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Why Fluidic Flow Dynamics Are Critical to the Design of Liquid Cooling in EV Charging Applications

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Executive Summary

Liquid cooling delivers superior thermal management with significantly better energy efficiency. This fact is driving rapid adoption of liquid cooling technology in high heat-flux electronic systems – such as in EV charging stations and infrastructure. Higher power makes faster charging possible, but it also generates significant heat. The heat load for DCFC and XFC load requires advanced cooling techniques to promote safe and reliable operation. Extreme fast chargers, for example, can push battery pack temperatures to 270ºC/514ºF after just a few minutes of charging.[1]

To optimize performance and enhance sustainability, designers must take into consideration how to manage fluid flow for liquid cooling for efficiency and reliability.

1 Heat transfer coefficient (*h*): thermodynamics and electronic design

Heat dissipates through liquids exponentially more efficiently than through gases. This can be illustrated by comparing relative heat transfer coefficients of gases and liquids using free convection and forced convection flows. A high heat transfer coefficient indicates comparatively greater heat dissipation. As shown in Table 1, from forced air cooling into the liquid realm we see forced single and two phase liquid cooling gives an exponential boost in capacity. Knowing that DC fast, and now extreme fast charging systems are seeing at a minimum 50kW, the need for liquid cooling thermal management is clear.

Table 1: **h* = **convective heat transfer coefficient** in Watts per square-meter Kelvin

Coolant	**Flow type**	**e.g.**	***h****	Efficiency
Gas	Free	Passive heatsink	2 to 25	Low
	Forced	Fan, RDHx (rear door heat exchangers)	25 to 250	↓
Liquid	Free	Static immersion	50 to 1000	↓
	Forced	Pump, closed loop or immersion	100 to 20,000	↓
	Phase change	2-Phase boil & condensation	2000 to 100,000	**High**

High heat transfer efficiency of fluids gives liquid cooling a distinct immutable advantage over air cooling. To reap these benefits in high performance applications requires integrating liquid components alongside the heat-producing electronics. Flow dynamics become critical to optimizing thermal management for power inverter insulated gate bipolar transistor (IGBT) modules, digital projector micromirror devices, and automotive lithium-ion batteries.

A holistic approach to design is essential to effective thermal management and the integrity of the entire system. All cooling components – quick disconnects (QD), tubing, pumps, etc. – must be compatible with and support the requirements of the application.

An ideal direct contact cooling loop will deliver high thermal performance while balancing efficient power consumption over the life of the application. Like the proverbial links in a chain, the right connectors can make the difference between optimal cooling and total system shutdown.

2 Flow coefficient (*Cv*): how to compare connector performance

Flow coefficient measures the relative efficiency with which a liquid can move through a system, making it a valuable tool for comparing individual connector alternatives when assessing overall system flow requirements.

Cv is a function of the volume in U.S. gallons per minute (*Q*) of a given fluid expressed in the fluid's specific gravity (*SG*) passing across a connector that will result in a system pressure drop (ΔP) of 1 psi. For example, the CPC LQ6 Series of quick-disconnect fittings have a *Cv* of 2.2, which means that 2.2 gallons of water (*SG* = 1) passing through a 3/8-inch LQ6 connector will result in a system pressure drop of 1 psi. By comparison, CPC LQ2 Series connectors have a *Cv* of 0.37, meaning 0.37 gallons of water passing through each 1/8-inch LQ2 connector will result in a 1 psi system pressure drop.

Although somewhat less common, an alternative to *Cv* can be found in the flow coefficient Kv; it is the same principle as *Cv* but representative of the volumetric flow rate in cubic meters per hour where the pressure drop across the valve set is 1 bar, or 10^5 Pa.

$$Cv = Q\sqrt{\frac{SG}{\Delta P}} \tag{1}$$

Where: *Q* is flow rate in U.S. gallons per minute
SG is fluid specific gravity (relative to water = 1)
ΔP is pressure drop across connector in psi

The *Cv* value of a given quick disconnect (QD) can vary widely based the cooling fluid used and system operating temperatures. Typically, published *Cv* values are standardized using pure water within a temperature window of 40 °F to 100 °F. However, alternative coolants or refrigerants which may provide performance benefits will likely have significantly different physical and thermal properties than water. Therefore, the optimal connector and internal diameter will vary based on cooling fluid flow coefficient and system environmental conditions. This is a critical consideration to avoid sizing errors.

To better understand flow coefficient, we'll consider how each variable impacts *Cv* and the implications for selecting optimal connectors for each application.

3 Volumetric flow rate (Q): efficient connectors enhance thermal management

The flow rate, *Q*, is the volume of fluid that passes a through a point in a system per unit of time, usually expressed in gallons per minute. In liquid cooling, efficient flow is essential to effective thermal management.

Similar to electrical current flow, fluidic flows are dependent on relative flow resistances. In this way, a cooling loop can be represented by a network of flow resistances correlating to physical components such as cold plates, filters, manifolds and quick disconnects or "fittings." These components affect how much fluid is able to circulate through the system and how rapidly. Each element of a liquid cooling system can be thought of as an off ramp, speed bump or roundabout in a road system, which collectively impact traffic volumes and flow.

Bernoulli's principle helps explain the effects of these resistances and losses, demonstrating that a reduction in pressure correlates to an increase in fluid velocity and vice versa. The fluid velocity contour plot below shows water flowing through a characteristic QD valve set. Red areas indicate constricted flow, where fluid pressure is lowest and velocity highest. Blue indicates areas of higher pressure, where velocity is diminished.

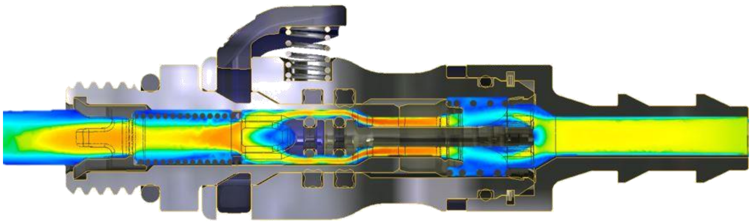


Figure 1 - velocity contour plot of water through QD valve

Increasing flow rate promotes thermal transfer, whereas speed bumps in a liquid cooling system will impede it. The most efficient systems will minimize constriction points that might slow flow rate.

4 Specific gravity (*SG*): fluid properties impact connector requirements

Simply put, dense liquids require more energy to move than equal amounts of lighter liquids. Specific gravity is the ratio of a liquid's density relative to water, which has *SG* of 1. So, a liquid with *SG* greater than 1 is denser than water, and a liquid with *SG* below 1 is less dense. High *SG* liquids have greater resistance to flow, while low *SG* fluids have less resistance.

Of course, there are a wide variety of liquid coolant alternatives. Fluid selection for a given cooling environment will be made based on the cumulative benefits of its relative performance characteristics. Specific gravity of the chosen coolant is a critical factor in selecting optimal connector sizes and materials. System designers should choose a coolant whose characteristics meet application demands and select connectors that deliver flow requirements for the chosen liquid.

The primary goal of direct cooling is to remove heat from the most concentrated areas within a system enclosure, specifically near semiconductors, transistors, batteries, etc. Single-phase, sensible heat removal systems most commonly use regulated water due to its high heat capacity and thermal conductivity (driving heat transfer coefficient), low viscosity, and its relative low cost and availability. An obstacle to implementation of water-cooled systems can be concern over damaging high-end information technology equipment in the event of a leak. A logical consideration is then to use non-conductive dielectric fluids that won't damage sensitive electronics. However, in single-phase applications dielectrics often have low heat transfer characteristics; where water has a thermal conductivity of roughly 0.6W/mK, an engineered dielectric may be an order of magnitude less.

Where engineered dielectrics may have an advantage is in pumped or immersive multiphase liquid cooling systems where the latent heat of vaporization can be leveraged to manage higher heat flux ranges and with a lower mass flow rate. Flow boiling of engineered fluids in microchannels has the potential to be a very effective method of cooling high heat flux devices. Alongside dielectrics, various refrigerants are being explored for use in two-phase cooling systems, but often require more complex, costly subcooled inlets and large vapor compression cycles.

In addition to system design driving coolant selection, viscosity and associated performance under temperature extremes is to be considered. For example, a fast-charging electric vehicle charging station in a colder climate still requires liquid cooling, but the environment becomes a factor in fluid selection. Water's properties and low cost make it easy on the math *and* pocketbook. The glycols (propylene glycol and ethylene glycol) will set the budget back a bit more. The two types of glycol most commonly used for liquid cooling applications are ethylene glycol and water (EGW) and propylene glycol and water (PGW) solutions. Ethylene glycol has appealing thermal properties including a low freezing point and high specific heat and thermal conductivity. It also has a low viscosity. Dielectrics like Flourinert™ or Novec™ are less corrosive than deionized water and may be a better choice for some applications. However, thermal conductivity is lower with these latter options *and* the fluids are more expensive.

Table 2 - Coolants: Comparison of select specific gravities and other properties

Fluid	*SG*	Thermal conductivity W/mK	Viscosity cP	Boiling °F	Freezing °F	Cost
1,1,1,2-Tetrafluoroethane (R-134A)	0.52	0.082	0.20	-15°	-154°	$$$
Mineral oil	0.92	0.106	6.64	392°	-15°	$$
Water	1.00	0.580	1.00	212°	32°	$
Propylene glycol, 50% solution	1.04	0.357	5.20	223°	-49°	$$
2,3,3,3-Tetrafluoropropene R1234yf)	1.10	0.064	0.16	-22°	-238°	$$$
Ethylene glycol, 50% solution	1.13	0.402	2.51	224°	-35°	$$
Hydrofluoroether (HFE)	1.61	0.075	0.45	93°	-189°	$$$$
Fluorinert FC-72	1.68	0.057	0.64	133°	-130°	$$$$
Perfluoropolyether (PFPE)	1.70	0.090	0.45	392° - 500°	23°	$$$$

5 Pressure drop (ΔP) and liquid cooling system performance

In another parallel between fluid and electrical systems, a pressure drop in a liquid circuit facilitates fluid flow in a similar way as a voltage drop drives current in an electrical circuit.
Pressure drop in liquid cooling systems is related to friction between the fluid and the tubing, valves, fittings, elbow bends and connectors through which it flows. Liquids have lower thermal resistance than air. Therefore, a direct contact liquid cooling system has higher pressure drop associated with flow, requiring substantially greater pumping power than air-cooled systems. Furthermore, pressure drops in typical two-phase systems are greater than their single-phase counterparts due in part to phase change.
It should be noted that an assumption for application of this flow coefficient is that the fluid is

incompressible, meaning flow rate depends only on the difference between inlet and outlet pressures. Compressible fluids and multiphase systems will require a modified approach.

The next critical element relative to consider the fluid heat transfer energy. Here Q'' refers to the heat transfer energy; ΔT is the change in temperature; m is the amount of fluid flowing around the loop, correlating to the mass flow rate (kg/s); and Cp is the specific heat capacity, a thermodynamic property unique to the coolant being used as a heat transfer medium.

Optimization of both fluid flow rate temperature rate are critical to efficient heat transfer in the cooling loop. In one scenario, a designer might consider using a low mass flow rate with a high temperature differential, while in another scenario a higher mass flow rate with a more tightly controlled temperature window might be preferred.

Heat transfer energy (Q)

$$Q'' = mC_p\Delta T$$

Where: m is mass flow rate in kg/s
C_p is specific heat capacity
ΔT is change in temperature

It’s also worth recognizing that the capacity for heat transfer rate in a liquid cooling system is directly proportional to the mass flow rate of the coolant. If the flow rate is increased, the heat transfer rate is also increased. That being said, increasing the flow rate will often come with added costs in the form of increased pump size and power requirements and higher system pressure ratings to accommodate the increase in pressure loss, for example.

6 Connector features affecting flow

Advanced design features in quick disconnect connectors can ensure enhanced system reliability, performance and serviceability without compromising flow requirements. Consider how these features can enhance your liquid cooling system.

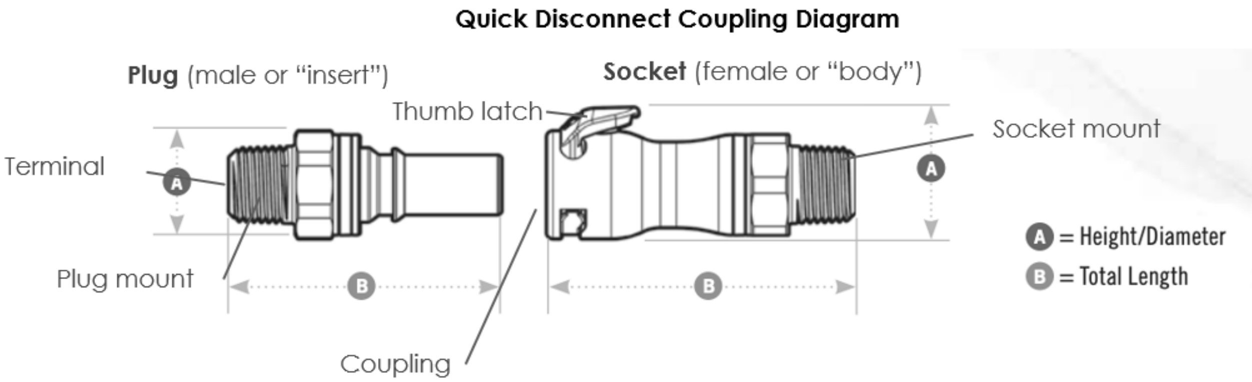


Figure 2

QD sizes may vary throughout a given application. However, as thermal densities continue to increase, space is a premium and direct liquid cooling systems must circulate thermal management fluids efficiently through constantly shrinking spaces. The physical space required must allow for easy, reliable installation and maintenance without adding unnecessary bulk to the application. Fluid handling components, including connectors, may require internal diameters of 1/16-inch or less. The goal is to minimize the impact on the thermal capacity via the flow coefficient, *Cv*, when circulating liquid through constricted conduits.

From a connector standpoint, shutoff configurations, valve design, and orifice size are critical in maintaining high *Cv* for more efficient cooling even through smaller connectors.

Table 3 – Shutoff Configurations

	Description	*Cv* impact	Use
Straight-Through	Free-floating; neither connector half features a valve, necessitating flow stop prior to disconnection.	Maximum *Cv* at connection	Unobstructed flow. Often for permanent connections. Requires flow stoppage prior to disconnect.
Single Shut-Off	One side of QD contains a valve to prevent coolant release.	Marginal *Cv* loss to flow resistance	Where nominal release of coolant will not threaten system components.
Double Shut-Off	Both QD halves contain valves; poppet valves trap a small amount of liquid within the coupling body that can drip when disconnected.	Increased flow resistance, consider during FNM	Typically < 1.0cc fluid loss on disconnect. Consider risk of conductive fluids near power electronics.
Non-Spill	Flush-faced valves ensure maximum containment of fluid upon disconnect. No significant drips, only wetted surfaces.	Increased flow resistance, consider during FNM	Typically < 0.1cc fluid loss on disconnect. Minimal threat to electronic components.

In addition to the shutoff configuration, mounting and mating configurations may induce further impedance to flow. Unlike with manual mate or latched couplings, blind mate couplings warrant extra consideration to ensure flow performance. As shown in Figure 3, the axial connection length directly correlates to the pressure drop across the connector set as the valves will be in various stages of opening. To mitigate this effect, specify QDs with an axial tolerance window appropriate for the system. Depending on the relative effective diameter of the QD, and axial tolerance may be defined in the 1 to 3mm range. However, tolerance studies relative to flow impedance should be considered per unique application and system.

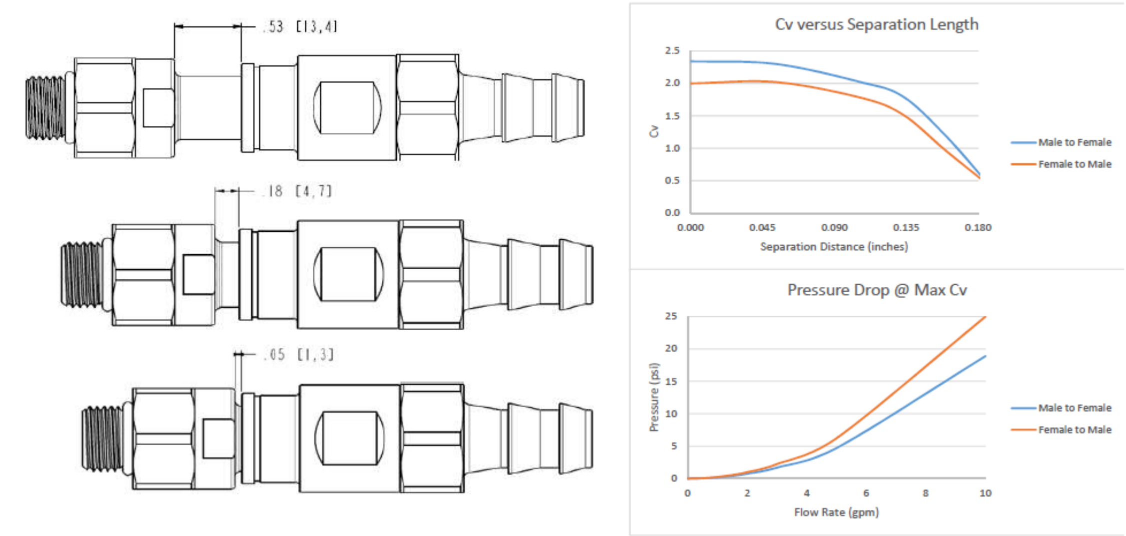
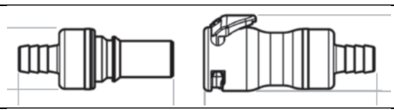
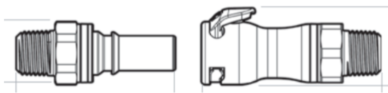


Figure 3 - Blind Mate Flow Impedance x Connection Length

Mounting options should be specified for every point of connection with a liquid cooling system, including inverter panels, heat exchangers, cold plates and battery packs, tubing, pumps and reservoirs. Consider each insert and body coupling individually, as the mounts may differ at a given connection point. In general terms, quick disconnects may come with a variety of terminations options for mating with tubing, or for installing into a rigid port perhaps in a manifold or plate. For either style, consider the orifice size and any geometries that might impede flow further such as 90° elbows.

Table 4 – Termination Type

Mount type		Application	Considerations
Hose barb		Insert into flexible tubing	Tubing material and diameter, erosional velocity limits
Threads		Screw into rigid port	Tapered versus straight, oring boss thread (SAE, BSPP)

7 Conclusion

While there are seemingly many variables to consider in understanding fluid flow performance for EV cooling applications, this presents an opportunity to truly optimize on a system to system basis. Knowing the key parameters of importance to flow in a cooling system enables system designers to not only fine tune the thermal performance, but also innovate with regard to packaging, mounting and other aspects of the system architecture. More specific to thermal management for electric vehicles and electric vehicle infrastructure, the future is bright and ripe with opportunities to explore the advantages of liquid cooling.

References

[1] U.S. Dept. of Energy/Office of Energy Efficiency and Renewable Energy. (Oct. 2017).

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Beth Langer, Engineering Manager, CPC leads a team of design engineers focused on quick disconnect coupling product development. Over the course of her career, she has been responsible for product design, reliability and technical innovation for industrial products. Besides leading design solutions that serve CPC customers, she is an active consulting member on ASHRAE and OCP committees. She earned her Bachelor and Master of Science degrees in Mechanical Engineering from the University of St. Thomas in St. Paul, MN.