1] Chen, X. , Zhou, L. , Zhang, C. , Wang, S. , Zhang, L. , & Chen, J. (2022). Research status and development trend of cooling technology for green and energy-efficient data centers. Engineering Sciences, 24(4), 94–104. https: //doi. org/10. 1016/j. engsci. 2022. 04. 009 (if available; otherwise, omit)

[2] Sun, Q. , Sun, Z. , Pan, H. , Chen, J. , Zhu, C. , Chen, C. , & Zhou, J. (2022). Optimal configuration of integrated energy systems for data centers considering multiple energy storage methods. Electric Power, 55(9), 1–7.

[3] Jiang, S. , Zhang, B. , & Teng, X. (2025). Research progress on the application of liquid cooling technology in data centers. Advances in New Energy, 13(2), 204–213.

[4] Bao, Y. , Chen, J. , & Shao, S. (2023). Research status of high-efficiency liquid cooling technology for data centers. Refrigeration and Air Conditioning, 23(10), 58–69.

[5] Gupta, R. , Asgari, S. , & Moazamigoodarzi, H. (2020). Cooling architecture selection for air-cooled data centers by minimizing exergy destruction. Energy, 201, 117625. https: //doi. org/10. 1016/j. energy. 2020. 117625

[6] Ji, A. , Zhong, J. , & Shuai, L. (2013). Heat dissipation methods for electronic devices with high heat flux density. Electronic Mechanical Engineering, 29(6), 30–35.

[7] Xiao, X. (2022). Research progress on the application of liquid cooling technology in data centers. Heating, Ventilation & Air Conditioning, 52(1), 52–65.

[8] Haywood, A. M. , Sherbeck, J. , & Phelan, P. (2015). The relationship among CPU utilization, temperature, and thermal power for waste heat utilization. Energy Conversion and Management, 95, 297–303. https: //doi. org/10. 1016/j. enconman. 2015. 02. 059