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A Proposal for the Use of Statorade Ferrofluid on BionX Hub Motors

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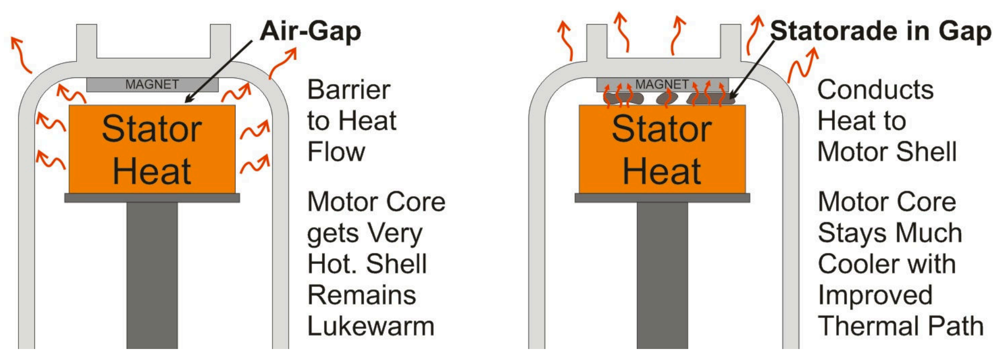
1 Objective

The point of this research is to characterize the effectiveness of Statorade Ferrofluid at increasing the heat dissipation in the BionX PL350 and 'D' series of hub motors. An increase in the thermal conductivity to ambient allows the motor to run at higher power and torque levels before overheating, resulting in faster hill climbing speeds and the ability to climb steeper terrain.

Increased thermal conductivity would similarly provide a lower average temperature in regular use. This reduced temperature can potentially increase the lifespan and reliability of the electrical components of the internal motor controller. Both the power mosfets and electrolytic bus capacitors have significant thermal derating factors, and can benefit from a cooler environment.

2 Background

Grin Technologies has been experimenting with the development of ferrofluids formulated to maximize the heat flow out of an electric bicycle hub motor without increasing the rolling drag. Early work in July 2015 showed that as little as 5-8mL could often double the heat flow from motor core to shell in direct drive hub motors with only an imperceptible change to the rolling friction. While other research has explored the use of ferrofluids inside motors to improve the airgap flux density for better motor magnetics, the point of this Statorade project was to find liquids that were only present for thermal reasons without any effect on the motor's magnetic characteristics.



Since the initial release as a product, we have seen Statorade used to very good effect in a number of ebike applications where people have been reaching the thermal limits of a motor. This includes hub motors used in cargo bikes and

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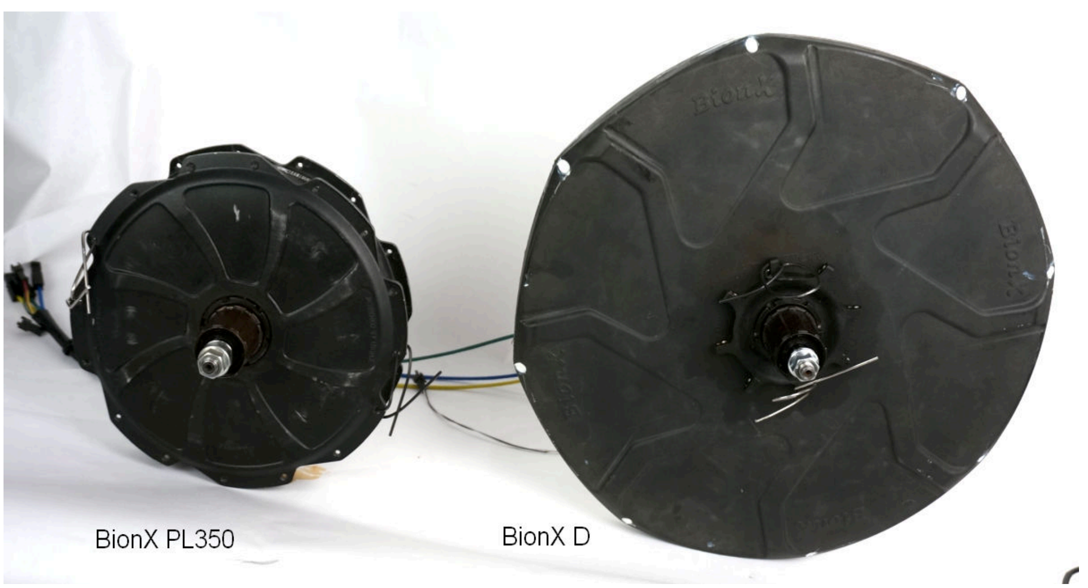
delivery fleets, in regions with many steep hills, and by people looking to push the power limits of a given motor setup. As of 2018 Grin offers 5 motor lines for aftermarket conversion kits (Crystalyte, TDCM, MXUS, Nine Continent, and Grin) that are available preconfigured with a port for injecting Statorade.

As a pioneer of direct drive hub motor systems for ebikes since their founding over 15 years ago, BionX continues to be a major market leader in the field of hub motor ebikes. The BionX hubs are direct drive outrunner motors and are already well sealed around the perimeter with a press fit shell to take Statorade without leaking.

Most interestingly, the BionX system also includes the motor controller inside the motor casing, exposing it to an ambient environment that is much hotter than the air outside. This adds an additional potential benefit to the use of Statorade, as it should not only increase the torque and power that the motor can produce before overheating, but also reduce the operating temperature of the controller electronics. In a cooler environment the electronics will can be used with less thermal derating and with higher reliability when driven to the same power levels.

BionX has provided Grin with samples of both their PL350 and ‘D’ series motor for thermal analysis. The PL350 motor is of conventional construction with an aluminum casing and has been prone to go into thermal rollback in heavy use, while the D series motor is much larger in diameter for better torque and uses a composite casing.



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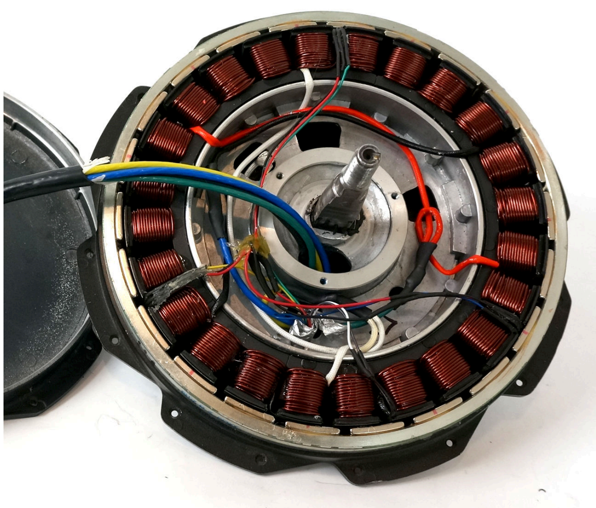
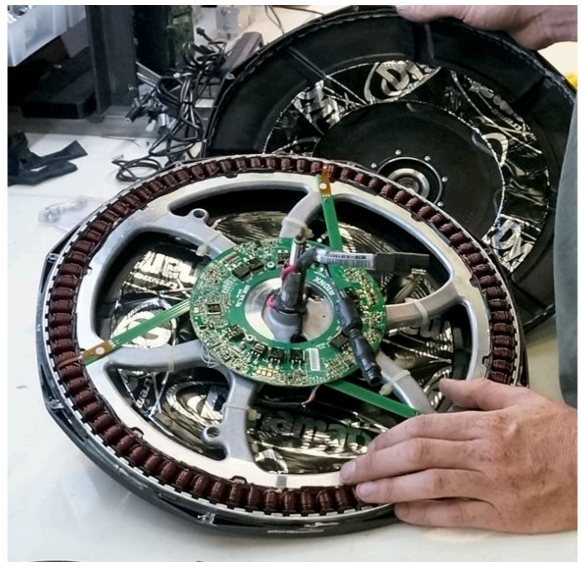
3 Motor Details

The BionX motors had to be opened up to remove the internal motor controller, attach a thermistor to the motor windings, drill a Statorade injection port, and bring out the motor phase wires from the axle for connecting to our external field oriented controller. The PL350 motor on the left disassembled with relative ease, while the 'D' series motor on the right has a chemically bonded plastic shell that required a combination of heat and razor blades to separate the seam and split apart.





The basic mechanical and electrical properties of the two motors are summarized in the table below:

	PL350	**D Series**
Total Weight	4.7 kg	4.2 kg
Motor Diameter	20 cm	36 cm
Stator Teeth	24	84
Rotor Magnets	22	88
Winding Constant	1.12 Nm/A	0.952 Nm/A
Winding Resistance	0.310 Ohm	0.113 Ohm
Winding Inductance	1.4-1.7 mH	0.32-0.35 mH
Hysteresis Torque	0.33 Nm	0.44 Nm
Eddie Current Torque	0.00054 Nm/Rad/Sec	0.009 Nm/Rad/Sec

We expected that the BionX PL350 motor would respond well to Statorade as it has a direct metal path for heat to flow from the magnets to the motor shell. The

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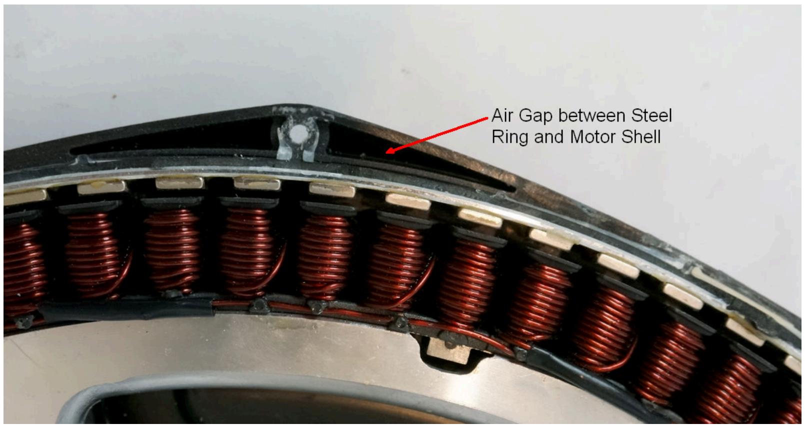
effectiveness of Statorade on the large 'D' series motor was much less certain, as this motor used a composite shell that did not have as direct a thermal link to the magnet ring back iron. In fact, there were large air pockets between the magnet backing ring and the outside of the motor shell where the enclosure expanded outwards at each fastener location.



4 Test Method

The thermal characterization of each motor was performed inside a wind tunnel, with a rim and tire placed directly in front to model the air flow expected around the motor in actual field use on an ebike.

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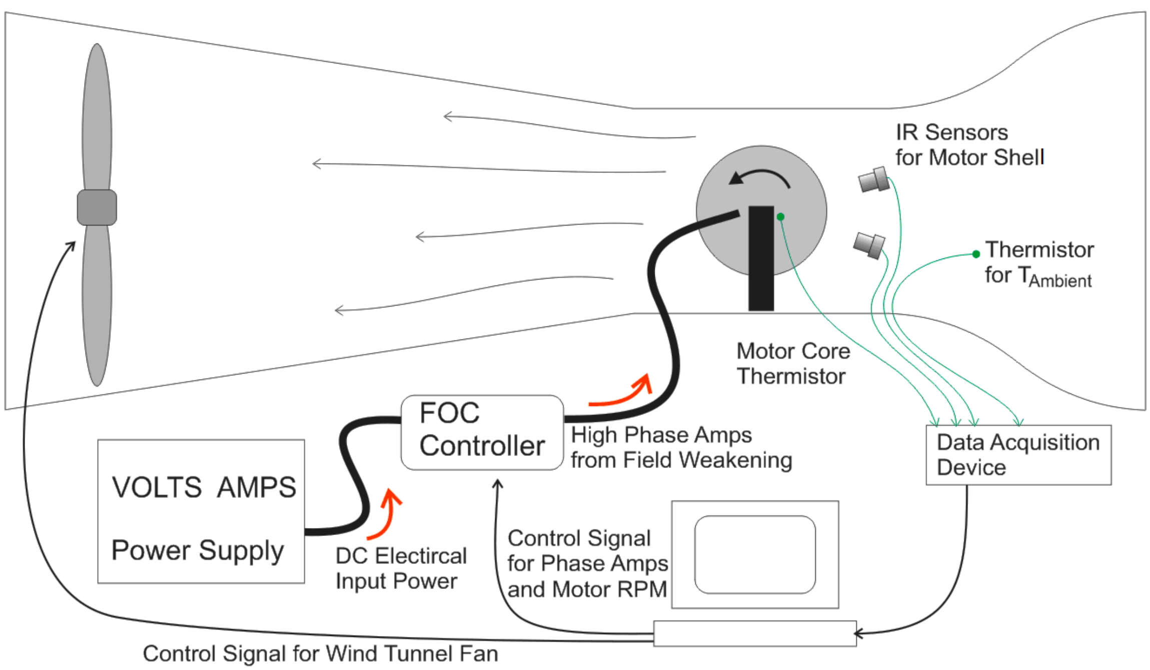
A total of 5 temperature sensors were employed in the test. A10K NTC thermistor bonded to the copper windings inside the stator sensed the motor core temperature, another 10K NTC thermistor located in the airstream of the wind tunnel to measure ambient temperature, while three IR sensors oriented at various parts of the motor shell recorded the casing temperature as the motor was spinning. These three IR readings on the motor shell were then averaged to provide an effective casing temperature to use for analysis.

In order to generate heat inside the motor while it was running, a field-oriented motor controller was employed to inject arbitrary field weakening currents through the windings. This field weakening current produced I^2R heating of the copper windings exactly the same way as an increase in the motor current from a mechanical load. But unlike a system with a mechanical load, we could assume that all the electrical energy going into the motor was turning into heat, as the motor was not producing any output power. This approach facilitated the thermal analysis as we did not need to measure and subtract off the motor's mechanical power to find the total heat generated inside the hub.



In our experimental setup, a computer was able to control the wind tunnel speed, the test motor RPM, and the motor field weakening current, while also monitoring the power into the controller and the temperatures of the motor core, shell, and ambient passing air.

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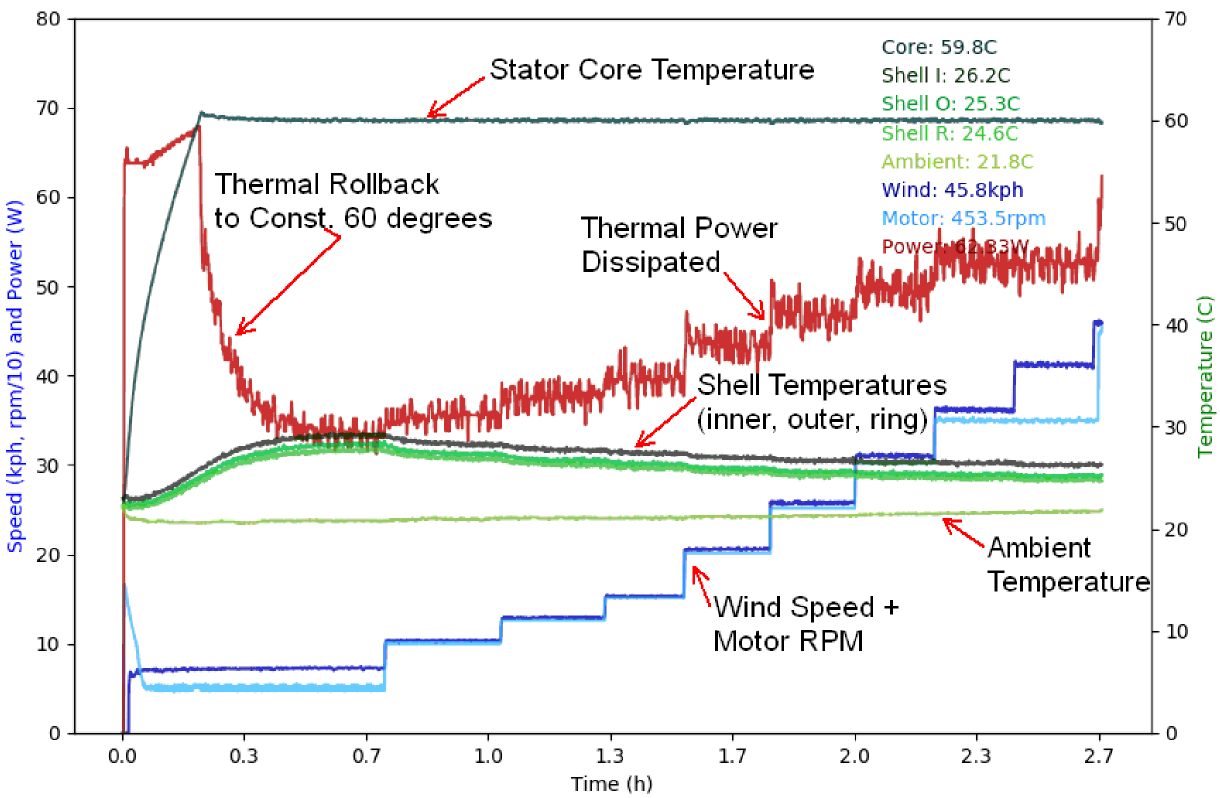
A script was then used to run the motor at a given RPM and wind speed and inject field weakening currents until the motor core hit a target set point temperature (60°C in these tests). When the set point temperature was reached, a feedback loop reduced and modulated the power into the motor to maintain this temperature. Once neither the core nor shell temperatures were changing and had been flat for 12 minutes, then the program assumed steady state temperatures have been achieved and saved this data point to a file. This data included the motor RPM, wind speed, input power, phase current, winding temperature, shell temperatures, and ambient temperature. At that stage the experiment was continued at the next motor RPM and wind speed.

The image below shows the data collection graph from a typical run going from 7 to 40 kph in 10 steps. The motor power is plotted in red, the various measured temperatures in green, and the wind speed and motor RPM in blue. The steady state data collection occurs just before each step in RPM and wind speed.



For the data analysis, we assumed that the motor can be characterized as two distinct thermal masses, the motor core and the motor shell. Heat is generated inside the motor core, and must first travel to the motor shell. As the shell warms up, it is then able to shed this heat to the passing ambient airflow.

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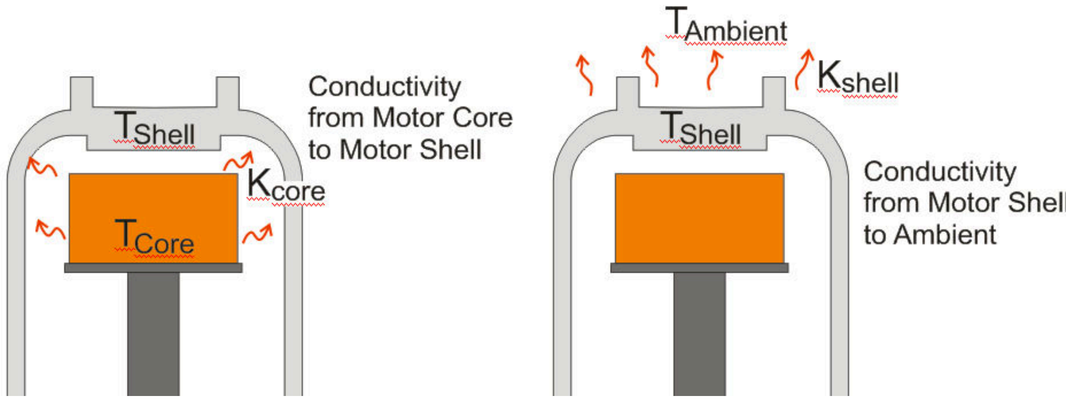

This provides two heat conductivity terms. The first K_{core}, from the motor core to the motor shell, we expect to vary with motor RPM, while the second, K_{shell}, we expect to vary mostly with the passing wind speed. In general the motor RPM and wind speed are related by the wheel diameter, though in the wind tunnel we could vary these independently.

The resulting first order conductivity terms were readily calculated from the collected steady state data points:

$$K_{core} = (P_{input} - P_{controller\ losses}) / (T_{core} - T_{shell})$$

$$K_{shell} = (P_{input} - P_{controller\ losses}) / (T_{shell} - T_{ambient})$$

The input power was measured directly from the voltage and current readings going into the test motor controller, while the controller losses were estimated from I^2R based on the known controller phase current and wiring + mosfet resistances.

5 Results

5.1 Characterization with No Statorade:

The stock BionX PL350 and D motors were tested first with no Statorade to establish the baseline thermal characteristic of the motor.

For thermal characterization we ran the motors from 70 rpm to 450 rpm in 10 steps, while simultaneously varying the wind speed from 7 kph to 45 kph. This 10:1 ratio of RPM to kph is roughly consistent with a motor laced in a 20” wheel.

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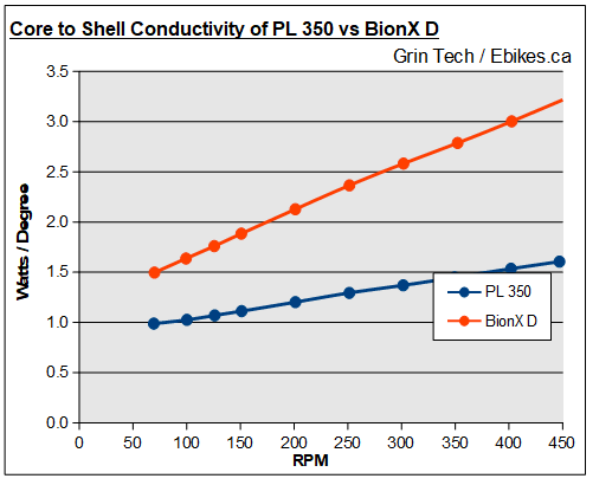
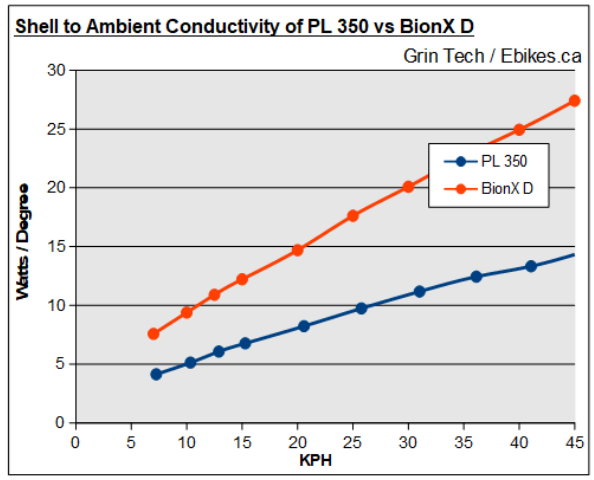
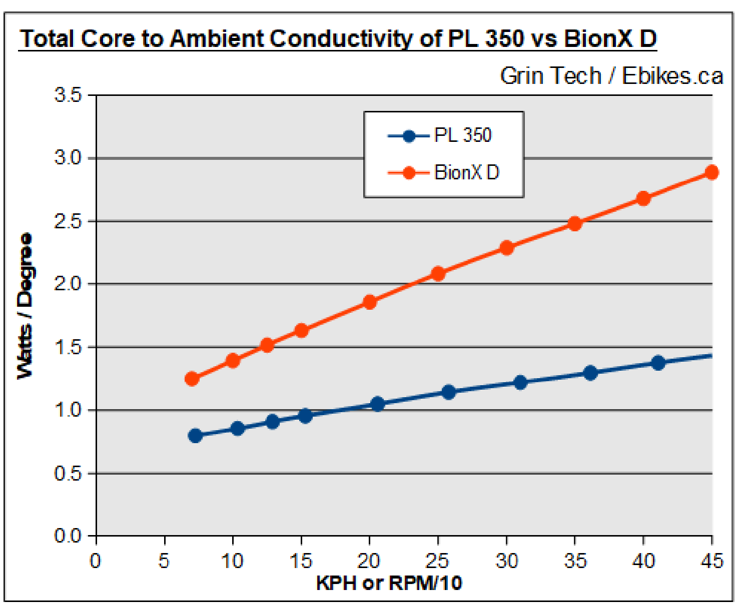
Throughout this test the power was modulated to maintain a core temperature of exactly 60 degrees Celsius. Here you can see the measured Core to Shell (K_{core}) conductivities on the left, and Shell to Ambient (K_{shell}) on the right.





Notice that on both PL350 and D Series hubs, the Shell to Ambient conductivity is many times higher than the Core to Shell conductivity. That means the primary barrier to heat flow out of the motor is getting it from the motor stator to the shell. Once heat is on the motor shell, it transfers easily to the ambient air.

The combined total conductivity from the Core to Ambient is what will ultimately determine the steady state winding temperature, and that plot is shown here



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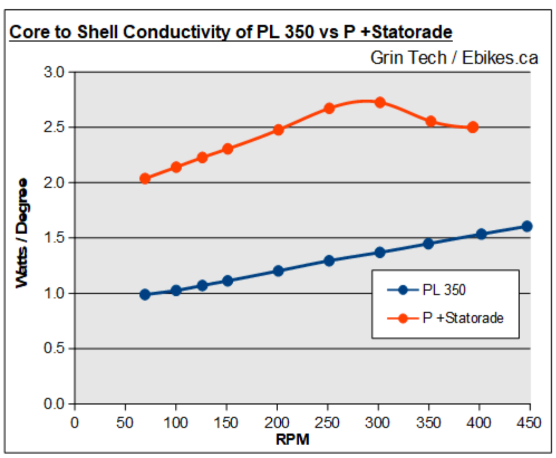
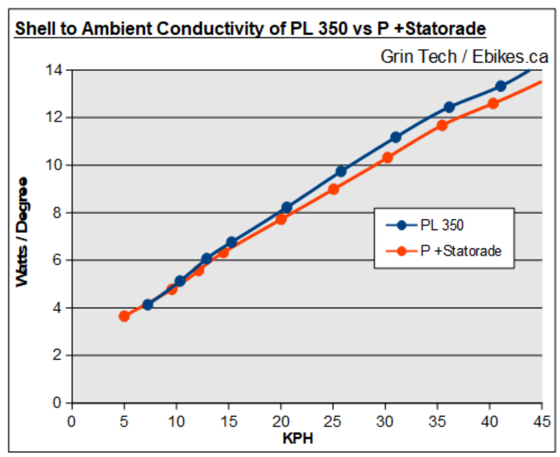
The BionX D motor has roughly double the thermal conductivity to ambient as the PL350 hub motor. In fact, the BionX 'D' motor at just 10 kph has the same ability to shed heat as the PL350 motor running at 45 kph. This can presumably be attributed to the much larger surface area of the motor and rotor for convective heat transfer both inside and outside the motor shell, which more than compensates for the reduced conductivity of a composite vs. metal casing.

5.2 PL350 with Statorade

The same tests were repeated on the BionX PL350 with the addition of 10mL of Statorade. In this case, one can see that the core to shell conductivity (left graph) is more than doubled with Statorade over the 70 to 250 rpm span. Above 300 rpm the conductivity starts to decrease somewhat. This is presumably a point where the centripetal forces are overcoming magnetic attraction and forcing Statorade to the perimeter, preventing it from forming an effective thermal bridge in the air gap.





The thermal conductivity from the motor shell to the ambient air (right graph) is of course not affected much by the presence of Statorade. However the net conductivity from core to ambient shown below is still markedly improved, with an average 80% increase in heat transfer from low speeds up to 300 rpm. The Statorade enables the small PL350 motor to have almost exactly the same heat shedding abilities as the much larger 'D' series hub.

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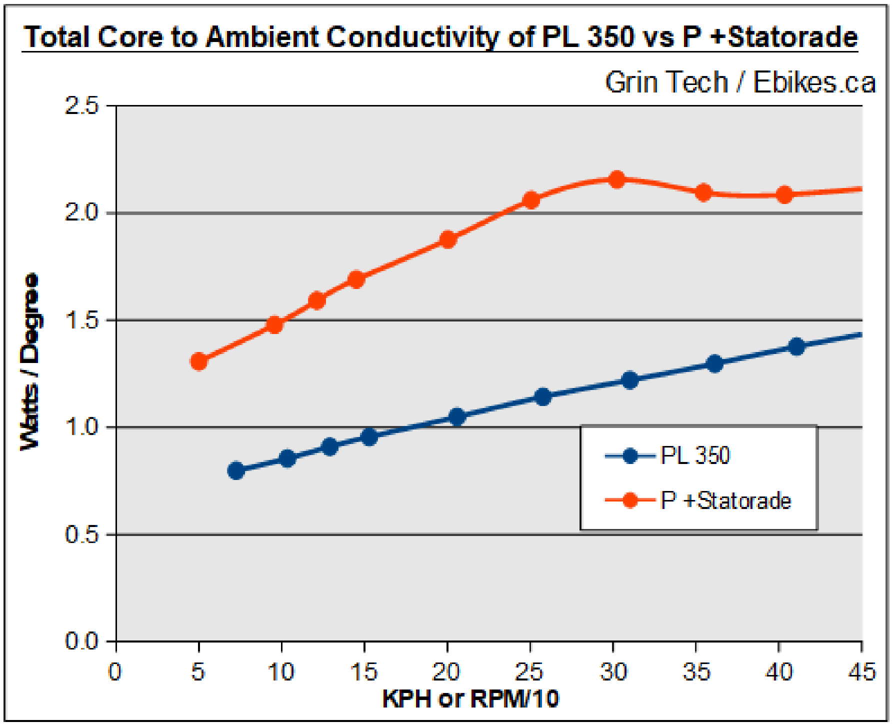

5.3 *Optimal Quantity Fill for PL350*

The amount of Statorade added to a hub motor should be sufficient to improve heat transfer in the operating speed range, but not so excessive as to cause a noticeable increase in the motor drag. The higher the motor RPM, the more Statorade is required to achieve an adequate thermal bridge.

For the next set of tests, Statorade was added to the motor in 1mL increments, and for each fill level the motor was run at 100, 200, and 300 rpm until steady state temperature equilibrium was reached. As well, the no-load current draw of the motor was measured in order to estimate the resulting wheel drag.

With the motor spinning at 100rpm. The addition of just 3mL Statorade had a pronounced effect, increasing the core to shell conductivity from 1.2 to 1.9 W/K, while adding additional Statorade beyond 4mL only gradually increases the conductivity curve, reaching 2.2 W/K at 12mL. The drag torque on the motor remained fairly flat at about 0.5 Nm until about 8mL, and then increased to 0.58 Nm at 12 mL and above.

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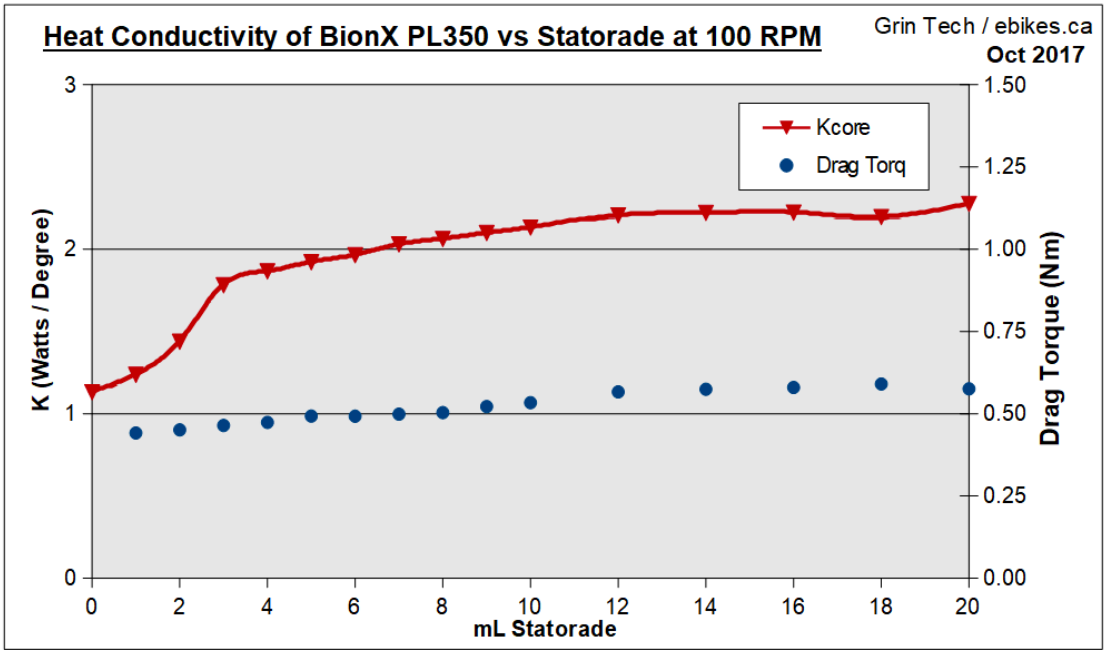
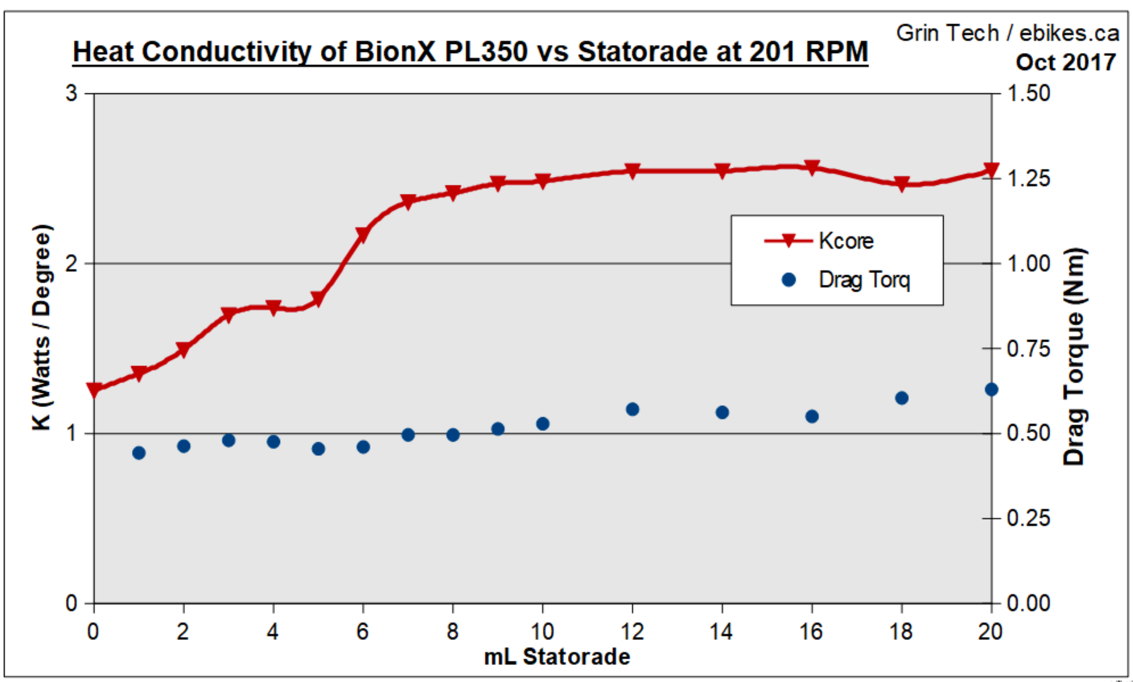


At a higher 200 RPM motor speed, the full improvement from Statorade was not observed until 7mL of fluid has been added. At this point, it has nearly doubled from 1.3 to 2.4 W/K while the drag torque remained largely unchanged at 0.5 Nm. Additional Statorade did not improve the heat flow much, but at 12mL and beyond it resulted in an increased drag to ~0.6 Nm.



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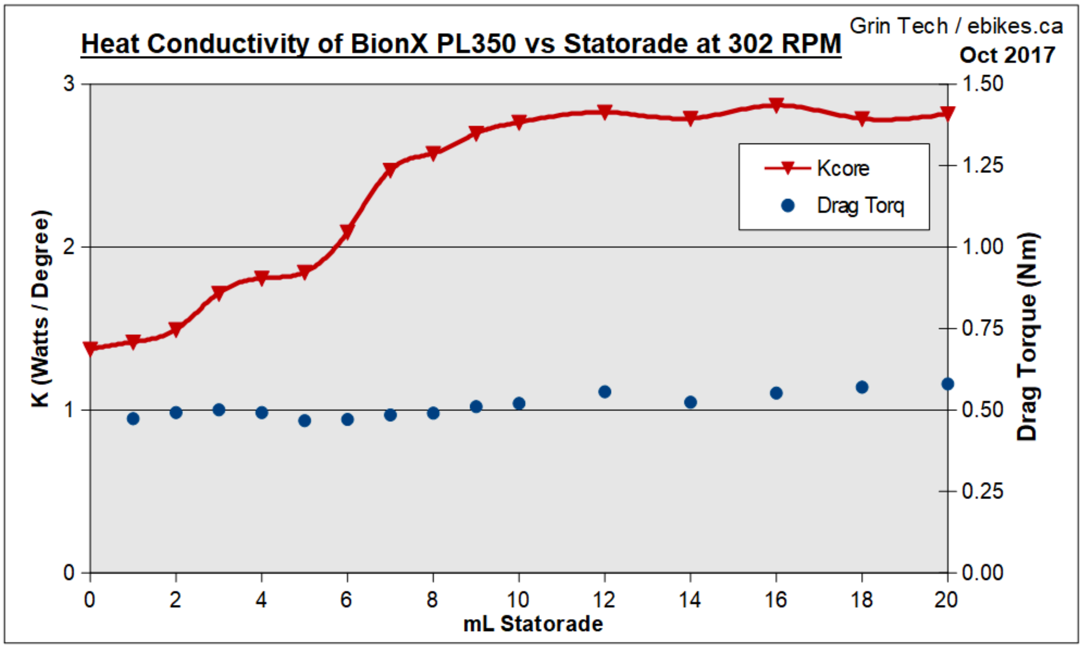
With the motor spinning at 300 rpm, the majority of thermal improvement happens with the first 8mL, but there is additional benefit up to a 12mL fill level.



From this data, we can conclude that a total injection quantity of 8-10mL would be adequate to produce full thermal motor benefits over the typical wheel speed range of an ebike. This quantity would have no detectable increase in drag torque at normal cruising speeds, and only a very slight increase at low speeds with the motor spinning at 100 rpm and below.

Lower quantities would still help with heat dissipation at low motor speeds but would not have as much effectiveness during high speed travel. Quantities above 10mL would have only marginal improvement in thermal transfer and would add viscous drag that increases the motor rolling resistance by about 0.1 Nm.

5.4 BionX D with Statorade

The D series motor was not designed to be opened and serviced in the same way as the PL350 hub, and there were some challenges in closing and resealing the hub after it had been modified to remove the internal controller and add the motor core temperature sensor.

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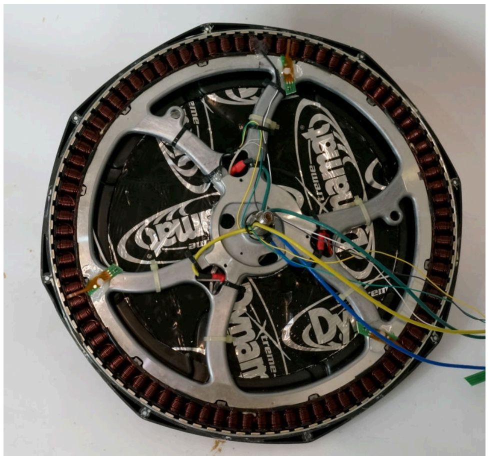
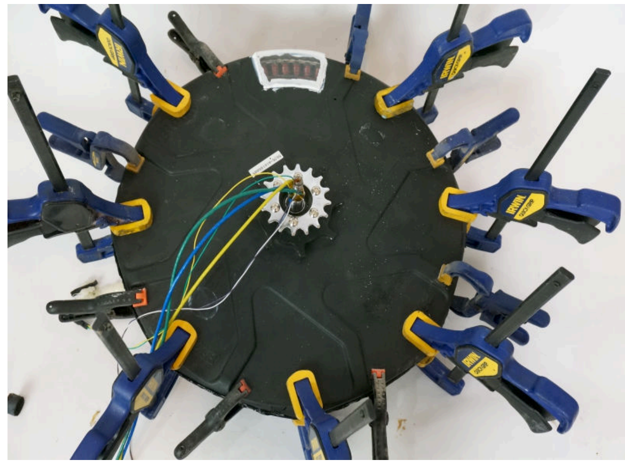
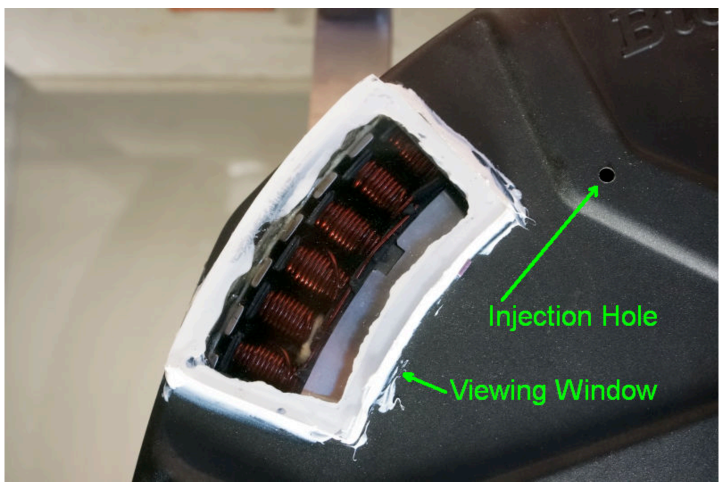




Nevertheless, we were able to reassemble and seal the modified motor and added a clear acrylic window to the motor side cover as a viewing port to see inside.



The motor was similarly tested 100, 200, and 300 rpm with Statorade added in 1mL increments while measuring the core to shell conductivity and drag torques.

At 100 rpm, the addition of 4mL Statorade increased the conduction from 1.64 to 1.97 K/W, or 20%. This is much less of an effect than the PL350 motor, but still not insignificant either. The drag torque at this low 100rpm speed did increase more than we saw in the PL350, from 0.65 Nm with no Statorade to 0.85 Nm once 12mL was added. That is presumably due to the larger radius on which the viscous drag is acting.

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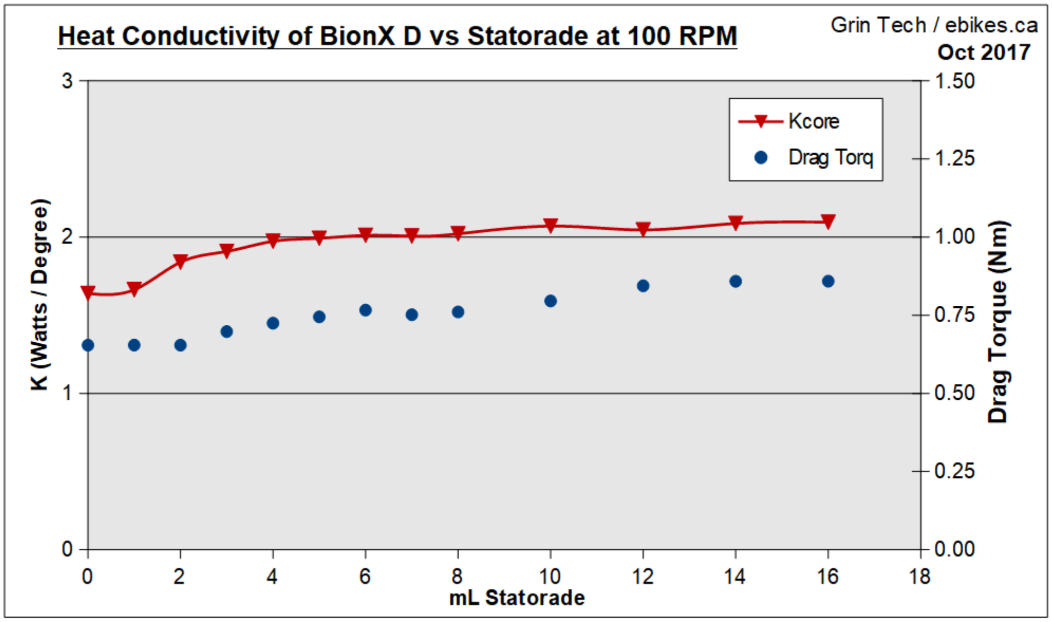
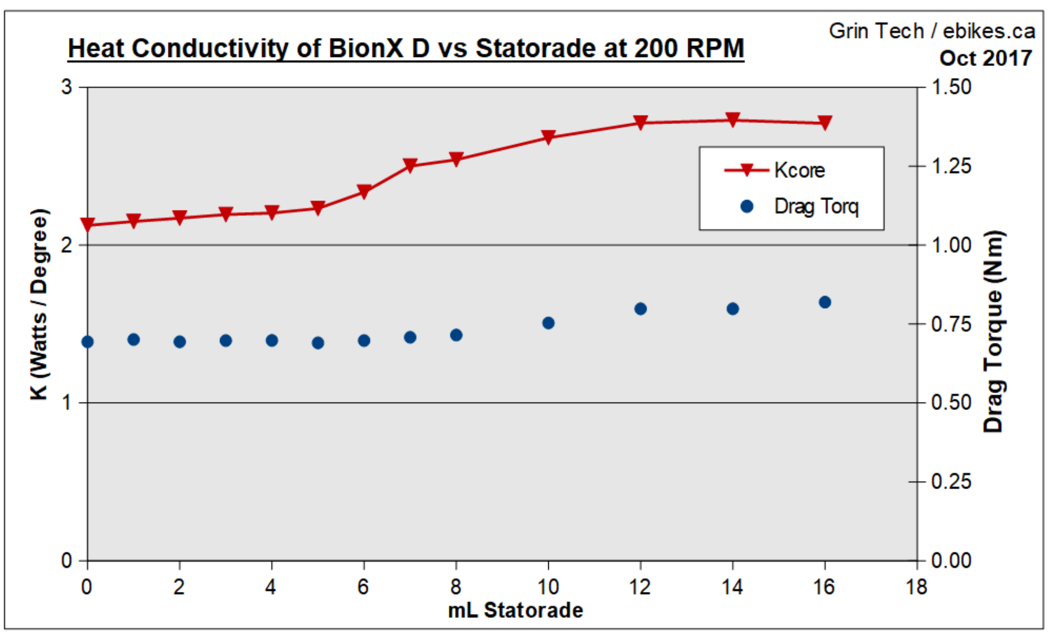
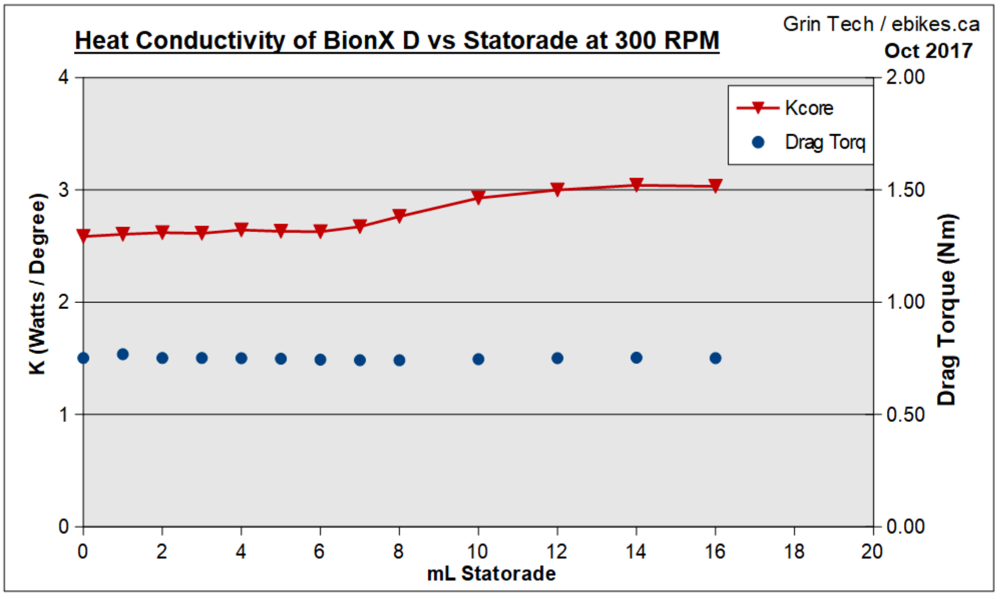


With the motor spinning at a faster 200 rpm, the onset of improved thermal conduction required 6mL and did not reach full effect until the addition of 12mL of fluid. At that point the conductivity had improved from 2.15 to 2.77 W/K, or 28%, while the increase in drag torque was less, going from 0.7 to 0.8 Nm.



With the motor running at 300 rpm, the benefit of Statorade was much less pronounced, with most of the effect happening between 8 to 12mL. At that point, conductivity had increased from 2.6 to 3.0 W/K, or 15%. Meanwhile, there was no measurable change in the motor drag, even when a full 16mL was added.



We can infer that at 300 rpm in such a large diameter motor, most of the Statorade was displaced by centripetal forces and was not bridging the gap between stator and rotor. That explains the lack of increased wheel drag and the reduced thermal effects.

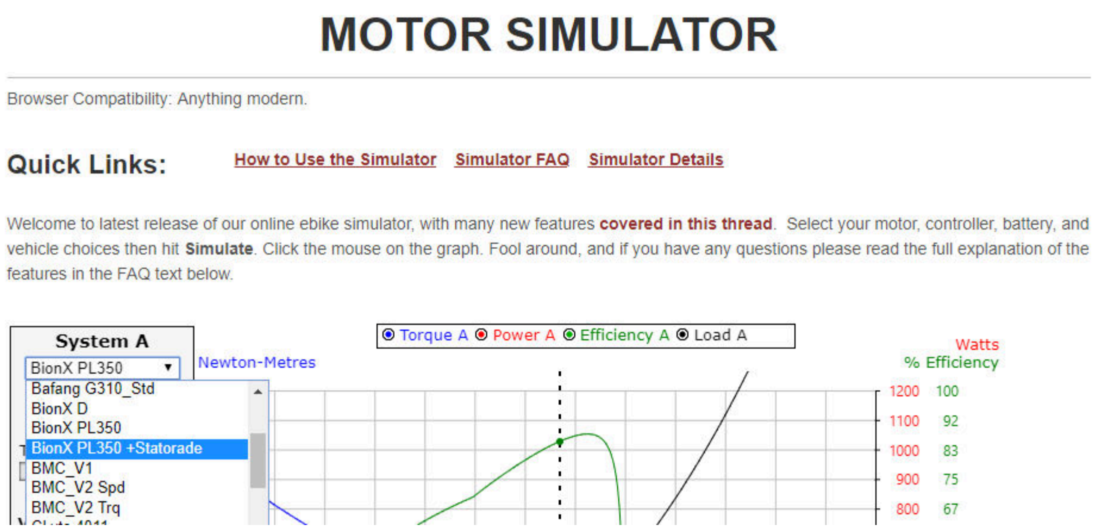
While Statorade does not offer as much of a percentage improvement in the BionX D motor as it does in the PL350, it still a measureable effect in these tests.

6 Performance Ramifications

The data presented so far shows the increased heat conductivity in units of W/K with the addition of Statorade ferrofluid. However, the customer on an ebike is more concerned with questions like "*how steep of a hill can I climb?*", "*How much power can I get from this motor?*", "*Will this hub motor make it to the top without overheating?*"

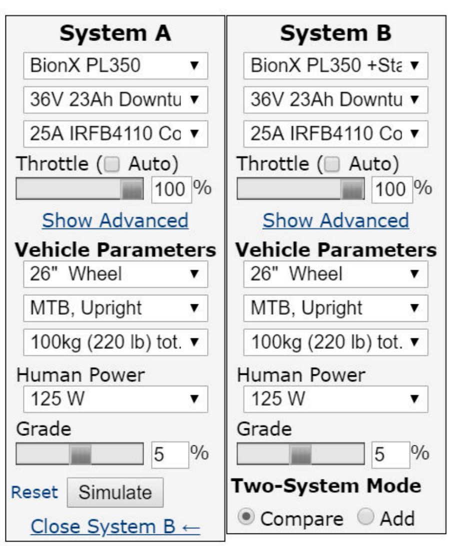
By measuring the thermal conductivities over a wide range of motor RPM's and wind speeds, we are able to model this conductivity as a general function of the bicycle speed. Given the electrical parameters of the motor in section 3.0, it's possible to compute the heat a motor must dissipate when generating a given amount of torque. This heating data combined with the thermal conductivities at the known RPM and wind speed allow for accurate prediction of steady state motor temperatures in real world riding situations.

The working models for the BionX PL350 motor with and without 10mL of Statorade have been added to our motor simulator database here: http://www.ebikes.ca/tools/simulator.html



This tool shows the predicted steady state motor temperature if it is run continuously at the given operating point. If that temperature is higher than 150°C, it also shows the time it would take to reach this overheat temperature.

As an example, suppose this motor is expected to move a 100 kg vehicle up a 5% grade hill using a 36V battery, with the rider contributing 125 watts of power.



Graph	Syst A	Syst B
Mtr Torque	20.1N-m	20.1N-m
Mtr Power	461W	461W
Load	594W	594W
Efficiency	75.2%	75.2%
RPM	219.3 rpm	219.3 rpm

Performance	Syst A	Syst B
Acceleration	-0.04 kph/s	-0.04 kph/s
Consumption	22.5 Wh/km	22.5 Wh/km
Range	38 km	38 km
Overheat In	27 minutes	never
Final Temp	187 °C	92 °C

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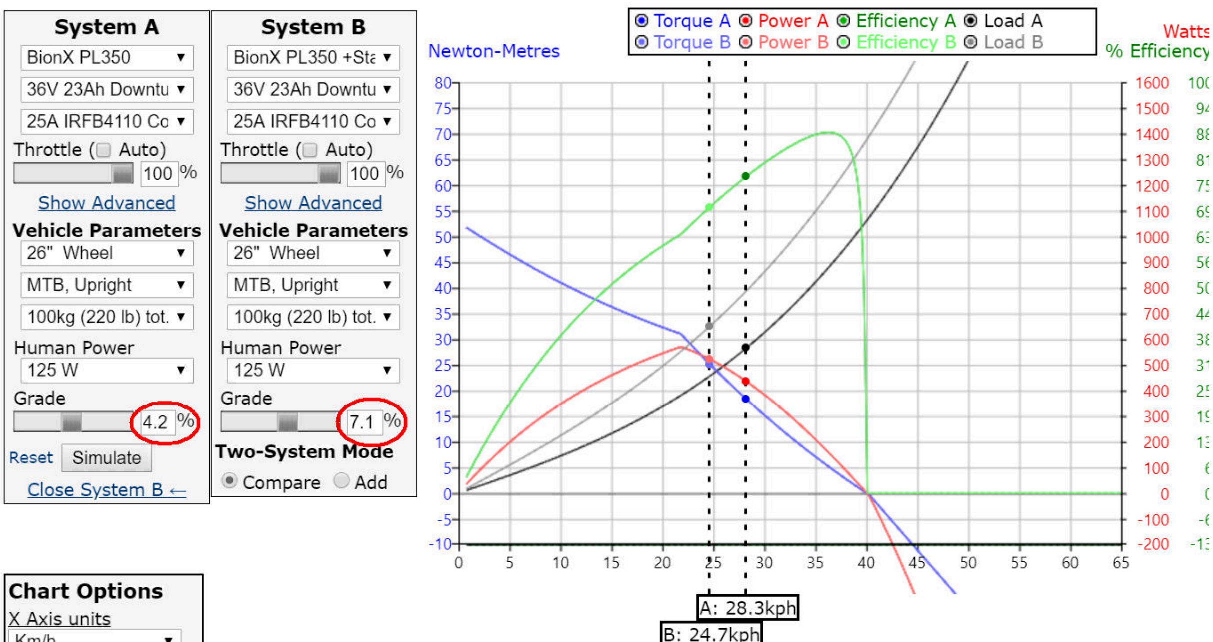
http://www.ebikes.ca/tools/simulator.html?bopen=true&motor=MPL350&motor_b=MPL350_SA&cont_b=C25&cont=C25&grade=5&grade_b=5&hp_b=125&hp=125

In this scenario, the motor is being asked to produce 20 Nm of torque while spinning at 219 rpm. The stock BionX PL350 will reach a core temperature 150°C after 27 minutes, and if the no thermal rollback kicks in it would get over 180°C before reaching steady state. Meanwhile, the PL350 motor with Statorade will be able to run indefinitely at this loading with the motor core stabilizing at a much more comfortable 92°C.

As another example, let's determine the steepest hill that this same rider can expect to climb on a continuous basis without the PL350 motor overheating? To do this we adjust the % Grade sliders on each system until the Final Temp is predicted to be just under 150°C.



Graph	Syst A	Syst B
Mtr Torque	18.3N-m	25.1N-m
Mtr Power	435W	522W
Load	566W	651W
Efficiency	77.1%	69.7%
RPM	227.1 rpm	198.4 rpm

Electrical	Syst A	Syst B
Mtr Amps	16.6A	22.7A
Batt Power	564W	749W
Batt Amps	15.3A	20.5A
Batt Volts	36.9V	36.6V

Performance	Syst A	Syst B
Acceleration	-0.03 kph/s	-0.02 kph/s
Consumption	20.0 Wh/km	30.3 Wh/km
Range	43 km	28 km
Overheat In	never	never
Final Temp	147 °C	148 °C

http://www.ebikes.ca/tools/simulator.html?bopen=true&motor=MPL350&motor_b=MPL350_SA&cont_b=C25&cont=C25&grade=4.2&grade_b=7.1&hp=125&hp_b=125

We can see that the maximum grade hill that can be sustained by the stock PL350 is just 4.2%, while the motor with Statorade is able to climb a 7.1% hill for the same final core temperature. That is a staggering 70% improvement in continuous hill climbing grade just from the addition of 10mL Statorade.

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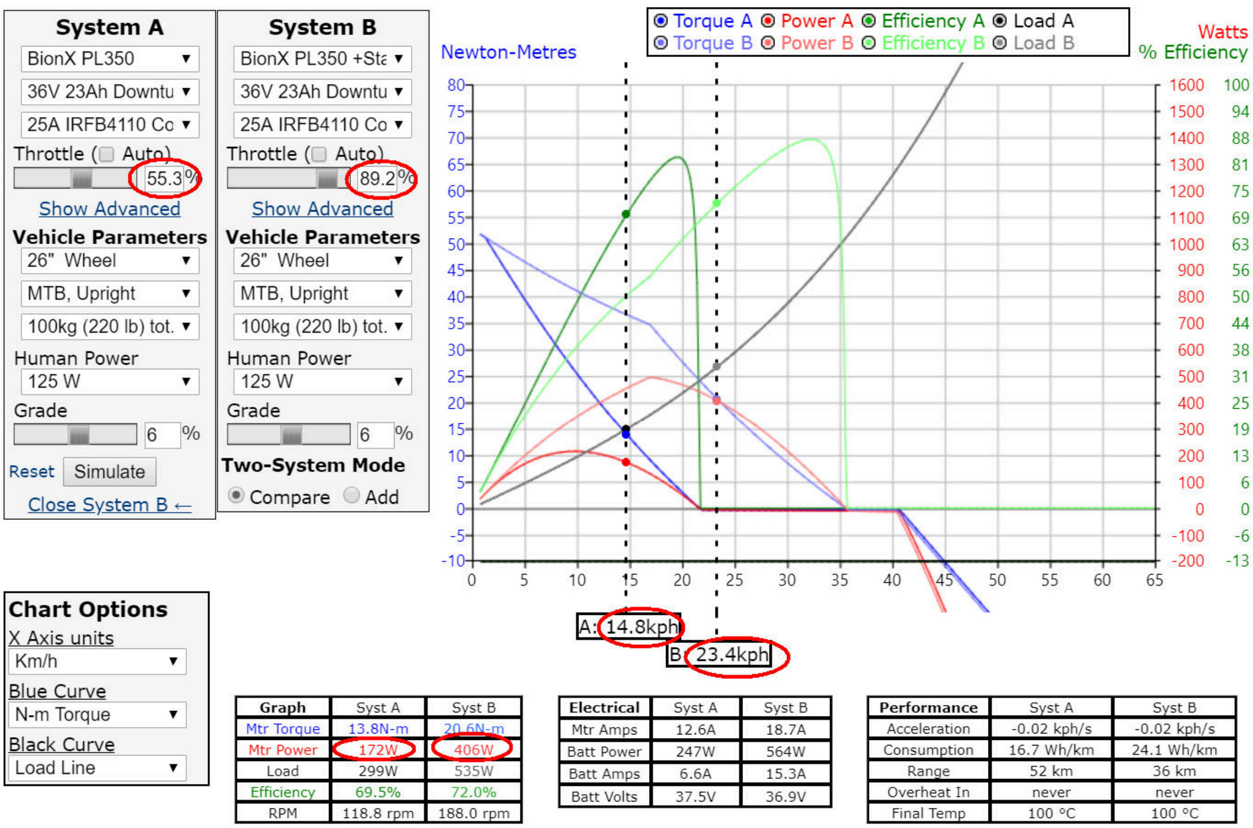
Another means to quantify the improvement is by looking at the continuous motor power output and cruising speed while operating in active thermal rollback. In this scenario, we will assume that the rider is climbing a 6% grade hill putting out the same 125 watts of leg power, and that the motor controller has gone into thermal rollback to prevent the motor from exceeding 100^{o}C. We can determine the resulting climbing speed by adjusting the throttle slider on the simulator to find one that results in a 100^{o}C final temperature.



Graph	Syst A	Syst B
Mtr Torque	13.8N-m	20.6N-m
Mtr Power	172W	406W
Load	299W	535W
Efficiency	69.5%	72.0%
RPM	118.8 rpm	188.0 rpm

Electrical	Syst A	Syst B
Mtr Amps	12.6A	18.7A
Batt Power	247W	564W
Batt Amps	6.6A	15.3A
Batt Volts	37.5V	36.9V

Performance	Syst A	Syst B
Acceleration	-0.02 kph/s	-0.02 kph/s
Consumption	16.7 Wh/km	24.1 Wh/km
Range	52 km	36 km
Overheat In	never	never
Final Temp	100 °C	100 °C

In this thermal rollback scenario, the rider with a stock PL350 would end up climbing the hill at 14.8 kph with the motor only contributing 172 watts of propulsion. Meanwhile, that rider pedaling with the same effort on the bike with Statorade would be climbing uphill much faster at 23.5 kph, with the motor contributing over 400 watts of power.

Not only is the motor putting out over twice as much power, but the motor efficiency would be higher as well due to the greater speed, at 72% versus 69.5%. The net effect in this scenario is that Statorade results in a 58% increase

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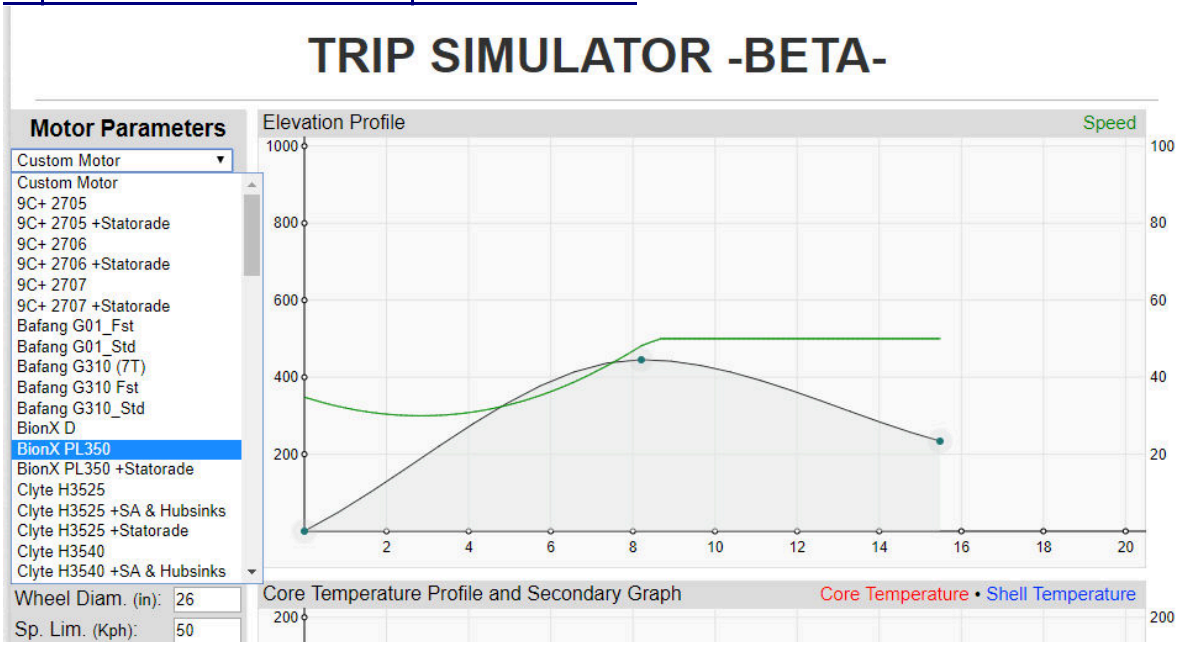
in climbing speed and a whooping 136% increase in the motor's output power, in account of the motor running both at a higher torque and higher RPM.

These examples show some of the expected real world performance benefits that result from improved heat conduction with Statorade, especially in the context of motors like the BionX system which have a built in thermal rollback behavior.

For even more comprehensive comparisons, we have these motor models included in our Trip Simulator web application that simulates and plots entire ebike trips over an arbitrary elevation profile, rather than just at a single point like the motor simulator.

http://www.ebikes.ca/tools/trip-simulator.html



We leave it to the reader to run comparisons of various example trips to see the quantified effects of Statorade in any kind of riding situation.

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7 Conclusion

Both the BionX PL350 and BionX 'D' series hub motors show measured improvement in thermal conduction with Statorade Ferrofluid, but the effects are much more pronounced in the PL350 than the D series hub. A fill level of 8-10mL in a PL350 motor can result in an average 80% improvement in the heat shedding from the motor core to ambient air with negligible effect on motor drag. This in allows the same motor to climb steeper hills, run longer and faster before going into thermal rollback, and experience lower average internal controller temperatures.

On the 'D' series motor, the improvements from Statorade are not as pronounced, in the 15-30% range, and there was a more significant effect of increased drag. This motor already has much better heat conduction than the PL350. It also generates less heat in the first place due to the lower normalized winding resistance, and so motor heating and thermal rollback are unlikely to be problems that need solving. The addition of Statorade would only seem justified in more extreme use cases where every additional benefit is needed.

These tests were all completed in a laboratory environment with motors that were stripped of their internal control electronics. As a next step, we believe that BionX should run field tests of their complete motor systems with and without Statorade added, and use their own data logging tools to independently record the internal controller temperatures and power levels during thermal rollback.

These test results should confirm our predicted improvement levels and provide BionX with firsthand field data to substantiate these claims. That data could further be used in marketing material should BionX decide to partner with Grin in a 2018 product pairing announcement.

Additional tests may be desired to confirm the chemical compatibility and long term stability of Statorade in the BionX motor product. However, after 3 years of field experience with Statorade in motors offered by Grin we have not seen any issues that should give pause for concern. .

As well, we have just recently completed evaporation tests on Statorade to determine if the ferrofluid would eventually loose effectiveness and require a top-up. We have a motor with Statorade that has now clocked over 500 hours running at 120°C at 400rpm without any apparent reduction in thermal performance, and are confident in the longevity of this product.