Mini Project Report

Thermal dynamics of tidal stream generators

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22/05/12

The University Of Sheffield.

ASSIGNMENT COVER SHEET 2010/2011

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Introduction

The ocean is a fertile breeding ground for organic life; conversely, this makes it a hostile environment for machines. Macrocellular life is pervasive enough to contaminate any structure placed in the sea within hours, the larger and more damaging life forms follow within a year [1].

However, if this barrier can be overcome then there is a plentiful supply of energy waiting to be harvested. Tidal currents alone have a technical potential of 0.17 EJ/yr, this is just a fraction of the power the oceans contain [2].

Tidal stream generation is an infant technology that harnesses tidal currents; it operates similarly to wind farms but takes advantage of the fact that water is far denser than air. In addition to the difficulty of operating machines underwater, it faces obstacles in transmission.

Tidal Generation are a team developing prototype generators, their distinguishing features are that they rotate with the tides so that blades need only be optimised for one directional flow, and that the main working part (the nacelle) is buoyant so can be retrieved with relative ease [3].

Aims

Initially, the aims of this project were to assess the role of heat in the degradation of underwater tidal stream generators. Later, these aims were expanded to incorporate some lab time in order to assist the experiments of a full PhD (Eleanor Ramsden) in the same field. The aims of the project as a whole are to aid industry in their development of tidal stream devices.

Outcomes of this mini-project would then hopefully be an understanding of the thermal dynamics of an underwater turbine and how this relates to corrosion and biofouling.

Experimental description

Two approaches were taken in this mini-project: mathematical analysis to construct a heat distribution model and corrosion testing in the lab.

The model was constructed on the principles and equations in [4]. Several parameters were known: the nacelle wall thickness, its thermal conductivity, the nominal flow rate, and both the ambient temperatures of the inside and outside of the system. Using this information to construct a heat map only needs two more pieces of information, the heat transfer coefficients of the air within and the seawater outside of the nacelle. It is reasonable safe to assume the first based on the literature, as for the second, we take over a range of values to guarantee its validity.

Below are the two equations that drive the model.

heat flux = temperature gradient / sum of resistances

surface temp = ambient temp + (heat flux/heat transfer)

Initially, we give the variables particular values to see how the system reacts to their changes. Based on this, the model is refined to examine these sensitive changes and we plot all the data that is meaningful. That is, data which is likely to correspond to real events and also shows what parameters are most crucial / problematic.

We further the model by analysing what effect biofouling and corrosion has on the heat distribution. Fouling and rust are treated as added layers of insulation for the nacelle.

In the lab, corrosion tests were done using a potentiostat. This involved electrolysis of metal samples in artificial sea water with a three electrode system. Corrosion rates for various metals are already well documented; these tests would study the influence of temperature, salinity, flow and dissolved oxygen. Four types of metal were chosen for testing, aluminium bronze, carbon steel and two types of cast iron. By controlling the four influencing factors, sixteen versions of the test could be operated on each of the four metals; with a complete set of data it will be possible to assess each factor and their relationships with each other.

Findings

The model is a very generalised one. We are trying to find a particular temperature in an environment that ranges from 3 ^{o}c to 30 ^{o}c. Also, depending on the flow conditions the heat transfer coefficient, h2, is likely to vary (from 10 to 400 W/m^{2}k). Immediately, this creates a two dimensional array of data for the heat flux q_r``as shown in the appendix.

We see that the variation in heat flux is more sensitive to the temperature gradient than it is to the heat transfer coefficient (values change more moving vertically than they do horizontally). With the data in the table we compute the outer wall temperature and compare this to the ambient sea temperature.

The highest temperature predicted by the model is 33.3 ^{o}c, with the warmest ambient temperature and the slowest flow. Reducing the flow rate allows the stagnant water to suck up more heat. Relatively, the biggest change in temperature is with low ambient temperature and low flow, an increase from 3 ^{o}c to 15 ^{o}c.

Considering the effects of fouling and rust on the nacelle's heat map we see that as their respective thermal conductivities are lower than carbon steel, they allow less energy to escape. If we look at the surface where the fouling or rust meets the sea then it is follows the same pattern as a clean wall, i.e. closer to the ambient temperature with higher flow. However, if we look underneath these layers of fouling or rust then the expected temperature is much nearer the inner temperature of the nacelle.

The findings of the lab tests are currently incomplete but are expected to be finished by autumn 2012.

Discussion

Using the model we can give reasonably accurate predictions of the temperature of the outer nacelle wall for a given environment. However thermal dynamics are more complicated than this, we introduce the concept of a boundary layer. Close to a surface the forces of friction acting on a fluid are stronger; a layer forms around the body that approximates its velocity and temperature [4]. Behind turbine blades and especially in the ocean, flow is likely to be turbulent. This makes the calculation of a boundary layer thickness difficult. In any case, temperature increases the longer a fluid flows inside the boundary layer so we would expect the warmest parts of the nacelle to be those furthest downstream.

Also, it is evident from the findings that with low flow comes greater heating, so we can expect some of the hottest parts of the nacelle surface to be those that are shadowed from the ocean current, especially those that are rotated with the changing tide and so are always shadowed.

Illustrations on Solidworks highlight these problem areas. See appendix.

Looking at the data we see that if h2 is equal to or larger than qr`` the temperature in the boundary layer insignificantly hotter than the ambient. At lower temperatures more energy leaves the nacelle, whilst with higher flow the energy is absorbed into the system quicker.

Also, we have that biofouling acts as an effective layer of insulation, so once a section of the nacelle becomes fouled then this fouling will both slow the flow of water around it and also trap more heat. Thus, once fouling kicks in it is likely to propagate its own growth. This fits in with observations of barnacle cultures, they need to cluster to mate as in their adult stage they are sessile.

Conclusions

Foremost, it is clear that conducting analysis into volatile systems (such as oceanic flow) is precarious. A simple model is easy to compute and to generalise but limited in its reliability and scope. The original aim for the model was for it to highlight the hotspots in the structure, to some degree this has been achieved. If the system behaves as the model assumes it will, then the hotspots highlighted will be accurate, but after discussion with members of Tidal Generation it seems more information is needed on the flow patterns of water to have any surety in these findings.

Also, one of the primary limitations of the model was thought to be treating the heat produced in the generator as an infinite source (constant 40 ^{o}c air temperature), however it after meeting the development team it seems that this is an accepted, standard method.

The model is a solid first attempt; it could be much improved with more data. Its main strength is not in how accurately it can predict but in what it shows to be the most crucial factors in causing hotspots. Essentially, stagnant flow, caused through shielding from the device itself or by attached barnacles.

Further work in this area could focus on the thermal dynamics inside the nacelle and rotor mechanism and use the results of the lab work to find out what areas need to be targeted for anti-corrosion/anti-fouling techniques.

Appendix

External temperature (vertical axis) vs Ocean heat transfer coefficient h2 (hortizontal)

	400	350	300	250	200	150	100	75	50	25	10
30	49.4	49.3	49.2	49.0	48.8	48.4	47.6	46.9	45.4	41.7	33.3
27	64.2	64.1	63.9	63.7	63.4	62.9	61.9	60.9	59.1	54.2	43.3
24	79.0	78.8	78.7	78.4	78.0	77.4	76.2	75.0	72.7	66.6	53.3
21	93.8	93.6	93.4	93.1	92.7	91.9	90.4	89.0	86.3	79.1	63.3
18	108.6	108.4	108.2	107.8	107.3	106.4	104.7	103.1	100.0	91.6	73.3
15	123.4	123.2	122.9	122.5	121.9	120.9	119.0	117.1	113.6	104.1	83.3
12	138.2	138.0	137.7	137.2	136.5	135.4	133.3	131.2	127.2	116.6	93.3
9	153.0	152.8	152.4	151.9	151.2	150.0	147.6	145.3	140.9	129.1	103.3
6	167.8	167.5	167.2	166.6	165.8	164.5	161.9	159.3	154.5	141.6	113.3
3	182.7	182.3	181.9	181.3	180.4	179.0	176.1	173.4	168.1	154.1	123.3

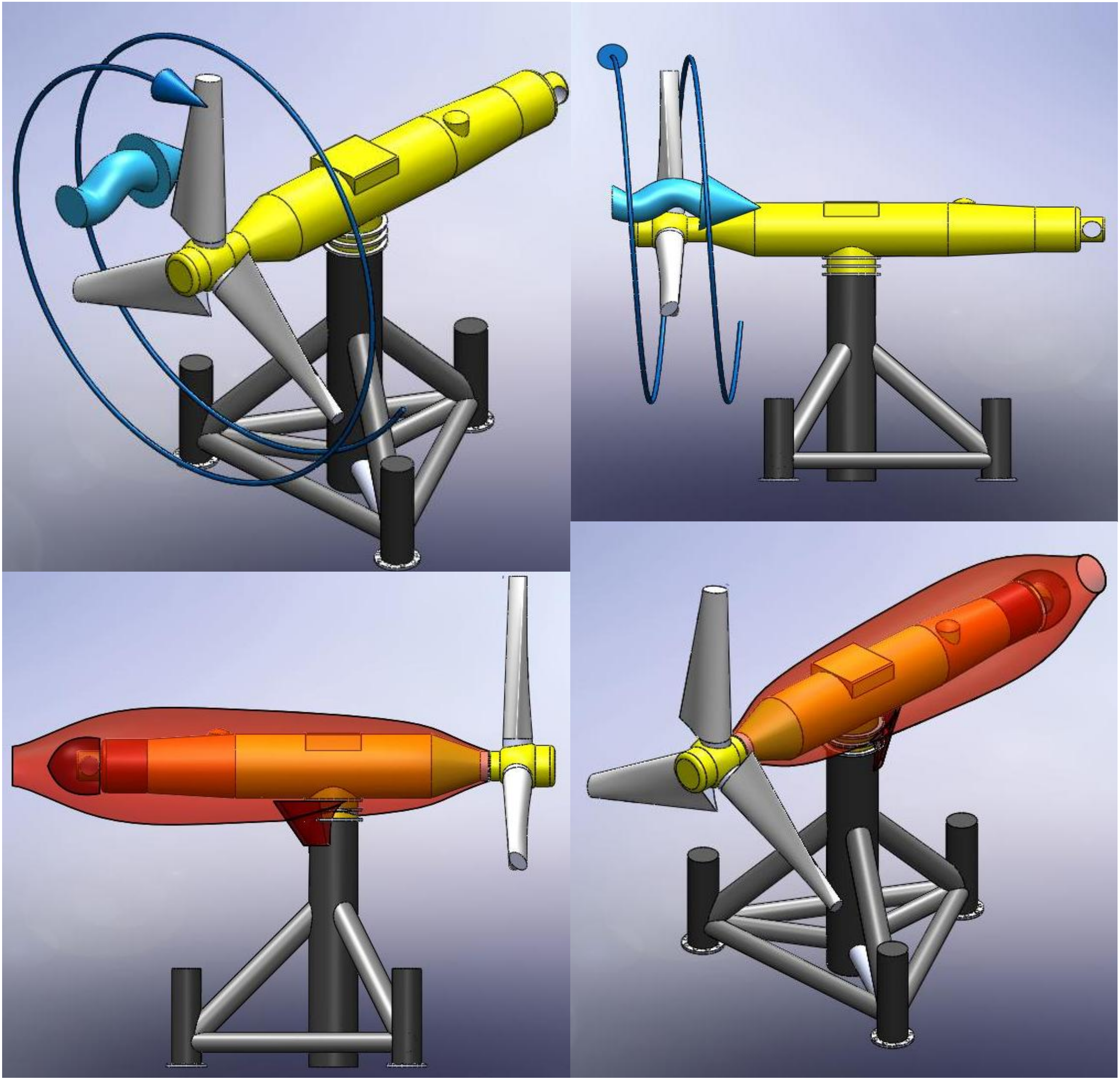
Figure 1: Values for q_r''

	400	350	300	250	200	150	100	75	50	25	10
30	30.1	30.1	30.2	30.2	30.2	30.3	30.5	30.6	30.9	31.7	33.3
27	27.2	27.2	27.2	27.3	27.3	27.4	27.6	27.8	28.2	29.2	31.3
24	24.2	24.2	24.3	24.3	24.4	24.5	24.8	25.0	25.5	26.7	29.3
21	21.2	21.3	21.3	21.4	21.5	21.6	21.9	22.2	22.7	24.2	27.3
18	18.3	18.3	18.4	18.4	18.5	18.7	19.0	19.4	20.0	21.7	25.3
15	15.3	15.4	15.4	15.5	15.6	15.8	16.2	16.6	17.3	19.2	23.3
12	12.3	12.4	12.5	12.5	12.7	12.9	13.3	13.7	14.5	16.7	21.3
9	9.4	9.4	9.5	9.6	9.8	10.0	10.5	10.9	11.8	14.2	19.3
6	6.4	6.5	6.6	6.7	6.8	7.1	7.6	8.1	9.1	11.7	17.3
3	3.5	3.5	3.6	3.7	3.9	4.2	4.8	5.3	6.4	9.2	15.3

Figure 2: Temperature of the external nacelle wall

	400	350	300	250	200	150	100	75	50	25	10
30	0.1	0.1	0.2	0.2	0.2	0.3	0.5	0.6	0.9	1.7	3.3
27	0.2	0.2	0.2	0.3	0.3	0.4	0.6	0.8	1.2	2.2	4.3
24	0.2	0.2	0.3	0.3	0.4	0.5	0.8	1.0	1.5	2.7	5.3
21	0.2	0.3	0.3	0.4	0.5	0.6	0.9	1.2	1.7	3.2	6.3
18	0.3	0.3	0.4	0.4	0.5	0.7	1.0	1.4	2.0	3.7	7.3
15	0.3	0.4	0.4	0.5	0.6	0.8	1.2	1.6	2.3	4.2	8.3
12	0.3	0.4	0.5	0.5	0.7	0.9	1.3	1.7	2.5	4.7	9.3
9	0.4	0.4	0.5	0.6	0.8	1.0	1.5	1.9	2.8	5.2	10.3
6	0.4	0.5	0.6	0.7	0.8	1.1	1.6	2.1	3.1	5.7	11.3
3	0.5	0.5	0.6	0.7	0.9	1.2	1.8	2.3	3.4	6.2	12.3

Figure 3: Difference between ocean and external wall temperatures



References

[1] Literature Review of Marine Biofouling; Eleanor Ramsden 2012

[2] IPCC report http://srren.ipcc-wg3.de/report/IPCC_SRREN_Full_Report.pdf page 506

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[4] Heat Transfer Essential: A textbook; Latif M.Jiji; Begell House, Inc. New York; Wallingford, UK