Energy evaluation in the High Velocity Algae Raceway Integrated Design (ARID-HV).

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Abstract: *The ARID raceway is an effective method to maintain temperature in the optimal growing range. However, the energy input is excessive. Thus, the ARID-HV raceway was developed in order to reduce energy input requirements. This was accomplished by improving pumping efficiency and using a serpentine flow pattern in which the water flows through channels instead of over barriers. A prototype ARID-HV raceway was installed in Tucson, Arizona in order to evaluate the flow and energy requirements of the raceway. Preliminary results show continued high energy usage, but this paper explores the possible energy reductions with the new ARID-HV design with efficient propeller pumps and properly engineered channel lengths. Channel lengths are evaluated with Manning's equation in order to determine the maximum channel length that could be implemented with the current pumping configuration.*

Keywords: *ARID raceway, algae culture, open pond, energy, pumps, channels.*

Introduction

Open pond microalgae production systems have been used for almost half a century (Oswald, 1969). They provide high solar energy and light exposure, and are less expensive than bioreactors. However, contamination and lack of temperature control can decrease the algae production rate. In order to improve temperature control and reduce contamination, while maintaining high solar radiation and low cost, the Algae Raceway Integrated Design (ARID) was developed (Ryan et al. 2010, Crowe et al. 2012, Waller et al. 2012). The original ARID raceway included shallow basins and a deep canal (fig. 1). Temperature was regulated by varying the water surface area between day and night. Removing the water from the shallow basins at night reduces long wave radiation to the night sky and convective heat loss; thus, the average water temperature is 5 to 10 ^{0}C warmer than a conventional raceway. For example, on nights when conventional raceways froze in Arizona during a cold spell, the ARID raceway had a minimum temperature of 12 ^{0}C. The canal was covered by insulation on these nights, which resulted in the canal acting like a thermos, and temperature drop on very cold nights was only 3 ^{0}C.

Figure 1. Original ARID raceway with deep canal in foreground and shallow channels behind.

The improved temperature regime in the ARID raceway resulted in a higher rate of algae growth during a winter experiment in 2011 in Tucson, Arizona. The ARID raceway had nearly double the volumetric biomass productivity compared to a small paddlewheel raceway during winter 2011 and (0.023 versus 0.013 g L^{-1} day^{-1}) (Crowe et al. 2012). However, there were several weaknesses in the design of the original ARID raceway. For example, the aerial productivity was the same as the paddlewheel raceway because the depth was much shallower in the ARID basins. Thus, the depth of water in basins was increased to approximately 0.2 m, which is a standard depth for many algae raceways. Another drawback of the original ARID raceway was inefficient pumps and low flow velocity. Thus, the High Velocity Algae Raceway Integrated

Design ARID-HV was designed in order to minimize energy input while creating a turbulent high velocity flow regime with effective mixing. This was accomplished by replacing the basins in the original ARID system with a serpentine flow path through channels.

In general, researchers have found that a minimum level of turbulence is needed for mixing and prevention of algae settling. Different mixing velocities (average water flow velocity in the channel) have been evaluated in open raceways (Oswald, 1960; Benemann, 1978). The best mixing velocity is a function of several factors including algae density, tendency for settling, algae size, oxygen concentration in water, and algae culture depth. In general, 0.06 m s^{-1} is the considered as the minimum acceptable mixing velocity while 0.15 m s^{-1} is at the upper end of the range (Benemann, 1982).

In conventional raceways, the flow is driven by a hydraulic gradient caused by a subcritical water surface gradient over a level channel bottom. Very little lift is required to cause water to flow in algae raceway channels. Thus, the two primary types of pumps used in algae raceways are air-lift pumps (Persoone et al., 1980), and paddle-wheels (Oswald, 1969). The general consensus at this time is that paddlewheels are the most energy efficient pumps for algae raceway channel systems. In addition, new paddlewheel systems are being tested that mix water effectively without increasing flow rate and further reduce energy input into the system. Lundquist et al. (2010) found that the paddlewheel system power requirement was 2.4 kW ha^{-1}. The general consensus at this time is that paddlewheel raceways are the most energy efficient open pond systems. Alternatively, very steeply sloped algae growth systems have been developed with turbulent flow over barriers and recirculation pumps that lift water more than a meter in order to recirculate water to the upper end of the raceway (Setlik et al., 1970). The original ARID raceway had a lift of approximately 1 m and used a sump pump to continually lift the water from the canal into the basins. The ARID-HV system reduces energy input through recirculation of water in the upper basin area and only dropping water into the canal when necessary for temperature management, cleaning, or harvesting.

At the minimum, the energy input to the pump and all other electrical devices in an algae/biofuel production system must be less than the energy produced in the algae. Pumps can be designed for a required flow rate and pressure, and the best efficiency point is reached during steady operation (Gülich, 2008); however, mixing efficacy in a gravitational flow system may be enhanced by pulsing or varying the flow.

The overall objective of the present research was to design and construct an ARID-HV raceway and to evaluate algae growth and energy input. There were three specific objectives:

1. Evaluate all of the energy inputs to the ARID-HV system, including air pumps, recirculation pumps, and canal lift pumps.
2. Evaluate alternative pumping systems for the ARID-HV raceway.
3. Compare the ARID-HV energy requirement to a conventional paddlewheel raceway.

Materials and methods

The experiment was conducted at the Campbell Avenue Agricultural Center of the University of Arizona. The geographic coordinates are: Latitude = 32° 16' 49" N, Longitude = 110° 56' 45" W. The raceway elevation is 655 m above sea level. The ARID-HV raceway includes a serpentine channel system for the upper section and a canal (fig. 2). The serpentine path includes 10 basins (channels), each 13 m long, 0.15 m deep, and 3 m wide. Water can spill over the last barrier into a deep canal that is 2 m deep, 5 m wide, and 16 m long (fig. 2).

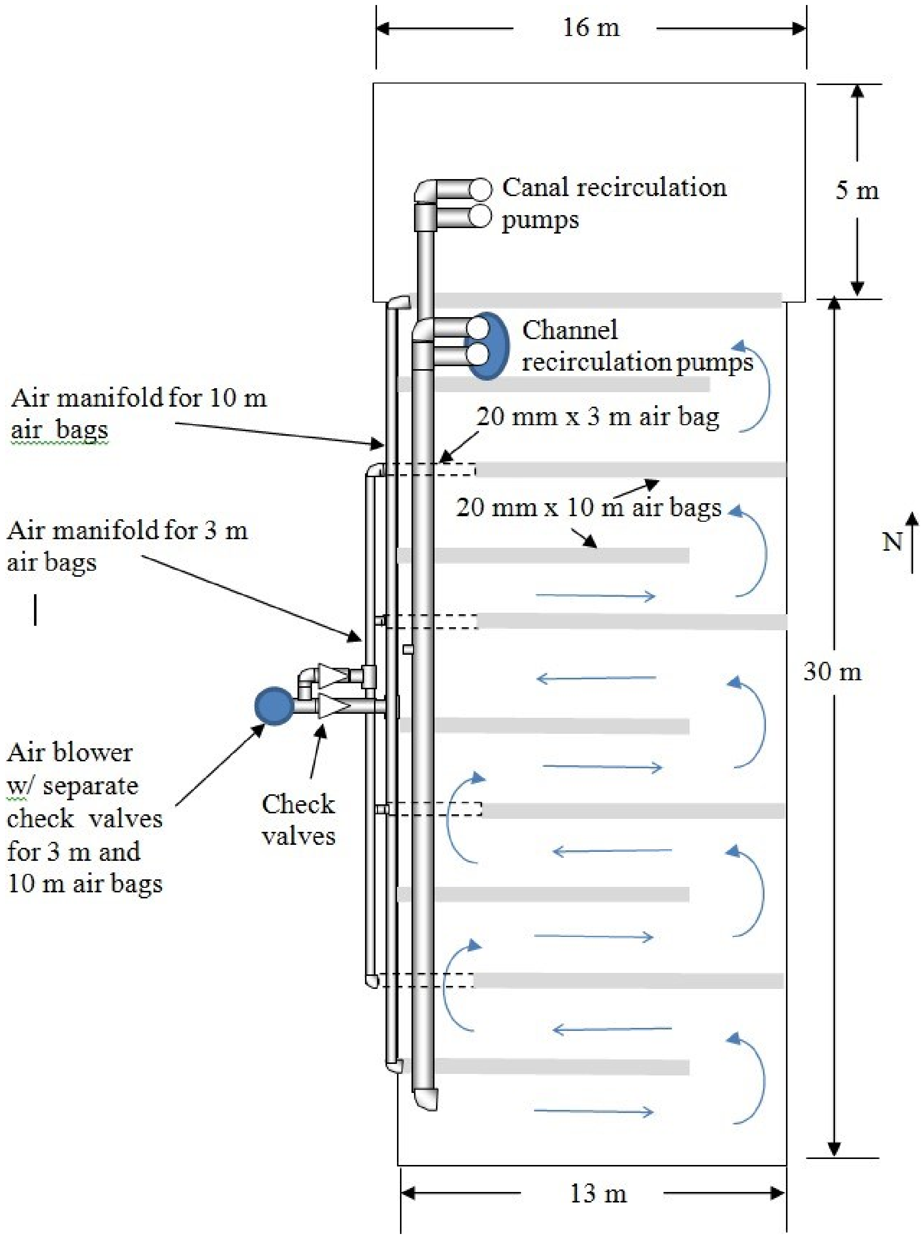
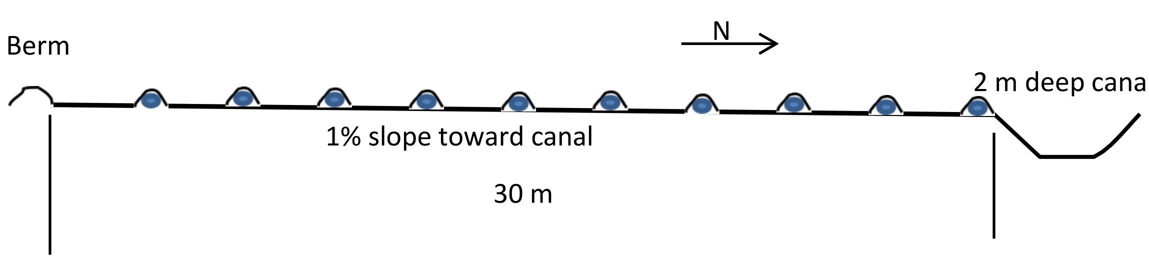


Figure 2. (a) ARID-HV dimensions; (b) canal dimensions, pipes not to scale.

The basin area was lined with two 7.6 mm thickness linear low density polypropylene sheets (LLDP Aquafarm E-300, Colorado Lining International, Parker, CO) that were laid lengthwise in the N-S direction and welded in the middle with a heat gun. The extra 2.2 m (in addition to 13 m) was used to cover berms on the sides. A single 7.6 m wide liner section was laid in the E-W direction in the canal with a narrow section welded on the south side in order to complete the covering of the canal. The profile of the basin cross-sections and the canal is shown in figure 3. Vinyl lay flat tubing (20 mm diameter) sections were laid on the upper section surface under the liner (fig. 4). When the air bags are inflated under the liner, berms are created that direct water flow in a serpentine pattern through basins (fig. 5).



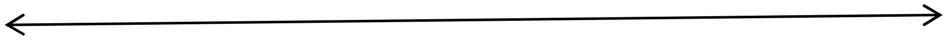


Figure 3. Profile of the ARID-HV raceway with air bag berms between basins and canal.

Figure 4. Installation of vinyl lay-flat tubing under liner.

Figure 5. Water directed through basins with air-bag berms.

Low lift pumps are used to recirculate algae culture from the lower basin to the upper basin and from the canal to the upper basin. The propeller pumps that were purchased for the ARID-HV project (fig. 6) were defective so the research team is in the process of manufacturing and testing new pumps. The initial design specified two propeller pumps with flow rates of 1.2 m^3 min^{-1} per pump for recirculation in the basins. One propeller pump with flow rate 0.6 m^3 min^{-1} was specified for recirculation of water from the canal to the upper basin. While the replacement propeller pumps are under construction, four sewage pumps are being used to recirculate water from the lower to the upper basin and two sewage pumps are being used to lift water from the canal to the upper basin for the summer 2012 algae growth experiments. The four sewage pumps for recirculation in the basins each produce 0.28 m^3 min^{-1} for a total flow rate of 1.1 m^3 min^{-1} from the lower basin to the upper basin, and the two sewage pumps in the canal each produce a flow rate of 0.4 m^3 min^{-1} for a total flow rate of 0.8 m^3 min^{-1} from the canal to the upper basin. If all six pumps are operated at once, then the total flow rate in the serpentine channel system is 1.9 m^3 min^{-1}. If all pumps are operated at once, then velocity in the 0.1 m depth channels is 0.1 m s^{-1}. However, only one of the canal pumps was generally operated so average velocity in channels was 0.083 m s^{-1}. Both of these velocities are in the normal range of algae raceway operation.

Figure 6. Original propeller pumps for recirculation from the lower channel to the upper channel.

Figure 2 shows two pipe systems: an air pipe system supplies the long blue vinyl tubes and the short blue vinyl tubes, and a 0.2 m diameter pipe that delivers that water from the lower basin and canal to the upper basin. The entrance to the water recirculation pipe is shown in figure 6.

The blue vinyl tubes were inflated by a small recreational equipment blower (Overtons 110V High-Pressure Inflator/Deflator 14209) that generates approximately 30 kPa pressure and inflates the air bags in approximately 3 min. The blower is connected to the long and short air tube manifolds by two separate check valves. This allows each air tube system to be deflated independently by valves on each manifold. The short length tube manifold is connected to the four short tubes (3 m length) that are represented by dashed borders in Figure 2. The short tubes can be inflated to varying pressures in order to back up the flow within the basins to the desired depth and can be fully inflated to enable storage of water in channels overnight or for any other extended period.

All of the air bags were deflated at night, if necessary, in order to allow the algae culture to flow back into the canal. Rapid air bag deflation results in a large flow into the canal, which helps to clean the basin section of the system. Air bag inflation and deflation and pump start times can be controlled with an automatic controller, but they were sometimes controlled manually.

The ARID-HV raceway in operation is shown in figure 7. Water is delivered from the lower channel to the upper channel through the large pipe at the left. A fertilizer tank with Peter's fertilizer and an iron fertilizer tank are also shown at the left of figure 7.

Figure 7. ARID-HV raceway in operation.

The algae in the raceway during the experiment shown in Fig. 7 was fresh water microalgae DOE1412, a new chlorella strain discovered by Juergen Polle of SUNY and the National Association for Advanced Biofuels and Bio-products (NAABB). This strain is very robust, fast growing, and heat tolerant. Maximum algae culture temperature during the summer experiments was 42 ^{0}C, and the algae did not die at this temperature. The same species was cultivated in the original ARID raceway for two months from May to July 2012 and in the ARID-HV raceway from June 17 to June 26 2012.

Two air spargers in the canal provided air (oxygen) to the algae culture when it is stored at night in the canal. A ceramic stone sparger adds carbon dioxide to the system during the day, either in the canal or at the channel recirculation pumps, depending on whether flow is allowed to cycle through the canal during daylight operation. The carbon dioxide injection is controlled with a pH sensor: carbon dioxide is injected when the pH rises above 6.5, from sunrise to sunset.

Temperature in the canal and channel, pH, salinity, and dissolved oxygen are recorded continuously with a Campbell Scientific data logger that is connected to a computer. The research team can actively monitor the status of the raceway with the computer.

Water is added each day to compensate for the evaporation and harvesting water losses. Nutrients are measured and added daily to the upper channel from the two tanks shown in Fig. 7, as needed. Inoculum is continuously grown in the laboratory in 0.018 m^3 carboys. These are then added on a weekly schedule to 1 m^3 semitransparent plastic tanks that are the same as the square tank shown in figure 7. Thus, new inoculum is always ready to reinoculate the raceways if the raceways crash. The normal procedure is to first add inoculum to the smaller ARID raceway and then use the ARID raceway to inoculate the ARID-HV raceway.

The volumes and areas of the raceway sections during the summer 2012 experiment are shown in table 1. Although the basins were designed for 0.15 to 0.2 m depth, the system was operated at 0.1 m depth during the experiment.

Table 1. Basin flow characteristics of ARID-HV cultivation system

Characteristic	Value
Water volume during operation (m^3)	44
Total liner surface area (m^2)	470

Surface area: volume ratio	10.5:1
Basin (channel) width (m)	3
Basin depth (m)	0.1
Average basin (channel) flow velocity (m s^{-1})	0.083
Basin (channel) flow rate (m^3 s^{-1})	0.025
Reynolds number (0.1 m depth and 0.083 m s^{-1})	8500

The algae culture was circulated in basins during daylight hours (table 2). During this experiment, a depth of 0.9 m was maintained in the canal and water was continuously recirculated to the basins from the canal. This level was maintained with a float switch on canal pump 1, which remained on but turned off when the level in the canal depth dropped below 0.9 m depth.

Table 2. Schedule for electrical components of the ARID-HV during the July 2012 algae growth experiment.

Component	Characteristics	Operating time
Canal		
Canal pump 1	1.1 kW, 6.3 L s^{-1} @ 2.4 m maximum lift, Eff = 13%	6:00 to 19:00
Canal pump 2	1.1 kW, 6.3 L s^{-1} @ 2.4 m maximum lift, Eff = 13%	6:00 to 6:15
(both pumps run during initial lifting of water from canal to basins)		
Canal air sparger	0.12 kW	19:00 to 6:00
Basins		
4 sump pumps[a]	0.72 kW, 4.7 L s^{-1} @ 0.9 m, Eff = 6%	6:30 to19:00
Vinyl air tube pump	0.6 kW	5:57 to 6:00

[a] The characteristics are for each pump. [b] CO2 diffusion does not require any energy. It is supplied from a pressurized tank.

A computer model was developed in order to calculate ARID raceway temperature and algae growth as a function of weather parameters and operation strategy (Waller et al., 2012). This model was used to develop a hypothetical schedule for raceway operation during the 12 months of the year in Tucson, Arizona. The primary question was whether the algae culture should be dropped into the canal at night or be allowed to remain in the basins at night. For example, in the summer, when the algae culture temperature is higher than the optimal growth temperature and all other things being equal, it may be preferable to leave the algae culture in the basins and allow the water to cool. Leaving the water in the basins overnight eliminates the energy requirement to pump the algae culture from the canal back basins in the morning. Weather data for the model was acquired from the Arizona Meteorological Network (AZMET) weather station in Tucson, which is located 100 m from the ARID experimental site. Data required for the model includes air temperature (^{o}C), relative humidity, solar radiation (J h^{-1}), rainfall (m), wind speed (m s^{-1}), and evapotranspiration (m h^{-1}). An algae growth component was added to the temperature model, and this was used to evaluate algae growth as a function of operation strategy (Khawam et al., 2012). The model was run based on parameters in the original ARID raceway, and scheduling for the ARID-HV raceway in this research was based on the model runs for the ARID raceway. The two raceways had similar temperature trends as long as they were operated similarly so it is reasonable to use model calibrated for the ARID raceway to estimate ARID-HV temperatures. However, this preliminary analysis will be updated in the future with a model based on the flow characteristics of the ARID-HV raceway. A published chlorella growth curve (Khawam et al., 2012) was used for the simulation, but this was not a 1412 growth curve, which is not available at this time.

Channel hydraulics were evaluated in order to evaluate the optimal raceway design and energy requirements. The ARID-HV raceway is lined with smooth polypropylene so the Manning's *n* coefficient was assumed to be 0.01. The head losses at the 180 degree turns between basins were calculated with the corner head loss equation for channels (Green, 1995).

Energy input to pumps and blowers was measured with a watt meter during normal operation.

Results and discussion

In this section, the energy input kWh ha^{-1} d^{-1} is calculated for several ARID-HV operational scenarios. There are four combinations of depth in the canal and basins and three different pumping methods: sewage pumps, propeller pumps, and paddlewheel pumps.

Unlike paddlewheel raceways, ARID raceways are not flat. Thus, the energy input can be divided by liner area, land surface area, or water surface area in order to calculate kWh ha^{-1} power or energy input, respectively. If the concern is water loss, then water surface area is used as the denominator in the energy calculation, which reflects the energy input per unit of evaporation. If liner area is used, then this reflects the energy input as a function of purchased and installed liner material. If land area is used, then this is the energy input per unit of land used for algae production. The total land area used for the ARID-HV raceway is 460 m^2. Thus, approximately 21 of the current ARID-HV raceways would cover 1 ha. However, the canal for the current raceway is larger than necessary for the current basin area, and the basin areas could be expanded with the current canal volume.

The summer 2012 practice was to maintain 0.9 m depth in the canal and 0.1 m depth in basins. However, other management scenarios with greater depth in basins and shallower depth in the canal are evaluated in this study (table 3). Table 4 shows the installed liner area, land surface area, and water surface area during daytime operation for the four management approaches.
Table 3. Depths, areas (surface area), and volumes for different operation scenarios: basin area 390 m2, bottom area of trapezoidal canal is 1 m by 6 m, & canal slopes are 45^0 on four sides.

Operation scenarios	Basin Volume with pipe			Canal day Area is top surface			Canal night Area is top surface		
Parameter	Depth (m)	Area (m^2)	Vol. (m^3)	Depth (m)	Area (m^2)	Vol. (m^3)	Depth (m)	Area (m^2)	Vol. (m^3)
Summer 2012 experiment	0.1	390	40	0.9	30	16	1.86	54	56
Shallowcanal & shallowbasin	0.1	390	40	0.3	14	3	1.58	47	42
Shallowcanal & deepbasin	0.2	390	79	0.3	14	3	2.29	66	82
No day canal & deepbasin	0.2	390	79	0	0	0	2.25	65	79

Table 4. Liner, land, and water surface areas.

Operation scenario	Basin Including berms	Canal Length is N-S	Areas

Parameter	Liner width (m)	Liner length (m)	Liner width (m)	Liner length (m)	Liner area (m^2)	Land area (m^2)	Day water surface (m^2)
Summer 2012 experiment	15	32	20	9	660	460	420
Shallowcanal & shallowbasin	15	32	14	7.5	580	430	405
Shallowcanal & deepbasin	15	32	18	9	640	460	405
No day canal & deepbasin	15	32	18	9	640	460	390

The power for each of the pumps and blowers is shown in figure 8. The device days per day refer to the fraction of a day that the device is used. Four basin pumps are used for 12.5 hours, which results in 50 hours or 2.08 days by the four pumps combined. During the summer experiment, the two canal pumps were only used for the 15 min while water was lifted from the canal to the basins. A single canal pump was used during day operation but two were used when the algae was lifted out of the canal into the basins. Thus, the operation time was 13.25 hours or 0.55 hr. The air sparger was used for 11 hours at night (0.46 days). Thus, the total energy requirement per day for the current ARID-HV raceway is 52 kWh d^{-1}. The energy requirement on per ha land area is calculated by multiplying by 21 since 21 of the current ARID-HV raceways cover 1 ha. Thus, the energy requirement is approximately 1,000 kWh ha^{-1} d^{-1}.

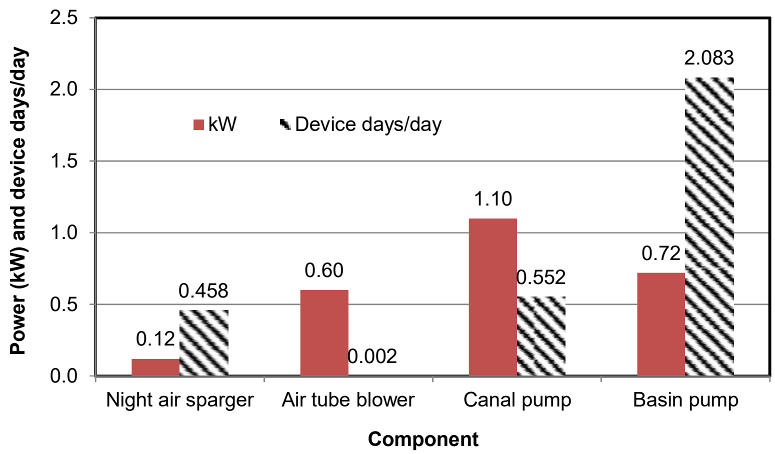


Figure 8. ARID-HV component power and operation times during Summer 2012 experiment.

The normal power requirement for a paddlewheel raceway is 2.4 kWh d^{-1}. Thus, if the raceway is operated for 13 hr d^{-1}, the energy requirement is 31 kWh ha^{-1} d^{-1}. Thus, the current ARID-HV raceway has 30 times the power requirement per ha as the normal paddlewheel raceway.

There are two primary sources of energy loss in the ARID-HV raceway: one is the small air bags that back up the flow in channels, and the other is the inefficient pumps. The total kWh for the raceway is the product of power and time of operation. Based on the performance of typical propeller pumps sold by reputable manufacturers, it is expected that the propeller pumps that are suitable for the ARID raceway will operate between 33% and 50% efficiency rather than the 6% efficiency of the basin pumps and the 13% efficiency of the current sewage pumps. For example, a 1 HP propeller pump performance curve from Carry Manufacturing that operates in the range of the ARID raceway lift and flow requirements is shown in Fig. 9. At a flow rate of 350 GPM and 4 ft lift, the calculated efficiency for the 1 HP motor is 35%. Other larger propeller pumps on the market have advertised efficiencies in the range of 60%.

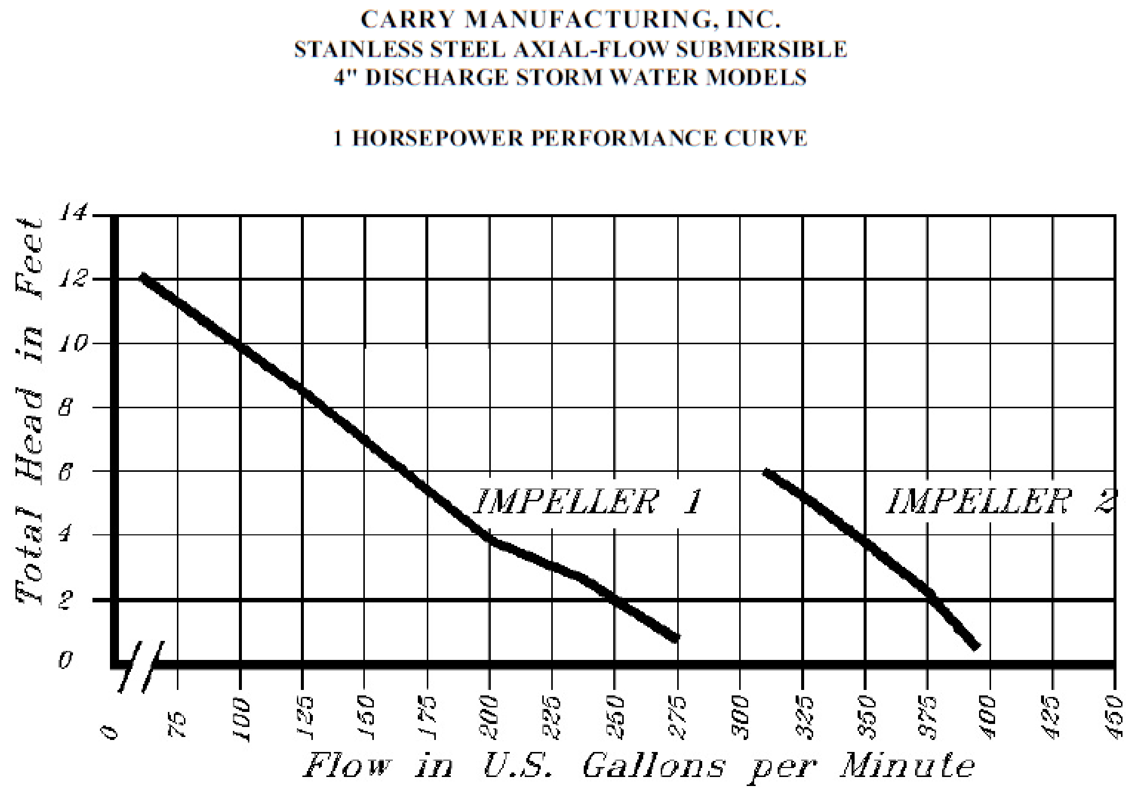


Figure 9. Carry Mfg. propeller pump curve.

The current raceway was constructed as a prototype in order to evaluate the serpentine flow path and pumping methods; however, the channels can be extended to a much greater distance with the 1% overall slope of the raceway. Using Manning's equation and the corner head loss formula for channels, the possible length of channels as a function of flow rate with 1% and 0.5% overall raceway slope is given in figure 10. For example, with a channel flow velocity of 0.12 m/sec and side slope of 1%, the recommended channel length is 500 m. This is 38 times longer than the current channel length of 13 m at a higher flow velocity.

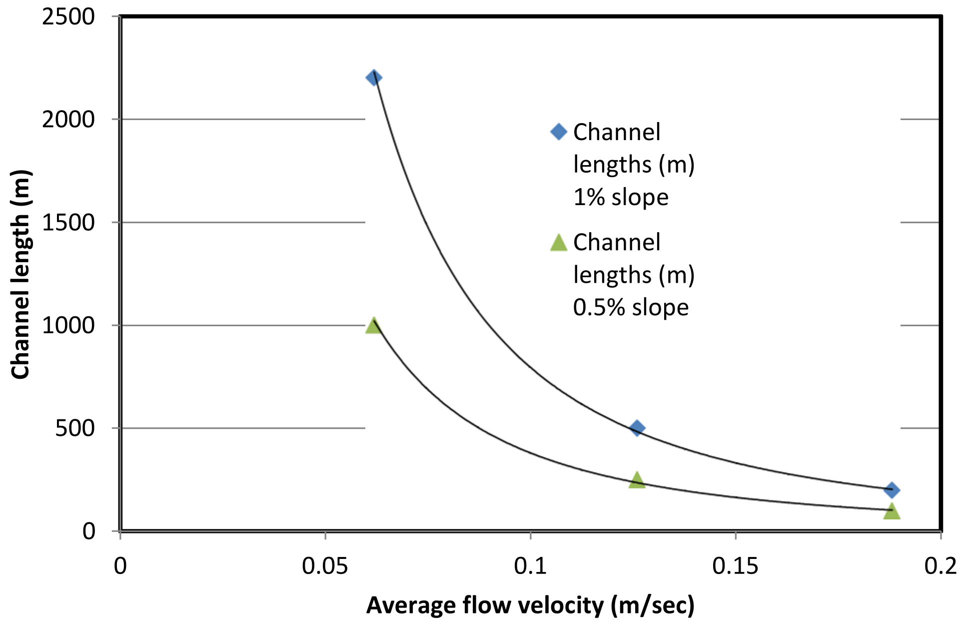


Figure 9. Channel lengths in ARID-HV raceway as a function of flow velocity and side slope (perpendicular to channels).

A final improvement to the current design is that water can be returned to the upper channel with a channel rather than a pipe, which would eliminate the entrance, exit and bend losses in the pipe. Combining the channel length calculations with the possible efficiencies of propeller pumps, the energy input requirement for an optimized ARID-HV raceway using propeller pumps with 25% and 50% efficiency are shown in figure 10, as a function of water surface area in basins. At the 25% efficiency, the energy requirement for running the raceway at 0.125 m s^{-1} flow velocity in 0.2 m depth in 3 m wide channels would be 0.9 kWh ha^{-1} (fig. 10). Operating for 13 hr d^{-1}, the daily energy requirement would be 12 kWh ha^{-1} d^{-1}.

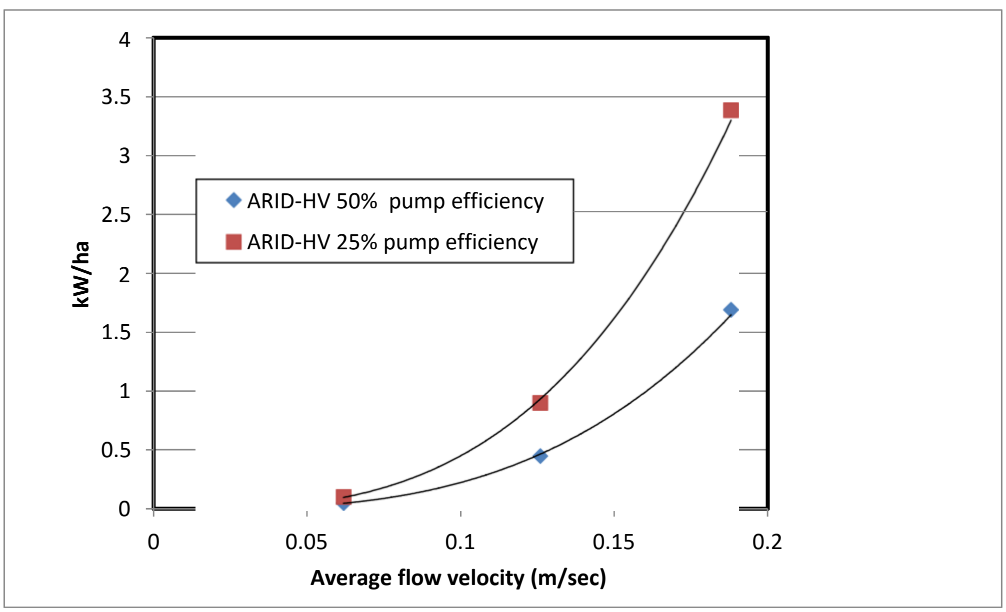


Figure 10. Recirculation pump energy requirement in an optimized ARID-HV raceway based on water surface area in basins.

The energy required to lift the water from the canal to the channels can also be reduced with an efficient propeller pump or Archimedes screw pump. A typical lift elevation required to lift the water from the canal to the basins in the morning is 1.3 m (4 ft). The Carry Mfg. pump with (79 m^3 hr^{-1}) 350 GPM at 1.3 m lift requires a 1 HP motor (0.74 kW). It would require one hour at this flow rate to lift 79 m^3 to fill the current ARID-HV raceway to a 0.2 m depth in channels. Thus, the energy requirement for the current raceway would be 0.74 kWh, and the energy requirement for 1 ha would be multiplied by 21 or 15 kWh ha^{-1} d^{-1}. Thus, lifting the water from the canal to the basins in an optimized ARID-HV raceway would add approximately 100% to the daily energy requirement. This energy requirement would generally not be required during summer when the night storage in the canal is not needed to keep the algae culture at an elevated temperature.

The energy requirement for the components of the ARID-HV raceway on a per ha basis with better pumping and canal design are shown in figure 11. The total energy requirement for 13 hr pumping per day is 55 kWh ha^{-1} d^{-1} as a function of water surface area (last case with canal drained during day in tables 3 and 4). Khawam et al. (2012) showed that the ARID raceway should be operated in summer as a conventional raceway because warming in the canal is not needed. Thus, the ARID raceway energy requirement would be reduced to 27.3 kWh ha^{-1} d^{-1} because the canal lift pump and the air sparger would not be required. This is for the water surface area of the last case in tables 3 and 4, where the canal is drained during the day.

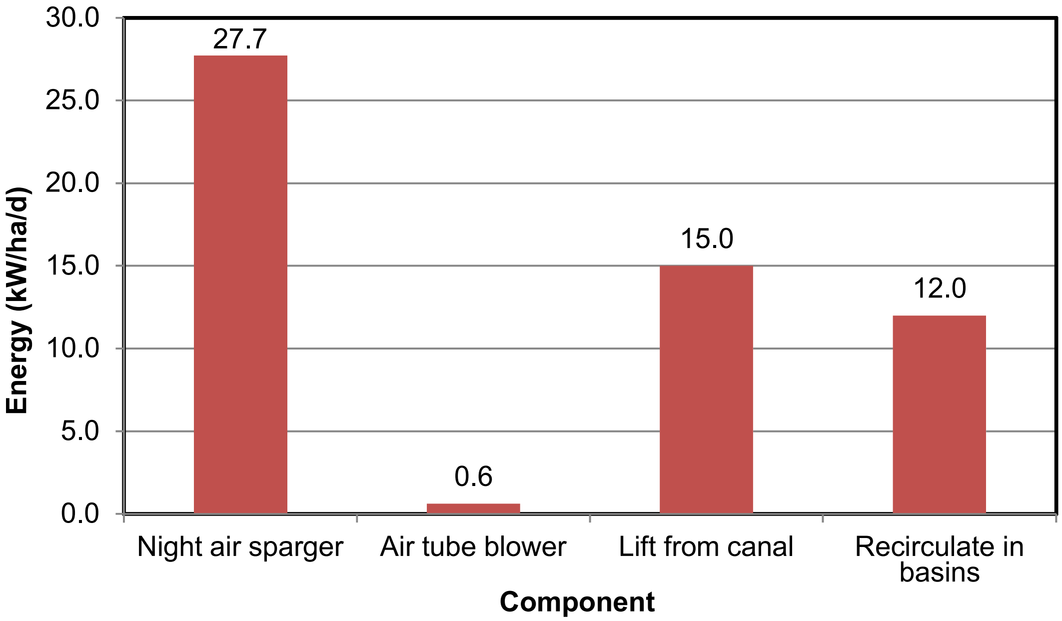


Figure 11. Energy requirement for components in ARID raceway.

The typical paddlewheel raceway energy requirement is 2.4 kW ha^{-1}. Thus, if a paddlewheel operates for 13 hr d^{-1}, then the daily energy requirement would be 31 kWh ha^{-1} d^{-1}. Thus, the ARID-HV has approximately the same energy requirement when the canal is not used but is approximately double the paddlewheel requirement when the canal is used. The air sparger energy requirement is very high. A key factor in reducing the ARID energy requirement is to reduce the air sparger energy requirement.

The ARID energy requirement can also be evaluated as a function of land area and liner area. A very large raceway would have nearly the same basin liner area as water surface area in basins. However, the canal area should be added to the calculation. Approximately 20% land area because of the canal should be added for a well-designed ARID raceway. Likewise, the linear area would be approximately 25% greater than the basin water surface area. The energy requirement as a function of land area or liner area would decrease, but not all of the land or liner area would be utilized. Thus, it makes most sense to calculate the energy requirement as a function of basin water surface area. On the other hand, algae production rate might be calculated as a function of land or liner area.

Conclusions

An ARID-HV prototype raceway was constructed and operated. An optimized ARID-HV raceway has approximately the same energy requirement as a paddlewheel raceway when it is operated without the canal, as would be the case in summer in Arizona, but the energy requirement is almost double when operated with the canal, as would be the case in winter in Arizona.

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