Why Fluidic Flow Dynamics Are Critical to the Design of High-Performance Electronics

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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 high-performance computing (HPC), data centers, edge computing, 5G, lasers, and EV charging stations/EV infrastructure.

To optimize performance and enhance sustainability, designers must take into consideration how managing fluid flow for cooling within an advanced electronics application differs from traditional air-flow cooling systems.

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

$$h = W/(m^2K)$$

Heat Coefficient (h)

HEAT TRANSFER COEFFICIENT (H): THERMODYNAMICS MEETS 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 the table, from forced air cooling into the liquid realm we see that forced single- and two-phase liquid cooling gives an exponential boost in capacity. Knowing that electronic systems are becoming hotter than ever, the need for liquid cooling thermal management is clear.

Mathematician and physicist Daniel Bernoulli, born 1700

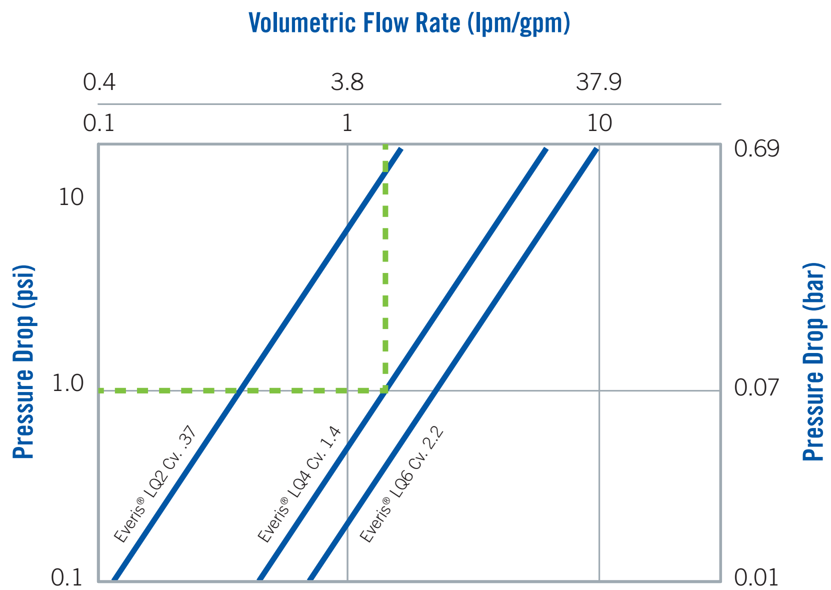
HEAT TRANSFER COEFFICIENT (H): COMPARING EFFICIENCY OF GASES AND LIQUIDS

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 data server CPUs, power inverter insulated gate bipolar transistor (IGBT) modules, digital projector micromirror devices, semiconductors, 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, cold plates, 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.



Volumetric flow rate vs. pressure drop

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

Flow coefficient (Cv)

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 volumetric flow rate 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 Everis™ 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 Everis LQ6 connector will result in a system pressure drop of 1 psi. By comparison, CPC Everis LQ2 Series connectors have a *Cv* of 0.37, meaning 0.37 gallons of water passing through each 1/8-inch Everis 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

COMMON CONVERSIONS:

Q - flow	1 gpm (US)	=	m^3/s	L/min
			6.30E-05	3.785
P - pressure	1 psi	=	kPa	bar
			6.895	0.069

Common conversions table

the pressure drop across the valve set is 1 bar, or 10^5 Pa.

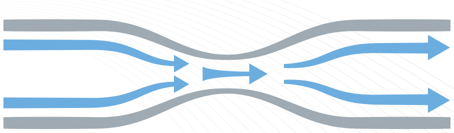
The *Cv* value of a given quick disconnect (QD) can vary widely based the cooling fluid used and system operating temperatures. Typically, published *Cv* values are standardized using pure water within a temperature window of 40 °F to 100 °F. However, alternative coolants or refrigerants which may provide performance benefits will likely have significantly different physical and thermal properties than water. Therefore the optimally specified connector (and its associated internal diameter) will vary based upon the selected cooling fluid's flow coefficient as well as 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 your application.

VOLUMETRIC FLOW RATE (Q): EFFICIENT CONNECTORS ENHANCE THERMAL MANAGEMENT

The flow rate, Q, is the volume of fluid that passes 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

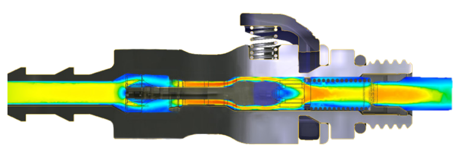


$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2$$

Bernoulli's equation

flow resistances correlating to physical components such as cold plates, filters, manifolds and quick disconnects (QDs)/quick release couplings (QCs) or "fittings." All of 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.



Velocity contour plot of water through QD valve

The fluid velocity contour plot above 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.

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.

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 application 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 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, which adds another layer of complexity relative to system design and compressible fluid dynamics.

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 costs less than the glycols (propylene glycol and ethylene glycol.) The two types of fluids 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 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.

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

COOLANTS: COMPARISON OF SELECT SPECIFIC GRAVITIES AND OTHER PROPERTIES

Fluid	SG	Thermal conductivity W/mK	Specific heat J/kgK	Viscosity cP	Boiling °F	Freezing °F
1,1,1,2-Tetrafluoroethane (R-134A)	0.52	0.082	1440	0.20	-15°	-154°
Mineral oil	0.92	0.106	1670	6.64	392°	-15°
Water	1.00	0.580	4181	1.00	212°	32°
Propylene glycol, 50% solution	1.04	0.357	3559	5.20	223°	-49°
2,3,3,3-Tetrafluoropropene R1234yf)	1.10	0.064	1382	0.16	-22°	-238°
Ethylene glycol, 50% solution	1.13	0.402	3283	2.51	224°	-35°
Hydrofluoroether (HFE)	1.61	0.075	1300	0.45	93°	-189°
Fluorinert FC-72	1.68	0.057	1100	0.64	133°	-130°
Perfluoropolyether (PFPE)	1.70	0.090	960	0.45	392° - 500°	23°

inlet and outlet pressures. Compressible fluids and multiphase systems will require a modified approach.

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

Heat transfer energy (Q)

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.

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.

CONNECTOR FEATURES AFFECTING FLOW

Advanced design features in quick disconnect connectors can support system functionality and serviceability without compromising flow requirements. Consider how these features can enhance your liquid cooling system.

QUICK DISCONNECT SIZES — ACHIEVE HIGH *Cv* IN SMALLER SPACES WITH SUPERIOR FLOW-TO-SIZE RATIO

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 ever shrinking spaces. The physical space required must allow for easy, reliable installation and maintenance without adding unnecessary bulk or weight 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. Remember, external QD dimensions are not a good indicator of *Cv*.

QUICK DISCONNECT SHUTOFF OPTIONS THAT IMPACT FLOW AND FLUID LOSS UPON SEPARATION

From a connector standpoint, shutoff configurations, valve design, and orifice

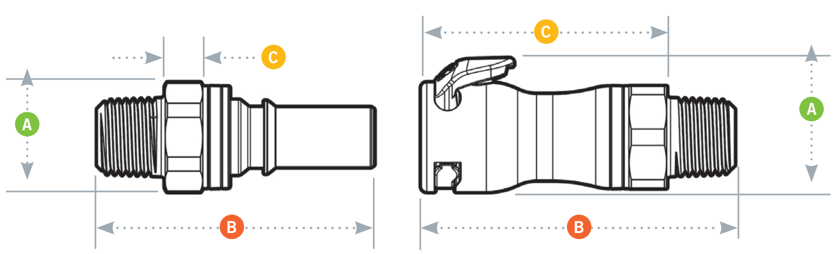
A = Height/Diameter

B = Total Length

C = Connected Length

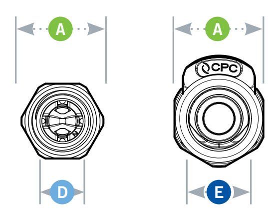
D = Insert Orifice Diameter

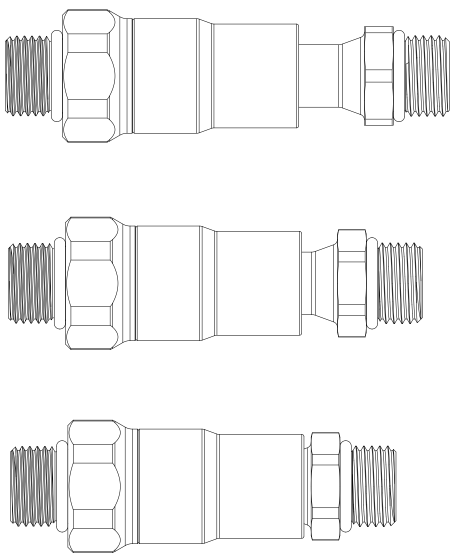
E = Body Orifice Diameter



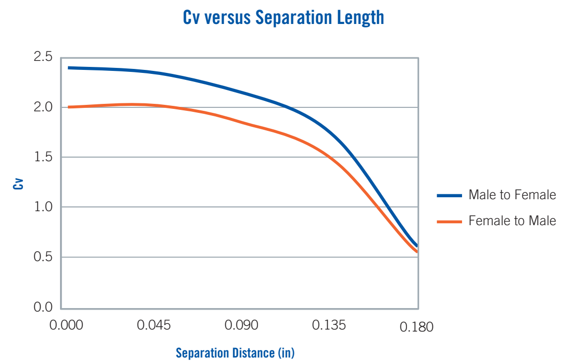
Plug (male or "insert")

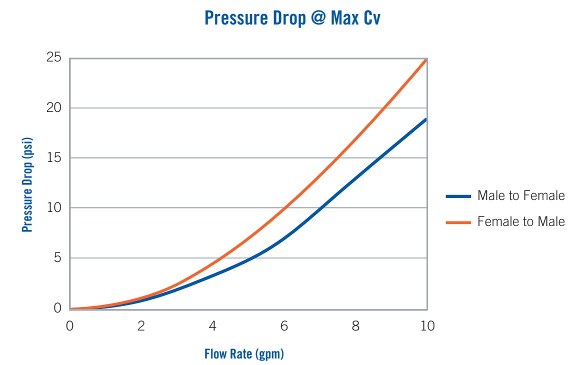
Socket (female or "body")





Blind mate flow impedance x valve engagement





size are critical in maintaining high *Cv* for more efficient cooling even through smaller connectors.

QUICK DISCONNECT CONFIGURATIONS FOR MOUNTING AND MATING

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 the blind mate illustration above, the axial connection length directly correlates to the pressure drop across the connector set as the valves will be in various stages of opening from full flow to full shutoff. 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.

Blind mate couplings work well for installation and maintenance in tight locations which may be difficult to see or access, like the backs of server racks. They provide high axial tolerance, enabling sustained flow rates through the length of the connecter. Blind mate couplings require separate retention mechanisms, such as a server blade latch.

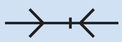
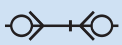
QUICK DISCONNECT GEOMETRIES AND TERMINATION ORIFICES

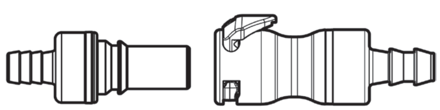
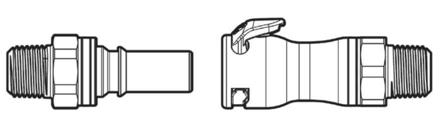
Mounting options should be specified for every point of connection with a liquid cooling system, including inverter panels, heat exchangers, cold plates and battery packs, tubing, pumps and reservoirs.

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.

COUPLING TYPES AND IMPACT ON FLOW AND COOLANT CONTAINMENT

Materials, seals, valve type and overall connector design impact the level of coolant released at disconnection. Most high performance electronic system manufacturers and operators and liquid cooling system technicians want no coolant to be present at disconnect – a performance requirement that is achievable with non-spill or dry-break quick disconnects.

QUICK DISCONNECT SHUTOFF OPTIONS THAT IMPACT FLOW AND FLUID LOSS UPON SEPARATION			
	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.	Nominal 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 flow network modeling	Typically <1.0cc fluid loss on disconnect. Consider risk of conductive fluids near power electronics.
 **Non-Spill / Dry Break**	Flush-faced valves enable containment of fluid upon disconnect. No drips, only wetted surfaces.	Increased flow resistance, consider during flow network modeling	Typically <0.1cc fluid loss on disconnect. Minimal threat to electronic components.

TERMINATION TYPES			
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, O-ring boss thread (SAE, BSPP)

WE SPECIALIZE IN CUSTOM-DESIGNED QUICK DISCONNECT SOLUTIONS

Contact CPC. If you don't find the ideal solution from among our line of over 10,0000 connectors, CPC engineers will design custom couplings to meet your unique application requirements.

TERMINOLOGY		
Term	**Definition**	**Units and/or Formulas**
External volume	Of a connector, the physical space required to house when coupled; length x width x max height (including QD release latch)	in^3 or mm^3
Flow coefficient	A measure of efficiency at allowing liquid to flow. Usually considered relative to the volume of water in US gallons per minute that will flow through a point yielding a pressure drop of 1 psi.	$Cv = Q\sqrt{\frac{SG}{\Delta P}}$
Heat flux	The rate of heat energy transfer per unit of energy per unit of time.	$q''=W/m^2$
Heat transfer coefficient	A measure of convective heat transfer between a fluid and the surface it flows over.	$h=W/(m^2K)$
Heat transfer energy	The energy exchanged between materials as a result of temperature difference.	$Q=mc_p\,\Delta T$
Internal diameter	Diameter of opening through which fluid or gas may flow, such as in a connector or tube.	in or mm
Pressure drop	The difference in total pressure between two points of a fluid-carrying network, caused by friction between the fluid and structural components.	$\Delta\rho = \rho_{in} - \rho_{out}$
Specific gravity SG	Relative density; the ratio of the density of a substance to the density of water at a specified temperature.	$SG = \rho_{substance} / \rho_{H2O}$
Termination type	Design style of ends where QD attaches to tubing or manifold. Threaded and hose barbed are the two common categories of terminations.	
Viscosity	The measure of a fluid's resistance to deformation at any given rate; "thickness"; higher viscosity increases frictional force	cP, cST
Volumetric flow rate	The volume of fluid passing a point in a system per unit time. Flow rate is inversely proportional to fluid viscosity.	*Q in GPM, m^3/hr, etc*