Who should read this paper?
Anyone with an interest in harvesting hydrokinetic energy in a cold ocean or fluvial environment where icing is anticipated.

Why is it important?
The innovative component of this work was to demonstrate kinetic turbine designs for deployment in cold water environments where icing is anticipated. Results of this work demonstrate the viability of various aspects of operational deployment of a vertical axis kinetic turbine including: anchoring of the turbine; optimization of the turbine design to achieve theoretical performance curves; and grid connection using net metering. Furthermore, the tests showed how the turbine performed in extreme cold weather and when subjected to icing and ice impacts. These results are applicable to river and ocean applications. The research group found that for cold weather applications where formation of frazil or flow ice is anticipated, all turbine components need to be kept below the waterline. The results of this work confirmed that a 5 kW vertical axis kinetic turbine could deliver consistent power to the grid, with peak rotor efficiencies of 35% or better. These results helped New Energy Corporation secure commercial sales and, according to the authors, represent only the third grid connection of a hydrokinetic energy system worldwide.

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OPERATING A 5-KW GRID-CONNECTED HYDROKINETIC TURBINE IN A RIVER IN COLD CLIMATES

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ABSTRACT

A 5 kW Darrieus-type hydrokinetic turbine was deployed in the cold winter climate of Manitoba in the Winnipeg River. Testing revealed numerous insights and considerations needed for the design of permanent installations of in-stream kinetic turbines in rivers located in northern climates. The water/air interface interaction with the turbine and anchored research vessel promoting rapid ice growth when supercooled water came into contact with sub-zero ambient air temperatures. The presence of passive frazil ice caused accumulations in front of the research vessel, impacting the vessel and changing the flow directed to the turbine. Icing negatively impacted the instrumentation deployed. Working on the water in cold temperatures proved to be challenging. Of importance was to establish safety protocols during deployment and operation of river kinetic turbines to ensure the safety of personal. The consistency of the output power was demonstrated during testing as the flow had a variance of 0.02 m/s during the course of a typical day: for the mean flow velocity of 2.06 m/s, the average total power output was found to have a mean of 540 VA with a standard deviation of 24.0 VA. Winter testing revealed that power output was within expectations; however, the total output during the winter test was much lower than expected because of design issues that had to be addressed. The turbine blade arms holding the hydrofoils caused significant power loss and required a series of additional tests to examine alternative arm designs to minimize resistive losses. The new support arms airfoil profile improved the overall efficiencies of the grid-connected turbine to 35%.

KEYWORDS

Kinetic turbine, river hydro, Darrieus, frazil ice, turbine performance, cold climate
INTRODUCTION

Hydrokinetic power is defined as power derived from the kinetic energy of water. There are two main applications where this energy can be commercially exploited: river and marine. Multiple sites for developing marine power have been surveyed and analyzed in Canada while the potential for kinetic hydro river sites has yet to be assessed. Marine kinetic energy can come from tides or ocean currents. Numerous sites have been identified as economically suitable for marine power generation. Preliminary studies conducted in 2008 concluded that there is a gross resource potential of 225 GW of wave and tidal current power in Canada [HATCH, 2008]. Tidal power estimates account in excess of 40 GW with the majority of this power coming from the Bay of Fundy. The other 160-180 GW can be obtained from wave power along the Atlantic and Pacific coast lines. Canada is a unique environment which may also have abundant kinetic hydro power resources from river flow applications. Hydrokinetic power from rivers has yet to be fully investigated and identified: operation of kinetic turbines in winter conditions has yet to be demonstrated. Canada has many river networks that have velocities that exceed 1.5 m/s, suitable for hydrokinetic power: these sites do not accumulate ice cover during the winter months. The potential for kinetic energy from rivers in Canada is presently undefined.

Kinetic turbine technology is currently undergoing much development both for marine and river applications although grid-connected systems remain rare. The National Research Council and Nova Energy were the first in Canada to connect an in-situ kinetic turbine in the St. Lawrence River to the power grid in 1983. The next grid connection within Canada was recently established by the University of Manitoba and New Energy Corporation Inc. (NECI) at the Pointe du Bois site on the Winnipeg River in collaboration with Manitoba Hydro.

This paper presents the findings from testing a 5 kW Darrieus turbine at the Pointe du Bois test site. Manufactured by NECI, the unit was deployed into the Winnipeg River at Pointe du Bois, Manitoba, starting in December 2007. Testing took place during the winter and summer months of 2008 where parameters, such as cold climate effects and overall system performance, were assessed. This is the first winter test of a kinetic turbine operating in a river, revealing many insights towards a permanent installation in northern climates.

ENVIRONMENTAL CHALLENGES IN MANITOBA

There are many issues related to cold weather conditions which have an effect on output and performance as well as posing risks to power generating equipment and personnel. Cold Canadian winters have the potential to negatively impact power production from kinetic turbines. Frazil ice, a sticky accumulation of ice particles within a flow, can have a serious impact on any device operating in supercooled water. Traditional hydro power dams have seen this phenomenon block inlet gates and reduce overall performance by altering the head of the river. The seasonal cycles of northern climates also introduce a variety of floating debris in the form of ice floes and logs. Small and larger hydro structures are designed to withstand the
forces of impacting debris and keep them from impacting the turbine. Kinetic turbines installed in rivers could potentially be vulnerable to these hazards as they are constructed with minimal protection. In addition, ice break-up during the spring season poses a serious threat to any installation as ice floes can potentially impact these units deployed in the rivers, forcing the turbines to be pulled out during winter, or forced to dive down closer to the river bed.

Furthermore, the generation from kinetic turbines for distributed power in various communities has additional concerns. Icing events and high winds can lead to power outages on remote feeders. Kinetic turbine technology could be a way to improve the reliability of the feeders by generating local power near communities whose power can be affected by climate. Therefore, it is essential that kinetic turbine technology be reliable during cold weather and operate problem free during cold temperatures.

**Frazil Ice**
A literature review reveals a limited quantitative knowledge on the phenomenon of frazil ice. Frazil ice exists in two forms: active and passive. Active frazil is sticky while passive is slushy and has poor adherence. More information is available for the active form while the passive form of frazil ice remains relatively unstudied. Qualitative observations have been documented recently because of its negative effect on river and oceanic systems. Frazil ice is defined as small discs of ice measuring 1-4 mm in diameter and 1-100 µm in thickness that form in turbulent, supercooled water [Martin, 1981; Clark and Doering, 2008]. Once formed, frazil ice crystals sinter together with others to form larger structures through what is called “collision breeding.” The larger structures, comprised of a collection of discs, are termed “flocs.” “Pans” are sheets of frazil ice which float to the surface. These have a diameter in the order of 1 m and a thickness in the range of 0.1-0.5 m. Floes are larger pans with diameters from 1-30 m and a thickness of 0.5-5 m.

For the formation of frazil ice, three main factors need to be present: supercooled water, low ambient temperature (our own observations documented at -20°C and lower), and turbulence. In areas of fast flowing water, the lack of ice cover allows heat transfer between the fluid and air resulting in supercooled liquid. Nucleation is the mechanism through which ice forms initially through the formation of small ice particles. High flow velocities may reduce the formation of frazil. Primary nucleation can occur spontaneously or induced artificially. Ice is virtually always nucleated by induced means. Heterogeneous nucleation is the nucleation of supercooled water onto a foreign particle or surface. After primary nucleation, secondary nucleation is the mechanism from which ice propagates. The most accepted means of secondary nucleation is the shearing of potential crystals from its parent crystals when the parent crystals collided with a hard surface or other crystals. From this, frazil ice production can be considered a secondary process. Turbulence is needed to generate the shearing and collisions between parent crystals. Although frazil ice formation is associated with turbulent flows, it does not guarantee its presence. Sufficient intensity must exist for the promotion of frazil ice growth. It is hypothesized that “increasing
turbulence intensity allows larger particles to form due to a higher turbulent energy dissipation rate, until a point when the eddies physically limit that average size of the particles because of their relatively weak mechanical strength” [Fonseca and Roberts, 1987]. Although particle size may decrease, the increased turbulence intensity increases the frequency of collisions and may in fact produce a higher density of smaller frazil ice particles.

The presence of frazil ice in a flow has been observed to adversely affect power generation. These observations have been linked to hydro production from dams. For example, the power loss at the Rivièrè-des-Prairies power plant located on the Saint Lawrence River was found to be up to 30% due to frazil ice blockage [Daly, 1987]. This loss was primarily due to a buildup of ice on the inlet vanes. The Niagara River has experienced reduction in flow as large as 25% due to frazil ice accumulation. The best solution to control frazil ice is to prevent its formation by promoting the growth of a stationary ice cover over the upstream river section [Bergander, 1987; Gemperline, 1991; Arden and Wigle, 1972]. The ice cover acts as insulation, keeping the waters from becoming supercooled. This eliminates the growth of active frazil ice locally under the cover, as well as reducing incoming active frazil to convert into passive frazil which is far less harmful. Passive frazil is derived from its active form when the waters warm above supercooled values. The passive frazil particles are slush-like in appearance and do not exhibit the strong adherence characteristics of the active form. Rather than attaching to foreign substrates, passive frazil clumps together and can clog hydraulic structures, reducing flow conveyance and increasing head losses [Arden and Wigle, 1972]. For kinetic turbines, the impact of frazil ice is difficult to control as experienced at the Pointe du Bois test site. Passive frazil was found to build up quickly around the research vessel at stagnation points. As the slush ice accumulates on these points, the potential to reduce and re-direct the flow becomes evident and this is the effect which poses operational concerns for river kinetic turbine power generation.

Anchor ice is another phenomenon of potential concern since an underwater anchoring system is used to secure kinetic turbines at the Pointe du Bois test site. When active frazil attaches to the river bottom, it forms anchor ice and this affects the hydraulic characteristics of the flow. The Niagara River saw a 20%-30% flow reduction due to anchor ice [Fonseca and Roberts, 1987; Faure et al., 1986]. It has been known to attach itself to rocks at the river bed and transport them hundreds of metres downstream of their initial position. Anchor ice could also release from its substrate and float to the surface, posing a threat of impact on the way up. This type of ice accumulation could pose serious risk from impacts and abrasion on the main underwater anchor lines used on some designs of river kinetic turbines in cold climates.

**Winter Testing Conditions**

Weather data for the past 10 years (1998-2008) was analyzed to quantify the degree of cold experienced during the test phase with relation to typical years. Figure 1 shows the daily average for each day of the three winter months during the tests along with the average temperature over the past 10 years taken from the Environment Canada web site. The year
2008 was, for the most part, on the colder fringe of what Manitoba experienced from year to year, so testing in this weather yielded valuable experience of what to expect for a long term installation.

The conditions at Pointe du Bois have the potential for frazil ice; however, documented observations of its presence are limited to mainly the passive form. The entire area, 400 m upstream of the dam and beyond, is fully covered by stationary ice all winter long and this prevented the formation of active frazil ice. However, the area in the vicinity of the dam where the test facility is located remains uncovered all winter long.

**Icing Observations**

A 5 kW vertical axis turbine manufactured by New Energy Corporation Inc. was deployed on the Winnipeg River and located upstream of the Pointe du Bois Hydro Dam: a hydro plant operated by Manitoba Hydro. The turbine was mounted on a large aluminum vessel that consisted of two large pontoons. The vessel was held in place by anchors drilled and cemented into the river bottom. Figure 2 shows the research platform as seen with the remote camera during a severe cold weather episode. Pancake ice consisting of a thin layer of transparent ice floating at the surface and causing no accumulation was observed when temperatures dropped below -20°C, as shown in Figure 3. Observations of frazil ice appeared in its passive and slushy form in early February when temperatures were below -20°C. The frazil could be seen floating in the water just below the pancake ice. The passive frazil ice flowed near the surface of the water and was observed to be in
the form of strips on the order of 0.1 m wide and 0.5 m long. This type of frazil ice is not sticky by nature and hence it did not stick to the research vessel or the turbine itself, but large agglomeration piled up in front of the pontoons. This caused a stagnation pressure, redirected the flow, and tipped the research platform so that the front of the vessel was almost submerged. The scale of the kinetic turbine with respect to the scale of the passive frazil build up presented no concerns for blockage for the turbine; however, the inlet flow to the rotor was altered by the accumulation on the leading edge of the research vessel. The chains present another object for passive frazil to build up on. The collection of frazil ice weighed heavily on the chains and contributed to increase the overall anchor load. Passive frazil creates a safety concern as anchor loads are increased, additional drag at the bow changes the pitch of the research vessel. Operation of a Zodiac safety boat causes performance issues: frazil ice impacted the Zodiac boat’s control by inducing jerky motions when the propeller hit a patch of frazil.

Hard ice which forms directly on the research vessel is primarily due to secondary processes and the turbine blades were never observed to be covered in ice during normal operations. However, ice forms on all surfaces just above and below the water line. Within a day, ice could form onto the aluminum pontoons and anything else that is placed at the water/air interface. Metallic objects in the water present a substrate which accommodates primary nucleation; plastic and rubber materials also let ice adhere to the surface. The main aggressor of ice formation above the waterline is splashing. As water collides with the research vessel or from the vessel’s rocking motion resulting from waves and wind, a thin film of liquid adheres and instantly freezes when in contact with colder air. Figure 4 shows a picture taken at the same time every day for five consecutive days, giving a time lapse view of ice growth on the research vessel.

Stagnation points and wakes result in a surge of fluid which rises and falls, splashing surrounding surfaces with a douse of water. When the water recedes, the thin film of water remaining on the surface turns mainly into glaze ice and eventually forms an ice sheet of several cm in thickness. As the splashing

Figure 3: Inactive frazil flowing under pancake ice.

Figure 4: Time lapse ice formation on research vessel.
continues, the secondary nucleation process freezes more water to the substrate layer after layer. Splashing allows the ice to grow out from the water and eventually it reaches the underside of the research platform. The chains that anchor the research vessel at the bow were the most susceptible to ice formed by splashing. Water droplets will splash along the length of the chain out of the water. Freezing on contact to the cold steel, ice grows along the chain and encases the linkage point with the research vessel. This process accelerates when the temperature dips below -20°C.

In addition, passive frazil was found to accumulate on the submerged portion of the chain. When the chain iced over, the smooth round surface of the ice cover reduced the severity of the splashing. At this time, a smooth wave occurs at the stagnation point where the chain ice meets the waterline. This encouraged further ice growth that propagates radially creating a flattened area of ice at the water’s surface. With the buildup of ice at its worst, the bow of the platform is only a few inches from the surface of the water and waves off of the nose of the pontoons are able to reach the deck. Removal of the ice would see an instant righting of the deck height to its original, non-iced position approximately 0.5 m above the waterline. Icing of the vessel altered the pitch of the research vessel and thus the turbine’s angle in the flow rotated from the vertical by a few degrees.

The pontoon design of the research vessel adds a new dimension to ice growth as the wake of the flow around the pontoons caused sizable waves which allowed the water to splash up half way between the waterline and the platform. The ice that formed directly on the pontoon was found to be up to two feet thick at times. As ice propagated outward, the ice from one pontoon extends to meet with the other pontoon, creating a flat surface of thick, solid ice under the deck. Figure 5 shows the free surface under the deck frozen from pontoon to pontoon. The thickness of the pontoon ice is also shown as well as ice which formed on the chains. The rear quarters were the first to ice over completely and there was no free surface aft of the turbine. The consistent rush of water and the rotating shaft of the turbine prolong ice from forming directly on the turbine’s shaft until the rear and pontoon ice grows in its way. The turbine would eventually be stalled by the ice when the ice came into contact with the top portion of the rotor blades.

Instrumentation which resides within or pierces the water line often did not survive long as ice growth and removal can have a damaging effect. Precautions were taken to support the flow meter, load cell, and cameras placed under water by incorporating rigid mounting structures. The sensors failed within the support structure and impacts from ice floes were enough to bend thick wall steel
pipes that protected the sensors. Working on the vessel also required cold climate considerations as working in sub-zero temperatures was detrimental to machine and humans alike. It was found that synthetic oil had to be used as many testing days the temperature was close to -50°C with the wind chill factor. The turbine gearbox and generator were covered by an insulated housing and heated to keep the oil warm. Tools and data acquisition equipment required heated housing and safe keeping from the elements.

TURBINE PERFORMANCE

The results of winter testing show the consistency and versatility of this technology. After the multiple ice floes impacts to the rotor during the winter, the blades were removed and inspected to find only minor small dents along the trailing edge. When replaced with new parts, the rotor operated without noticeable improvement showing the versatility of the vertical axis design. Direct impacts from floating objects were deflected by the rotor, proving the design’s durability in northern climates.

The turbine’s mean output was steady, giving hydro power its advantage over intermittent generation. Using hourly averaged data over a day, the turbine produced 539.3 VA with a standard deviation of 24.3 VA. The flow held steady with a mean rate of 2.06 m/s, having a standard deviation of 0.02 m/s. The consistent trend of power output continued day by day. Throughout winter testing, the turbine exhibited efficiencies around 15.9%, which is significantly less than rated performance as there was a significant source of power loss: the support arm design.

The four-blade Darrieus turbine used two sets of four arms. The original design of the 5 kW turbine had arms that are profiled to reduce their drag. The turbine tested during the winter, however, had flat bars for arms. The drag forces created by the blunt arms significantly reduced the overall performance. This prompted a study into the power loss due to support arms to find the source of the power loss. Other theories were put forward including the effect of the pontoons on the turbine.

To quantify the amount of power loss due to support arm design, the 5 kW unit was tested with three arm profiles, shown in Figure 6, in four different configurations:

1. Flat bar arms: These arms were used during the winter test phase.
2. Profiled arms: Flat bars were CNC machined to the general shape of a symmetric airfoil.
3. Profiled arms in front: The turbine location was changed from the rear quarter to the forward quarter to quantify the effect of the wake from the pontoons on power.
4. Hydrofoil arms: Extruded arms in the shape of the hydrofoil were used as the supports.

Note that the turbine was originally designed to use the profiled arms. All data which refers to rated turbine parameters are based on that configuration.

**Rotor Output**

The results of the support arm testing show that the optimum tip speed ratio (TSR) varied with the different arm profiles as shown in Figure 7. The performance curves shift to the right as the drag on the arms reduces through the various arms tested. Along with the shift, there is a broadening of the top peak, translating into efficiencies being less sensitive to TSR fluctuations. The higher drag of the blades made for a sharp and steep power curve. The smoothest hydrofoil arms perform the best, peaking at 35.4% at a TSR of 2.24. The higher level of performance is maintained over a wider range of TSR with a broad power curve. During testing it was noticed that the wake off the back side of the turbine was noticeably reduced for the hydrofoil arm, the overall performance improved. The turbine self started easily without the requirement of a motor, and it ran noticeably smoother.

The increased output to the grid between the profile and hydrofoil is 6.3%. The delivered power to the grid was used to determined the overall efficiency; however, the losses incurred by the inverter, the drive train (gearbox and generator), and the wakes off the pontoons all contribute to a reduction in the efficiency at which the rotor operates. Accounting for these losses and adding it to the power output yields the true rotor efficiency. The pontoon losses are quantified by the two profile arm tests. The difference in power output between the profile in the rear and front sections is attributed to the pontoon wakes.

Table 1 shows a breakdown of the power lost due to all sources along the path from grid to rotor. Figure 8 shows the power extraction breakdown from the available kinetic energy in the flow to the power delivered to the grid. It shows the limitation imposed by Betz and the power output after the various losses. Note that each test series is subjected to the available flow velocity in the river during that test period. Dam maintenance operations downstream sometimes required spilling water.

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Table 1: Power losses and rotor efficiency.
upstream of the kinetic turbine resulting in reduced flow velocities.

During summer and winter tests, the turbine installed with a flat bar performed at a constant efficiency, delivering 15.9% of the kinetic power from the water to the grid. This result indicates that the cold climate does not affect power output when the free stream is unobstructed by ice. Outfitted with the profiled arms, the rotor delivers 28.6% of the kinetic energy to the drive train. With minimal wake interference at the front, the TSR increases and the rotor output of 29.1% reaches closer to the design mark of 30.3%. The hydrofoil arm exceeded the rated rotor efficiency. This result was expected as the rated design is that of the profile arms. With far smoother contours, the hydrofoil reduced drag enough to see a 6.3% increase in rotor efficiency.

Other tidal applications have found efficiencies in the range between 33%-35% for a straight, non ducted design [Faure et al., 1986; Antheaume et al., 2008]. Ducted systems show great promise in maximizing the kinetic energy extraction from a flow. Efficiencies were found to increase up to 55% [Kiho et al., 1996]. Optimization models have shown an accelerated flow by factor of 1.5 [Ponta and Jacovkis, 2008]. Kinetic hydro offers the opportunity to build natural and artificial ducting networks; however, the added costs, design efforts, and ecological considerations of such a structure remain the major trade off when designing a kinetic turbine. The addition of these factors significantly increases the potential level of risk during turbine deployment and retrieval [Gaden and Bibeau, 2008; Khan et al., 2008].

CONCLUSIONS

The 5 kW vertical axis kinetic turbine delivered steady power to the grid, peaking with rotor efficiencies over 35% and delivering power consistently. The technology proved itself versatile in the summer; for winter conditions, icing issues need to be addressed. The advantages of the vertical axis turbine include its ability to deflect impacts and minimize significant damage to the rotor, and maintaining its power output throughout the various seasons, thus demonstrating its durability and reliability. Hydrofoil support
arms perform the best because they contribute the least amount of drag to the rotor’s dynamics. With these support arms, the turbine was able to self start in flows of over 2 m/s, contrary to some literature studies which list the Darrieus turbine as unable to self start when grid connected.

During the coldest days of the winter of 2008, the entire research vessel would be encased in ice along with the turbine within a week’s time. This situation proved itself to be dangerous to the equipment, so ice was cleared on a regular basis. It would not be viable to operate this technology with the upkeep of de-icing the unit throughout the winter. The unit’s support structure would either be designed to freeze in place or be submerged if no design consideration is made to mitigate the icing issue. If placed at the surface, the unit still requires protection for floating debris all year round.

REFERENCES


