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Energy harvesting in a diver's rebreather system

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1 Appendices

Appendix A Alternate sources not investigated

Alternate methods are available but have not been investigated in this project due to impracticalities imposed by the method or the method not being viable in the underwater environment. (Paradiso & Starner, 2005) And (Dewan, et al., 2014) summarise available sources of energy scavenging below.

- Vibrational excitation
- Piezoelectric
- Solar cells
- Ambient radio

Appendix B Feasibility calculations

Thermoelectric energy harvesting

Assumptions

- 10 kelvin temperature differential (based of temperature of breathing from (Wikipedia, 2014)and (Carpenter & Buttram, 1998) and the loss of heat from piping to water)
- Atmospheric conditions
- Specific heat capacity of 1.005 KJ/Kg.K from (Haywood, 2005)
- 2 litres of air per breath from ((Wikipedia, 2014) and Avon mentoring)
- 1 breath every 3 seconds (from practical timing)
- Density of air 1.184 Kg/m^3 (Haywood, 2005)

To find the energy in the air the below equation was used. From (Cengel & Boles, 1998)

$E = mc\Delta t$

E is energy in KJ
M is mass in Kg
C is specific heat capacity of air in KJ/Kg.K
Δt is the temperature differential in K

First finding the mass of air being breathed out by the diver.

Mass of air = volume* density

$0.002 * 1.184$= 0.0024 Kg

Then applying this to the original equation

Mass * specific heat * temp differential = energy in air

$0.0024 * 1.005 * 10$ = 0.02412KJ
0.02412 / 3 = 0.008004 KW
Or 8 W
Required power is 3 mW

Therefore device needs to operate at 0.0375% efficiency

Total energy provided by latent heat of evaporation and sensible heat is simply

8 W + 35 W = 43 W

As device could cause condensation on internal heat sinks operating like a heat pipe described in (Wikipedia, 2014) and (AAvid Thermalloy, n.d.).

Therefore the device could run at an efficiency of 0.0069%

Kinetic energy harvesting

This first feasibility calculation is reproduced from (Delnavaz, 2012)

$$Breath = 2\%\ above\ atmospheric$$

$$W = p\Delta V$$

$$0.02\left(\frac{1.013 * 10^5}{m.s\,\hat{}2}\right)\left(\frac{301}{1\ min}\right)\left(\frac{1\ min}{60\ Seconds}\right)\left(\frac{1m^3}{1.0001}\right) = 1\ W$$

Therefore 1 W available energy to be harvested however the Device will only operate at a certain efficiency in the case of the mask only 3.1 microwatt was generated (Delnavaz, 2012) which is not nearly enough to power systems in the Rebreather.

Another way to harvest the kinetic energy is to take breathing force out of the air using fans

Assumptions

- Diver breathes 40 litres/ min (Wikipedia, 2014)
- Going through 0.015 m Diameter pipe (measurements taken whilst at Avon Offices)

Therefore 0.6 litres per second or 0.0003m^3/s
Velocity of Human breath through the pipe is given by the equation found in (Engineering toolbox, n.d.) and (E How, n.d.)

$$v = \frac{1.274 * q}{d^2} = \frac{6 * 10^{-4} * 1.274}{0.015\,\hat{}2} = 3.3973m/s$$

Air is 1.19grams per litre at 25 C (Haywood, 2005)

$1.19 * 0.6 = 0.714g$ or 7.14*10^-4 kg/s

Therefore energy can now be calculated using equation from (Cengel & Boles, 1998)

$$\frac{1}{2} * m * v^2 = \frac{1}{2} * 7.14 * 10^{-4} * 3.3973^2 = 4.12 * 10^{-3}W$$

Or 4.12 mW. Therefore would only be effective is captured near 100% which would be impossible.

Electrostatic droplet jumping

This technology harvests latent heat of condensation energy therefore calculations have been done to identify how much energy there is available in the latent heat provided by the diver's breath. And at what efficiency the device would need to run to achieve the desired power requirement.

Assumptions

- 2 litres of air exhaled per breath (based upon tidal volume (Beadsell , 2009)and Avon mentoring)
- 1 breath per 3 seconds (basic breath timing measurements)
- Breath at 100% relative humidity (Wikipedia, 2014)

- 25 degrees Pipe temperature (based upon an average breath temperature of 34 degrees Celsius found in (Hopkins Medicine, n.d.) and (Carpenter & Buttram, 1998)
- Latent heat of condensation 2,260 kJ/kg found in (Datt, 2014)
- Device harvests latent heat of condensation energy (Miljkovic, et al., 2014)

There will be $23g/m^3$ of water at these conditions found in (Haywood, 2005)
Diver breaths 2 litres of air per breath and there are 1000 litres in a cubic meter

$$23 * 0.002 = 0.046\ g$$

Therefore 0.046 g of water in each breath
Using the equation below from (Datt, 2014) the power per breath can be found.

$latent\ heat\ of\ condensation$* Mass of water = power per breath

$$\frac{2260}{1000} * 0.046 = 0.10396\ kJ\ per\ breath$$

Diver produces 2/3 litres of air per second therefore Diver produces 0.035 kW or 35 W
Required power is 3 volts at 1 mA Or 3 milliwatts (figure discussed from Avon Management)
Therefore device could be 0.0086% efficient and still achieve desired power

Appendix C Matching requirements to the method

As can be seen from Table 1 thermoelectric energy generation generates the most power at 43 watts closely followed by 35 Watts of power from electrostatic droplet jumping techniques and kinetic Power sources seen in table 1 are lower. All but kinetic breathing force are from energy sources big enough to easily power the systems in the Rebreather (demonstrated in the required efficiency's). The question becomes how much of this power source can be harnessed and what other requirements affect method selection. A process of reduction is used to select the most effective method.

Removing the kinetic energy in the diver's breath means the diver will have to work harder in order to breathe this will reduce diver comfort. Ease of breathing is a major selling point in a Rebreather and is one of the important tests found in the standard BSEN14143. In this case the negatives outweigh the gains also it has the lowest power source and therefore is removed from selection.

Electrostatic droplet jumping technology is in its infancy conversations with (Miljkovic, 2014) through emails revealed that results generated were "obtained in a pure vacuum environment" and that using actual air would decrease the power scavenged. Therefore as this technology is still in its infancy it shall be removed from the selection.

Therefore thermoelectric energy generation is the method of choice it also has the highest potential power source and should operate under the requirements so long as heat sinks don't restrict breathing.

Appendix D Other similar experiments

A similar test was conducted by Avon underwater systems into the temperatures throughout the Rebreather loop over time and showed similar numbers to this data however over a shorter time period and slightly different gradients further they measured the core of the Scrubber rather than the air coming out of it.

It is difficult to replicate the results from this experiment due to the large amount of time it takes to run the test and the fact that a person must remain breathing into the inlet throughout that time hence the singular test result.

There are no previous demonstrations of thermoelectric energy harvesting from divers breath however in the paper (O'Halloran, 2014) wrote there was a study to "determine the efficiency of a commercial thermoelectric generator". The generator only cost £3 and was 40 mm x 40 mm x 3.5. The device was tested at different temperature differentials and efficiency and power output were measured. One particular test was run at 20 degree temperature differential this is similar to what will be experienced in the Rebreather application looking at 11 you can see that the power output is 0.11 watts at 20 degrees C with an efficiency of 0.71% these values are much higher than the values seen in this experiment however only a small amount of the thermal energy from the difference from air to water (37 degrees C) is fully transferred over the TEG resulting in a much lower power output.

Other examples of power generation at low temperature are seen in the paper by (Leonov, n.d.) . Which was an investigation into thermoelectric generators on living beings therefore at low temperature differentials. One example was a watch sized wrist TEG which was used at ambient temperatures and generated a power of 0.2-0.3 (mW) on average also utilising a waterproof casing made of 0.5 micron thin polyethylene which may also need to be used in the Rebreather application.

The report states that the average power production on human beings at 22 degrees c for a 1- 1.5 cm thick TEG is 0.03 W/cm^2. This is however skin contact directly to the TEG which has much higher thermal conductivity than air.