DISCRETE PROPORTIONAL VALVE TECHNOLOGY
An Innovative Solution for Automotive Thermal Management

Design Constraints

Designs for electric vehicle (EV) cooling systems are significantly more complicated and challenging than are designs for internal combustion engine (ICE) vehicles. The cooling system must accommodate several points of heat generation in the vehicle (Figure 1), including:

1. Inverter electronics to control the motors used for the vehicle's propulsion
2. Charging electronics (may or may not be integrated with inverter electronics)
3. Motor(s) used for vehicle propulsion and energy recovery
4. Vehicle propulsion (high voltage) battery

Each of these heat sources may require maximum flows of eight to ten liters per minute of coolant in a typical EV drive train, however sizing the cooling system to accommodate maximum flows for all heat sources would result in an energy and weight penalty in the pumping system. A more efficient scenario would be to control flow to each heat source based on temperature feedback. In this scenario, coolant flow is only delivered to each heat source as required to maintain optimal temperature. This would allow for a pump with somewhat smaller capacity, and would have the added benefit of providing for different optimal "setpoints" for the various heat sources. For example, inverter electronics could be operated at their optimal temperature of 40°C to 65°C, while motors or battery could be cooled further, or allowed to run warmer for very short periods as performance demands dictate.

The heat generated by EV components ideally would not be completely wasted. In cold-weather operation, it would be desirable to recycle the waste heat from electronics and motors to provide cabin heat. Avoidance of electrical resistance heating for cabin heat would greatly reduce parasitic electrical loads during cold weather operation.

The above requirements result in an optimal cooling system configuration that is significantly different from what is required for ICE cooling applications. The need

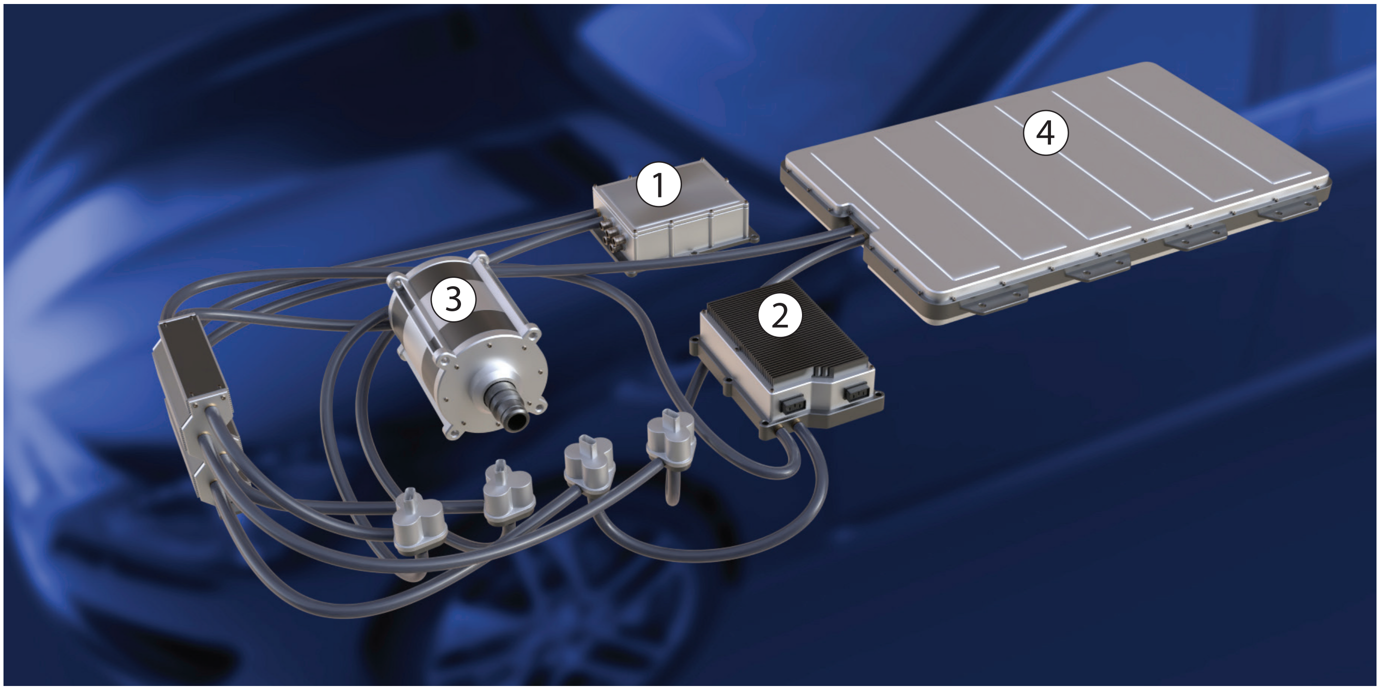

Figure 1: Electric Vehicle (EV) Cooling Components

for independent control of temperature at multiple points in the vehicle drive and charging systems, and the desire for efficient management of heat (re-use when possible) drive a more complicated system design. Core to this type of cooling system is a method for controlling the coolant flow between components. The key attributes of such a proportioning method would be:

- Predictable relationship between setting and flow (lack of hysteresis)
- Zero steady-state power at any setpoint
- Capable of fully shutting off flow (leak-free off state)
- Fail-safe condition when power is lost, e.g. full open

Issues with Extant Solutions

The combination of above attributes is not shared by any extant control valve. Specifically, valves that incorporate near-zero hysteresis, zero steady-state power and a near-zero flow state are available, e.g. rotary valves actuated by stepper motors. In stepper-driven rotary valves, hysteresis is not truly zero, but is determined by the repeatability of the step position, and by the backlash between the motor shaft and the valve element (backlash may be zero if the valve element is an integral part of the shaft). Stepper-driven rotary valves have some undesirable attributes, however:

Figure 2: Discrete Proportional Valve (DPV) section

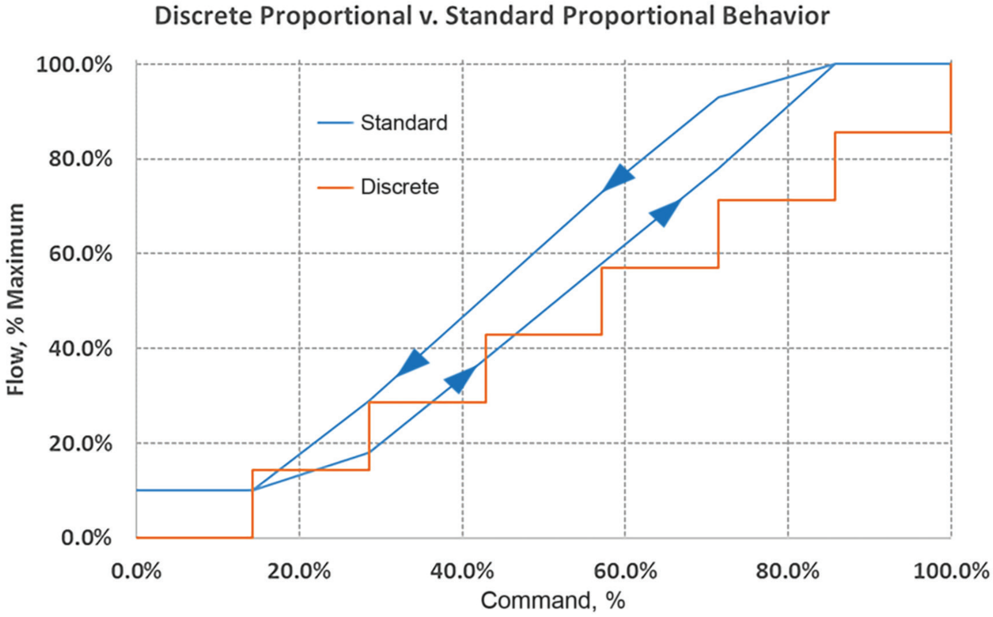

Figure 3: DPV and Continuous Proportional Valve Performance Curves

1. A rotating seal is required on the stepper shaft. Rotating seals are prone to leakage.
2. Lack of a fail-safe condition; if power is lost to the stepper, the valve will remain in the last-commanded position.
3. Stepper motors are relatively complicated devices, so applications demanding their excellent levels of control of angular motion pay a penalty in cost, and also potentially in weight.
4. A stepper motor controller is required, as well as (potentially) a position sensing/feedback system

The DPV Concept as an Alternative

An alternative solution for enabling all of the desired attributes, while relying on simpler forms of valve actuation and control is a discrete proportional valve (DPV). The DPV concept relies on intelligent combination of simple binary (on-off) solenoid valves (Figure 2). Two or more on-off valves with differing flow coefficients are combined in a single manifold to achieve a stepped approximation of a linear flow response using selective actuation of the valves. For example, a system of three valves gives 2^3 or eight possible flow states. The flow states can include a zero-flow state, or by design may include a designed-in minimum flow state. Table 1 shows the possible states for a 3-valve system where the individual valves are sized for flows of 1.0, 2.0 and 4.0 volumes per unit time at a given pressure differential. Figure 3 shows the resulting relationship between flow and valve command for such a system, compared to the typical response of a continuous proportional valve.

Referring to Figure 3, the blue curve reflects the typical performance of a continuous proportional valve. At 0% command, the valve has some minimum flow due to bypass leakage. As the command is increased, there must be some built-in deadband to accommodate part-to-part variation in response. This is shown by the flat portion of the curve between 0% and 15% command. As command is further increased, the valve begins to open, and the flow response follows the lower blue curve. An upper deadband at 100% flow occurs, typically between 85% and 90% command. As the valve is commanded to reduce flow again, the response follows the upper blue curve. The difference between the upper and lower blue curves is the hysteresis of the system, and is due to mechanical friction and magnetics. Hysteresis also increases the effective deadband at full flow. The orange curve in

State	Valve 1 State	Valve 2 State	Valve 3 State	Total Flow
0	OFF	OFF	OFF	0
1	ON	OFF	OFF	1
2	OFF	ON	OFF	2
3	ON	ON	OFF	3
4	OFF	OFF	ON	4
5	ON	OFF	ON	5
6	OFF	ON	ON	6
7	ON	ON	ON	7

Table 1: Three-Valve DPV States

Figure 3 shows the response of a 3-valve DPV system. The response is not smooth, but stepped. There is no hysteresis by definition; a given command will always result in the same valve members opening, and thus the same flow coefficient. In addition, there is no requirement for either lower or upper deadbands. What appears to be a lower deadband is actually the controlled true off state. It can be designed as such, or designed to be a minimum flow value such that there is always some flow through the system, to avoid pump damage, for instance.

For any given combination of valves opened, the system will always have the same overall flow coefficient, and thus is inherently hysteresis-free. The trade-off for this is the stepped approximation to smooth proportional control. As we will see, however, this trade-off has other benefits.

The DPV concept in its simplest form does require steady-state power, however by incorporating a latching solenoid design into the valve actuator, the steady-state power requirement can be eliminated. In a latching design, permanent magnets are used to hold the solenoid in the "latched" condition without power, and a reverse-polarity pulse is used to release the valve. The result is a valve that maintains the set flow condition with zero power input. Components that eliminate steady-state power draw are critical to achieving the highest efficiencies from EV designs.

A true zero-flow state is a native attribute of a DPV valve system (all valves off). Other implementations of proportional control can also provide effectively zero flow, however tight mechanical tolerances can be required, which raise the risk level with regard to debris sensitivity and wear. Tight mating tolerances also increase cost. The DPV concept achieves a zero-flow state without requiring this trade-off. The debris tolerance of a DPV design can be tailored to the application, since it is a simple combination of on-off valves. The actuator (solenoid) can be isolated from the main fluid flow via a diaphragm in order to limit ingress of debris to the actuator.

DPV Control

The control system to drive a DPV valve system can be implemented in essentially two ways:

1. Control system embedded in the valve system; analog or digital input used to command the system
2. Electrical connection only to the DPV system, control centralized remotely

The first schema requires some intelligence be built into the valve system, as well as power electronics to control each valve. This "DPV Control Board" would require a minimum of only three incoming wires; power, ground and signal. The Control Board would translate the desired state, communicated on the signal line, into commands to the valves. The Control Board would also provide for the fail-safe state if it detects a loss of power.

The second schema requires two wires for each valve in the DPV system. The control electronics can then be centralized, which may provide advantages in environmental protection, but increases the amount of wiring required. In an actual vehicle application, some of the benefits of both options may be realized by co-locating multiple DPV systems on a manifold, and locating the control electronics close by. Such a configuration would also be desirable from a fluidics perspective.

The control electronics for a DPV system is inherently simple. Since hysteresis need not be accounted for, complicated PID control algorithms are not required. A simple mapping of desired flow to DPV state is all that is needed. The single complicating factor for DPV control is a result of the zero steady-state power. Opening a valve requires a forward current pulse, while closing the same valve requires a reverse current pulse. The requirement for both polarities eliminates the possibility of a common ground, and requires two independent connections to each valve. Even with remote electronics, however, the wiring requirements for a three valve system are not onerous.

The DPV concept addresses reliability with a two-prong approach. The primary driver for high reliability is the employment of simple, well-characterized solenoid valve technology. The second is the elimination of the need for continuous duty electromagnetics, which dramatically reduces heat build-up. The DPV design also has two additional built-in fault-tolerant features:

1. The control system can be designed such that on loss of power, the valve fails in a specific condition. Since only a momentary current pulse is required to set valve position, a capacitive charge can be used to provide the pulse on power loss, either setting the valve open or closing it.
2. The DPV system does not have a single point of failure that can disable the entire system. The multiple-valve design of the system, and the independent wiring of each valve imply that a failure of one valve would leave the others functional, and still able to control flow to a degree. While a failed valve is still highly undesirable, a failure-tolerant system is a highly desirable attribute.

Conclusions

The discrete proportional valve concept provides advantages that match the unique needs of electric vehicle cooling and energy management systems. The advantages are directly related to the simplicity and design flexibility afforded by the approach. While the DPV concept does not provide for smooth control of output, but rather stepped control, it alleviates the need for deadbands and eliminates hysteresis completely, simplifying control algorithms. Importantly, it is also a power-efficient solution, in line with the demands of next generation EVs; not only is the DPV concept power-efficient in its own right, it also has the potential to enable further efficiency gains by aiding in re-use of heat that otherwise would be rejected to the environment.