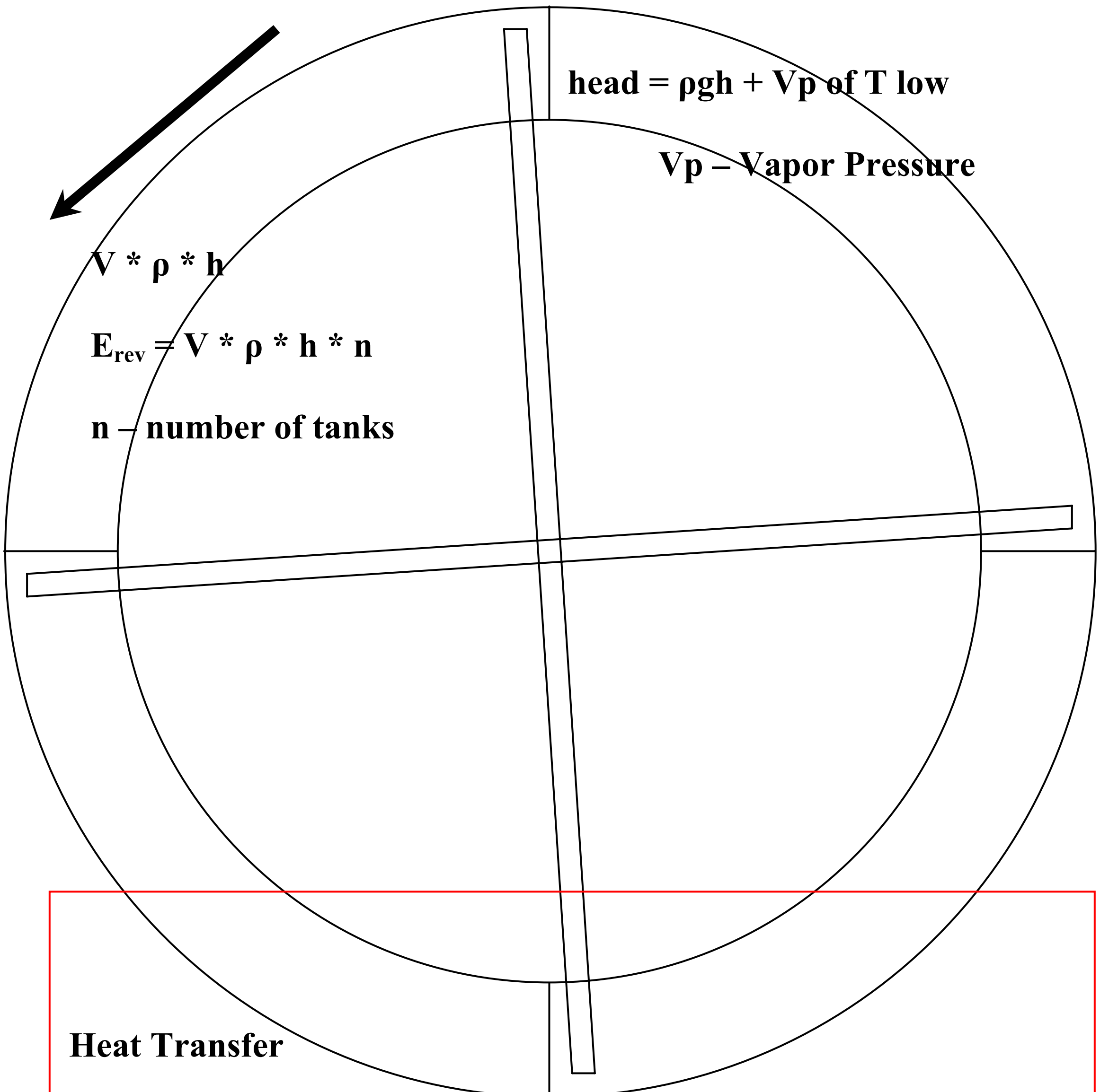
Minto Wheel Calculations



Heat Transfer

$Gr = (g*\rho^2*\beta*\Delta T*L^3) / \upsilon^2$
$Nu = a(Gr*Pr)^m$
$h = Nu*k / L$

$q = h * A * \Delta T$
$q_{rad} = \xi * \sigma * A\ (T1^4 - T2^4)$

By Terry Tharp

There are various heat engine designs and models that can use readily available solar heat for operation. The most famous of these is probably the dippy bird design which can be purchased as a novelty item at many of the novelty shops throughout the U.S.A.

The Dippy bird heat engine is a low temperature heat engine that works on the principle of evaporative cooling. However, the simple design was developed only as a novelty toy item and there are some major basic problems with the design as far as efficiency is concerned. However, it does provide a simple readily available method of demonstrating that we can make a machine which works from one heat reservoir. As far as I know the original Dippy Bird patent is U. S. Patent 2,384,168, granted in June of 1944. It is titled "Activated Amusement Device."

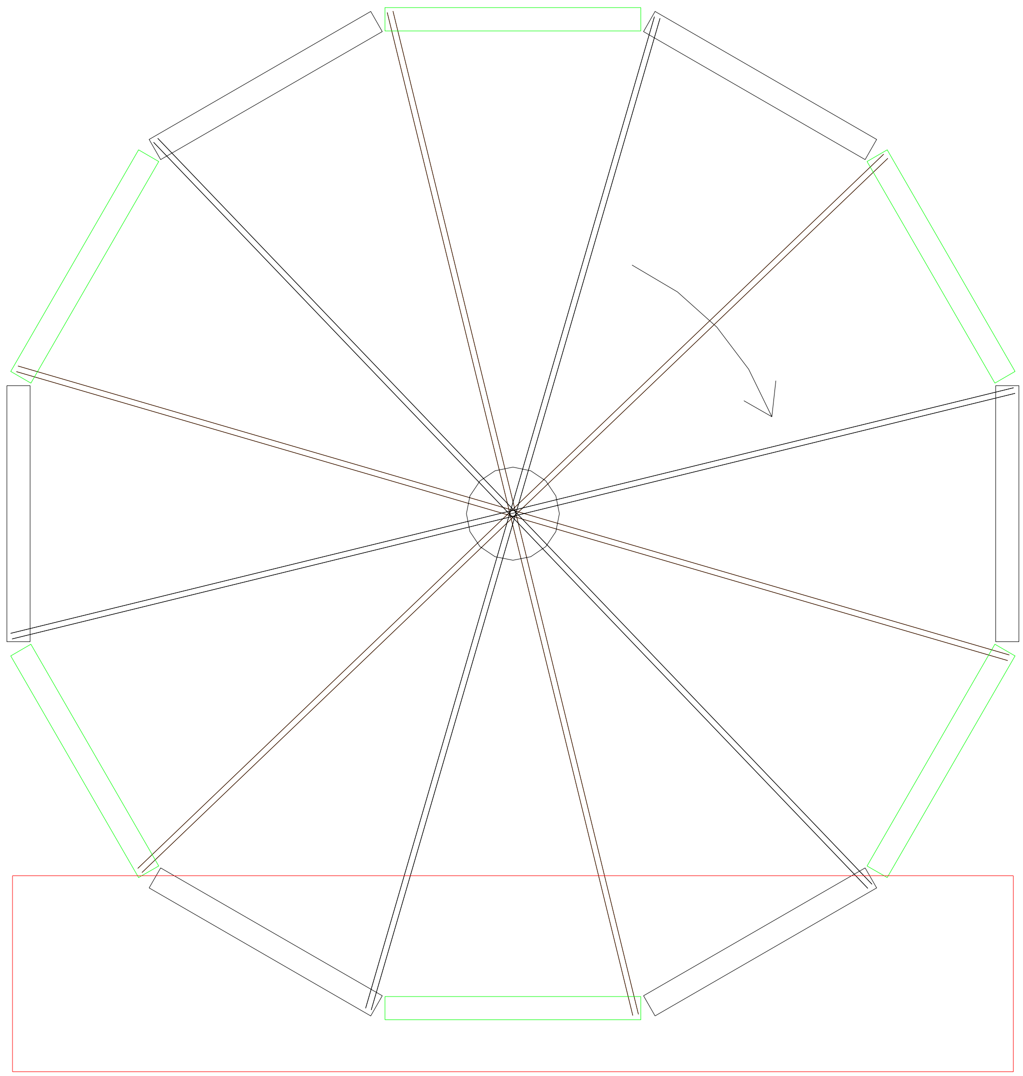
Then another solar powered heat engine that made it into the public eye was a solar powered heat engine that was developed by William Minto. This heat engine has come to be known as the Minto Wheel. It works on similar principles to the dippy bird heat engine and like the dippy bird heat engine this heat engine has a few problems which lead to major operational problems when the system is scaled up. I did a brief patent search and found that the basic Minto Wheel design was actually invented and patented by the Iske brothers back in 1881 (U.S. Patent 243,909).

What I propose to do here is show the basic Minto Wheel design and then explain and discuss some of the strengths of the system and also some of the obvious problems with the basic system.

Hopefully the mathematical development here will help everyone to better understand the basic principles on which the Minto Wheel operates. Learning how to do some of the calculations involved with this design and seeing the results of these calculations has helped me to get a better insight into the strengths and weaknesses of this basic engine.

Please forgive me for any spelling errors I may have committed in this paper. I had no one prove read it and my calculations may also have errors as I had to learn how to do many of these as this is my first exposure to calculating heat transfer. Positive feedback and constructive criticism is appreciated.

The Minto Wheel as shown in the Mother Earth News article looks something like this:



Looking at the diagram heat is added at the bottom in order to vaporize part of the fluid and force the non vaporized liquid part up the tube. The liquid fluid that is force up to the upper tank then causes the wheel to turn by the gravity overbalancing wheel effect. This is really a rather simple machine. However, its simplicity is I believe what has drawn so much attention to it from the general public.

From reading the Mother Earth News article I gather that Mr. Minto had built a 6 foot model that worked fine. However, when a 22 foot model was built by Mother Earth News they ran into some problems and changed fluids midway into the construction and the system did not perform very wheel.

In the Mother Earth News article they mentioned that they believed the problem was related to limited fluid transfer rates. However, this is highly unlikely from looking at the size of the transfer tubes in the pictures of their system and considering the low transfer rate of the system, I would say this is not a problem and was not the problem with their system.

That there is a problem with the system is obvious from the poor performance that they got with the 20 foot wheel and I believe that it is related to the thermal cycling of the system (only 1/5 RPM). You see all of the fluid in the tank is exposed to the heat source in the bottom of the cycle with a fluid to surface heat exchanger. This will vaporize some of the fluid while heating the rest of the fluid. This would not be bad except for the fact that at the top of the cycle this heated fluid and the vaporized fluid needs to be cooled back down so that the vapor pressure at the top the of cycle is reduced. This is achieved by condensing the vapor and cooling the heated fluid.

So the heated fluid has to be cooled back down without serving any useful purpose in the cycle. We can see that the fluid gets heated and then cooled in the cycle without contributing to the operational output of the system. This is a waste in the thermal cycle and reduces system thermal efficiency. This also increases the thermal heat dissipation load on the low side heat exchanger.

The heat dissipation in the upper part of the cycle is achieved by air to surface heat exchangers and this type of heat exchanger is about 25 times less efficient at heat transfer than a fluid to surface heat exchanger. So what will happen is that when the system is started up the fluid in the tanks will heat up until it is close to the temperature of the heat source and then it will cool slightly and then be heated back up to the high heat source temperature.

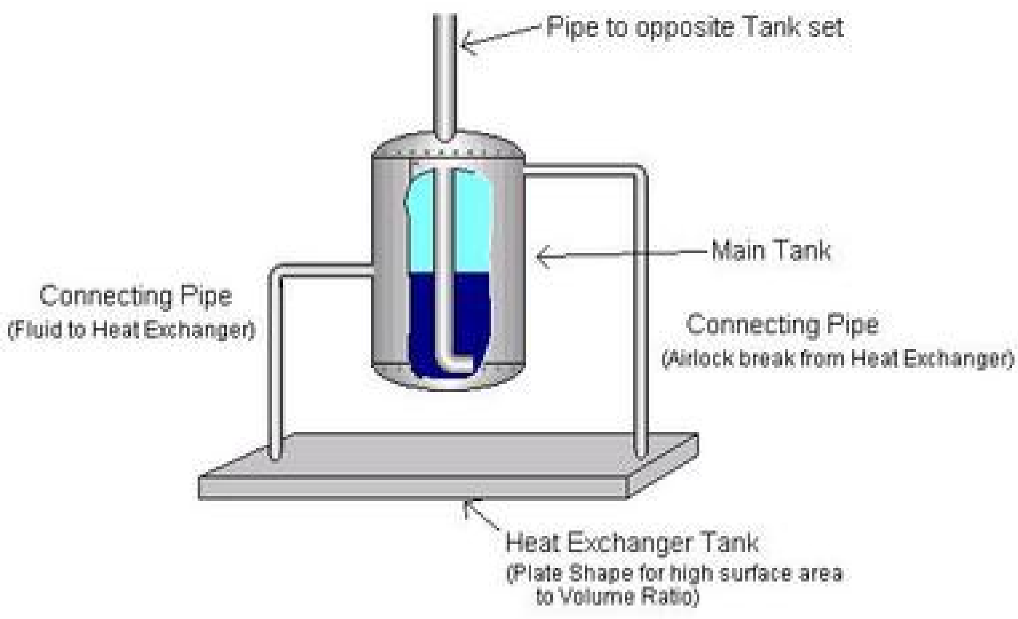
This thermal cycling of the fluid in the system is what I believe lead to the failure in the Mother Earth News Design. Exposing all the fluid to the high temperature heat source with a high rate heat exchanger and then trying to cool the fluid later in the cycle with a low rate heat exchanger leads to a less then desirable performance of the system.

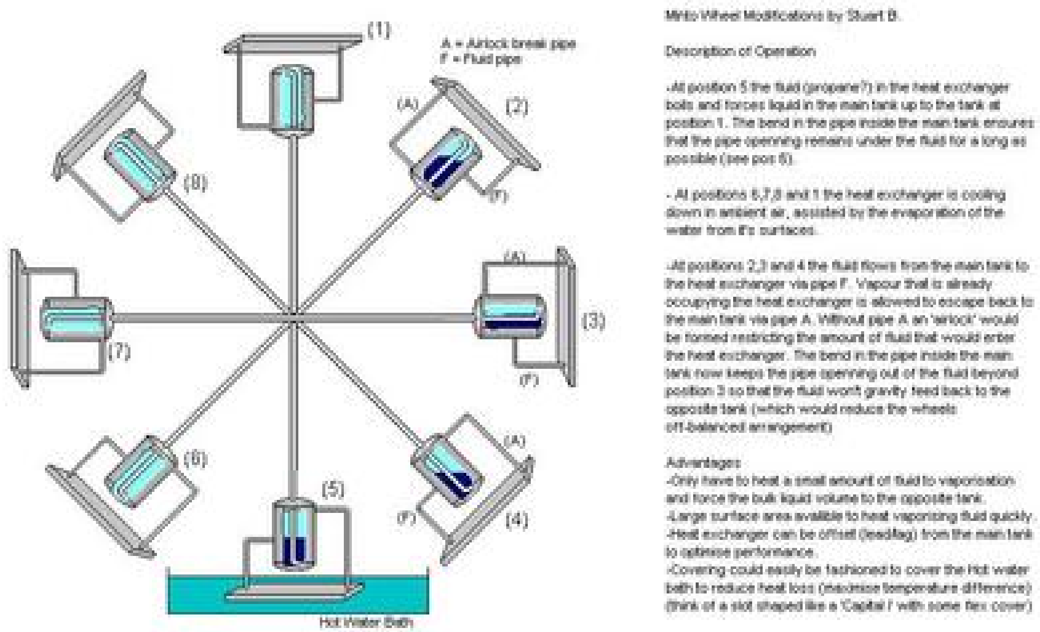
The Minto Wheel concept is an excellent concept. It just needs to be optimized by eliminating and or reducing the obvious system design mistakes, which hinder the desired outcome.

The most obvious problem has already been discussed. So how do we eliminate or reduce this problem. Will the simplest way to do this is to use a double tank system. The main tank which holds most of the fluid is not exposed to the heat source. The second tank which is an extension of the main tank is exposed to the heat source so that its fluid content is heated and vaporized. The vapor from the small tank then forces the liquid fluid from the main tank up to the upper tanks.

The volume of the small tank should be designed to hold the minimum amount of liquid fluid that when vaporized will force all the liquid fluid from the larger main tank.

This can be easily incorporated into the Minto Wheel design with minimal increase of system complexity. Take a look at the design that Stuart Brown came up with to solve this problem.





At this point I think we need to do a simple calculation of the basic Minto Wheel design and then do a simple calculation with the improved design to see how the two systems compare. I am not sure how to go about doing this so will consult a few thermodynamics books and see what I can come up with.

Basic Minto Wheel Design Calculations

Let's start off with developing a method of mathematically modeling the basic Minto Wheel design. This will help us to gain a greater insight into the dynamics of the system and will help us to better understand the fluid flow and energy relationships of the system. This will probably lead to us gaining some insight into why a larger 22 foot model of the system did not perform very will.

For these calculations I am going to use the parameters as given for the Mother Earth News Minto Wheel, as this is the only real system that we have any data on. Going back over the details of the system it is a 22 foot wheel and turned at a rate of 1/5 RPM with a temperature differential of 70 to 100 degrees F using R11. There are no other dimension given, however, taking the diameter of wheel as 22 feet and using some crude measurements on the given photo, I come up with the tank pipe diameter as 6 inches and the riser pipe diameter of 1½ inches roughly. Also from looking at the pictures it looks like the heated fluid tube is large enough for 3 sections of the total 12 to be immersed in the heated fluid. We also know from the data in the article that it needed a temperature differential of 70 to 100 degrees Fahrenheit. I will assume an ambient temperature of 70 degrees F. and a 70 degree temperature differential for our purposes. This will make the heated fluid temperature 140 degree F. We now have some data that we can work with. So let's get started on the calculations and see what we learn about this system. I am sure we will discover some overlooked aspects of the system operation which are significant.

Taking the wheel to be 22 feet and dividing it up into twelve sections well give the main fluid tanks as 66 inches long (5½ feet). This will leave a little room to play with on each side (about 4 inches to play with). The main tank volume is $\pi * r^2 * L$, 3.1416 * $(0.25\text{ ft})^2$ * (5 ½ ft) = 1.08 cubic feet. So the **main tank capacity is 1.08 cubic feet**. **The main tank surface area** will be $2*\pi*r*L$, 2 * 3.1416 * (0.25 ft) * (5 ½ ft) = 8.64 square feet. The end caps will have a surface area of 0.39 square feet. This gives a total of **9 square feet**.

The volume of fluid that will be maintained in the riser tube during the transfer process will be $\pi * r^2 * L$ which gives, 3.1416 * $(0.75\text{ ft})^2$ * (22 ft) = 0.27 cubic feet. So the **riser tube capacity is 0.27 cubic foot**. The surface area of the riser is approximately $2*\pi*r*L$, 2 * 3.1416 * (0.065 ft) * (21 ft) = 8.25 square feet.

R11 Properties

The liquid density of R11 does not vary much over the operating temperature of the system (70 to 140 degrees F). At 70 degrees F. the liquid density of R11 is 93 lbs per cubic foot and At 140 degrees F. the liquid density of R11 is 87 lbs per cubic foot. The effect that this would have on a 22 foot rise is (pressure = liquid density * height = 93 lbs / ft^3 * 22 feet = 14.2 psi and 87 lbs / ft^3 * 22 feet = 13.2 psi) about 1 pound per square inch. For these calculations I will just assume a head pressure of 15 pounds per square inch.

At this point I am not sure what the density of the fluid will be so will assume an average density of 90 lbs per cubic foot. I could have just as easily selected the minimum density for the work output calculations. There is only a 6 pound per cubic foot difference between the low temperature higher density and the high temperature lower density fluid, so a wrong assumption here will amount to a maximum output error of about 4%.

Our heat source has a temperature of 140 degrees Fahrenheit. The vapor density of R11 at this temperature is listed as 1.05 pounds per cubic foot. To find how many pounds of vapor we need you simply multiply the tank volume by the vapor density. This gives 1.08 ft^3 * 1.05 lbs/ft^3 = 1.13 lbs. So we need 1.13 pounds of R11 vapor at 140 degrees Fahrenheit to completely fill the tank volume.

To find out how much heat energy is needed to vaporize 1.13 lbs of R11 at 140 degrees, we again refer to the R11 data and see that at 140 degrees the heat of vaporization at this temperature is (h_{fg}) is 71.39 BTU's per pound. Taking the heat of vaporization times the amount of fluid to be vaporized in pounds gives one the answer to how much heat is needed. Therefore: 71.39 BTU / lb * 1.13 lbs = 80.95 BTU's. This calculation is based on the assumption that only the required amount of fluid is heated and subsequently vaporized. Now we know that for this design there is going to be heating of the rest of the fluid so we will need to also determine the amount of heat input that this will add to the system thermal load. I am going to postpone this until I can get more info on how to calculate this. So for know let's just assume perfect conditions where the only heat needed is the heat required to vaporize the required amount of fluid only. I will update this to a more realistic model later when I gain access to more information related to this type of problem.

The amount of fluid displaced and forced up to the upper tank will be equal to the total tank capacity minus the amount of fluid that is vaporized. At 140 degrees Fahrenheit R11 has a liquid density of 87 lbs per cubic foot and at 70 degrees it has a liquid density of 93 lbs per cubic foot. However we are assuming that the fluid doesn't get much extra heat added to it. So for a good approximation I will assume that the fluid gets heated to 87 degrees F in the process and this gives us a fluid density of 90 lbs per cubic foot. Taking this as the density gives the total tank capacity as tank volume times fluid density, which equals 1.08 ft^3 * 90 lb/ft^3 = 97.2 lbs. Subtract the amount that gets vaporized and we have the total weight of the fluid transferred to the upper tank. 97.2 lbs – 1.13 lbs = 96 lbs. So we have 96 pounds of fluid that gets transferred from the lower tank to the upper tank in each vapor expansion cycle.

Now for the amount of heat energy that gets transferred by the system as a result of the heating of the fluid. I am going to assume that the fluid gets heated to 87 degrees F. This is about ¼ the temperature differential. At 70 degrees F the heat capacity of the fluid R11 ((h_f) is 22.45 BTU/lb and at 87 degrees the heat capacity of the fluid R11 ((h_f) is 25.98 BTU/lb. Therefore it will take 25.98 BTU/lb – 22.45 BTU/lb of heat input to rise the temperature of the fluid from 70 to 87 degrees F. So we have 3.53 BTU/lb input for the heating of the fluid. Remember now that this is energy that is being input to the system which serves no purpose in the operation of the system. This a wasted part of the energy cycle. Taking 3.53 BTU/lb times the total weight of the transferred fluid gives the total amount of this heat input energy which is, 3.53 BTU/lb * 96 lbs gives 343.39 BTU's.

The input energy needed to vaporize the amount of fluid needed to completely displace the liquid fluid from the tank was 80.95 BTU's. However, before the fluid will start to vaporize it has to have enough heat energy added to it to bring its temperature up to the boiling point. At 70 degrees F the heat capacity of the fluid R11 ((h_f) is 22.45 BTU/lb and at 140 degrees the heat capacity of the fluid R11 ((h_f) is 37.15 BTU/lb. Therefore it will take 37.15 BTU/lb – 22.45 BTU/lb of heat input to rise the temperature of the fluid from 70 to 140 degrees F. So we have 14.7 BTU/lb input for heating the fluid up to the boiling point. Therefore it take (14.7 BTU/lb * 1.13 lbs) 16.67 BTU's of heat energy to heat the fluid to the boiling point. Therefore the total energy input for boiling the fluid is 80.95 + 16.67 = 97.62 BTU's.

Energy Output

From our previous calculations we know that 96 pounds of fluid are transferred from each tank. The wheel is 22 feet in diameter so each tank full of fluid will gives us:

96 lbs x 22 feet = 2112 ft lbs of energy.

Since 12 tanks will be transferred per revolution then we will get:

12 x 2112 ft lbs = 25,344 ft lbs per revolutions.

At 70 degrees Fahrenheit R11 has a vapor pressure of 13.34 pounds per square inch (psi) and at 140 degrees Fahrenheit R11 has a vapor pressure of 45.11 psi. This gives us a pressure difference of 31.76 psi for forcing the fluid up to the upper tanks. It will take a minimum pressure of ρgh to force the fluid up to the upper level tank. At 70 degrees F. the liquid density of R11 is

92.72 lbs per cubic foot. So for ρgh we get $(92.72\ lb/ft^3)(32.2\ ft/s^2)(22\ ft)$ = 14.2 psi. The pressure difference of 31.76 psi is more than sufficient for the minimum system pressure requirement.

At this point many of you are probably questioning my assumptions on this energy input thing and this is understandable. To gain more insight into whether these assumptions are correct we will need to determine what the heat transfer rates of the system are, at least we need to come up with a realistic calculation for this. Then we will be able to determine if these energy input assumptions are good approximations and if not then we can adjust them accordingly.

Heat Transfer Rates

Ok I purchased a copy of "REA's Problem Solvers Heat Transfer". On page 330 is a simple problem for "Free Convection Heat Transfer From Pipes". Using that problem as a sample I will attempt to solve our heat transfer problem in the Minto Wheel design.

Taking our operating temperatures of 70 degrees and 140 degrees Fahrenheit we get an average temperature (70 + 140) / 2 = 210/2 = 105 degrees Fahrenheit. We take this average and use it to find the fluid properties of water and of air at this temperature. With these properties we can then calculate the heat transfer rates for the cylinder when in air and when in water.

Water properties at 105 degrees	Air properties at 105 degrees
ρ = 61.93 lb / ft^3	ρ = 0.0705 lb / ft^3
cp = 0.9981 BTU / lb – F	cp =0.240 BTU / lb - F
k = 0.365 BTU / hr – ft – F	k = 0.0157 BTU / hr – ft – F
υ = 1.57 lb / hr – ft	υ = 1.29 lb / s – ft
β = 1/(460 F+105 F) = 3.186 x 10^3	β = 1/(460F+105F) = 3.186 x 10^3
Pr = 4.305	Pr = 0.705
$\Delta T = 70^o$ F	$\Delta T = 70^o$ F
$g = 32.174\ ft / s^2$	$g = 32.174\ ft / s^2$
L = D = 6 inches	L = D = 6 inches
A = π * D * 5 ½ ft = 8.64 ft^2	A = π * D * 5 ½ ft = 8.64 ft^2

The Grashof number is calculated from the data above. The equation is:

$$Gr = (g*\rho^2*\beta*\Delta T*L^3) / \upsilon^2$$

For water $Gr = (g*\rho^2*\beta*\Delta T*L^3) / \upsilon^2 = 1.005 \times 10^{10}$
For air $Gr = (g*\rho^2*\beta*\Delta T*L^3) / \upsilon^2 = 1.488 \times 10^{-3}$

Then the Rayleigh number is the product of Grashof (Gr) and Prandtl (Pr) numbers:

For water $Ra = Gr * Pr = 1.005 \times 10^{10} * 4.305 = 4.326 * 10^{10}$

For air $Ra = Gr * Pr = 1.488 \times 10^{-3} \times 0.705 =1.049 \times 10^{-3}$

The logarithmic value of the Rayleigh number is then used with a data chart to determine the log value for the Nusselt number.

The $\log_{10}$ of Ra for water is $\log_{10}(1.005 \times 10^{10}) = 10.636$
The $\log_{10}$ of Ra for air is $\log_{10}(1.488 \times 10^{-3}) = -2.979$

These log values are out of range for the supplied chart. So I checked in the book and found a table on page 319 which gives some numbers for determining the Nusselt number along with an equation.

The equation is $Nu = a(Gr*Pr)^m$

For water with a Gr*Pr value greater than 10^9 we get a = 0.13 and m = ¼. This gives $Nu = a(Gr*Pr)^m = 59.286$.

For air with a Gr*Pr value between $10^{-3} – 1$ we get a = 1.09 and m = 1/10. This gives $Nu = a(Gr*Pr)^m = 0.549$.

Since Nu = h*L / k then rearranging we h = Nu*k / L, where h is the convective heat transfer coefficient. Solving for this gives:

When submerged in the heated water the heat transfer rate is

$$h = Nu*k / L = 0.721 \text{ BTU / min - ft}^2 – \text{F}$$

When in air the heat transfer rate is

$$h = Nu*k / L = 2.873 \times 10^{-4} \text{ BTU / min - ft}^2 – \text{F}$$

Now that we have the heat transfer coefficients for convective heat transfer we can calculate the total heat energy transferred per unit of time.

$q = h * A * \Delta T$

$q_{water} = h * A * \Delta T = (0.721 \text{ BTU / min - ft}^2 – \text{F}) (8.64 \text{ ft}^2) (70^o\text{F}) =$
$= 436.222$ BTU/min

$q_{air} = h * A * \Delta T$
$= (2.873 \times 10^{-4} \text{ BTU / min - ft}^2 – \text{F}) (8.64 \text{ ft}^2) (70^o\text{F}) =$
$= 0.174$ BTU/min

From this calculation we can see that the heat transfer rate of the cylinder submerged in water is about 2500 times higher than when exposed to air. However when exposed to air there is also a heat transfer rate that is produced by radiation. The radiation heat transfer is calculated by this equation (on page 333):

$q_{rad} = \xi * A * \sigma * (T1^4 – T2^4)$

q_{rad} = emissivity * Area * Stefan-Baltzman constant * $(T1^4 – T2^4)$
I assume an emissivity of 0.9 so this gives:
$q_{rad} = 0.9 * (8.64 \text{ ft}^2) * (0.171 \times 10^{-8} \text{ Btu/hr ft}^2\ ^o\text{R}^4) [(600\ ^o\text{R}^4)\text{-}(530\ ^o\text{R}^4)]$
$= 11.234$ BTU/min

Stefan-Baltzman constant (σ) = 0.171×10^{-8} Btu/hr ft^2 ^{o}R^4

Adding $q_{air} + q_{rad}$ = (0.174 BTU/min) + (11.234 BTU/min) = 11.408 BTU/min.

From these calculations we can see that the heat transfer rate of the cylinder when submerged in water (436.222 BTU/min) is about 38 times higher than the heat transfer rate of the cylinder exposed to air.

From this sample calculation we can see that the heat transfer rates of the system are not balanced very will and from the results of these numbers it is not surprising that the Mother Earth News Minto Wheel did not perform as expected.

We had previously calculated that it would take 97.62 BTU’s to vaporize the required amount of fluid. Now if we take the lower number of the heat transfer rate which will be acting as a bottleneck in the system we can see what the maximum operation would be based on these calculations. Taking

97.62 BTU's and dividing by 11.41 BTU/min gives us 8.56 min for this cycle and since this cycle is only ¾ of the total cycle then the total cycle time would be (8.56 min)*4/3 = 11.41 min. So at full load the wheel will turn at a rate of one revolution every 11.4 minutes.

Conclusions From Heat Transfer Calculations

From the above calculations the Mother Earth News Wheel should have turned at a rate of 1 rev every 11.4 minutes.

My assumption about how much the work fluid would be heated up is apparently wrong. This is the first time that I have worked with this type of problem and I had to find the data and equations for doing these heat transfer calculations. I hope that I have not made any major mistakes here.

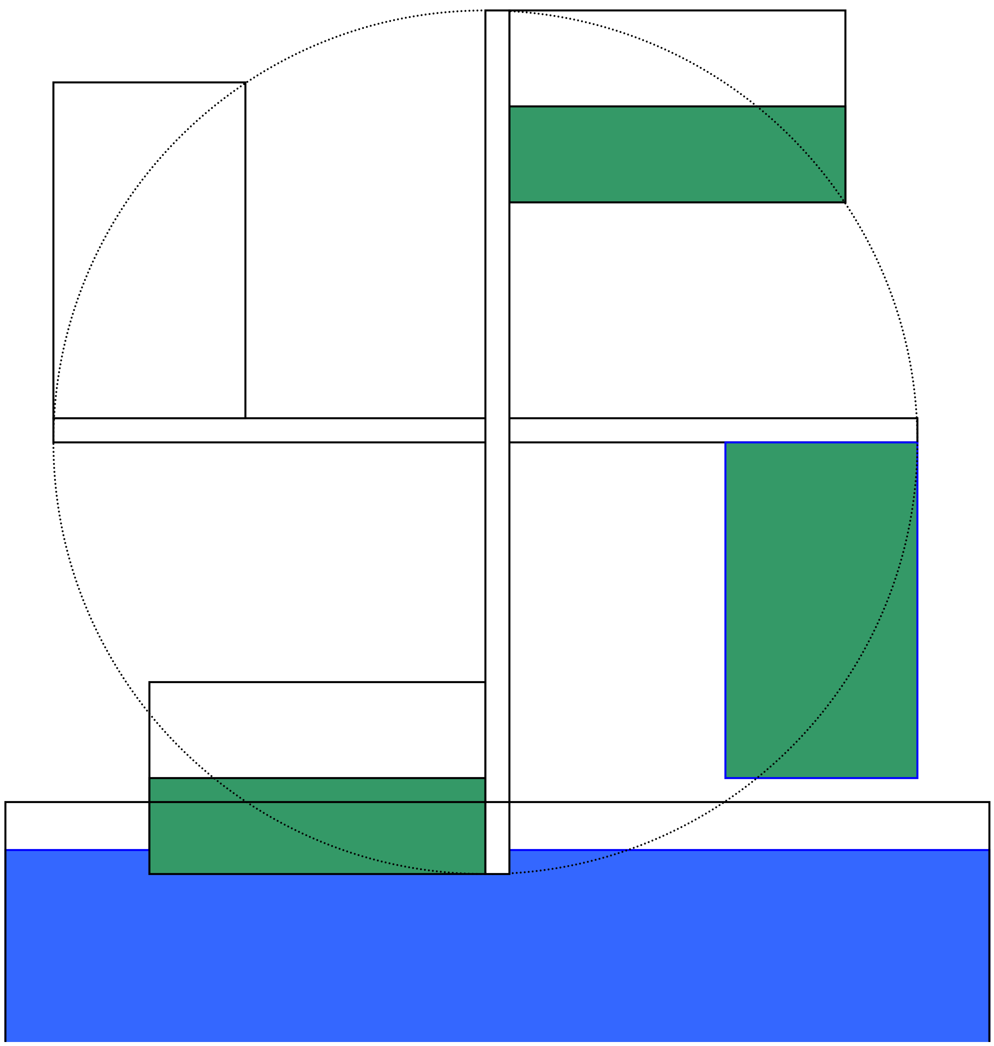
Even though my original assumptions were apparently wrong the solution that was offered is still a valid solution. By using a double tank system, the system can be designed so as to insure a balance between the heat input and the heat dissipation of the system. Also with a proper design of a double tank system the maximum heat input will be only that amount needed to heat and vaporize the required amount of fluid for the riser fluid displacement.

Whether one uses a double tank system or a single tank system the biggest problem with the basic Minto Wheel design is the poor performance of the heat transfer system while in the air. At the present time I am not sure about how one would solve this problem. However I believe one good low tech solution would be to incorporate evaporative cooling. I do not have the equations yet but evaporative cooling should be able to provide a simple way of balancing the heat transfer rates in the system.

Here is another design concept that is similar to the basic Minto Wheel design. This design uses only one tank just like the basic Minto Wheel design however this design uses rectangular tanks. These tanks can be proportioned so as to obtain optimal design parameters. Another feature that can be easily employed in this design is to basically have only a part of the rectangular tank exposed to the heated water, this will help to ensure a balance between the thermal transfer capacities of the system.

Minto Wheel

With Thermal Balance Design Enhancement



Only a part of the thin rectangular tank is immersed in the heated fluid. Doing this will insure a thermal balance between the thermal heat input and output of the system. This is severely lacking in the basic Minto Wheel design.

Energy and Power Calculations

I previously had forgotten to do these calculations. So let's see what we learn from this.

We had previously calculated that 96 pounds of fluid could be transferred from a full tank. Taking 96 lbs times the distance of 22 feet gives us the total work for one tank, which is 96 lbs x 22 ft = 2112 ft lbs of work per container. There are 12 containers so taking 12 * 2112 ft lbs gives us 25344 ft lbs of work per revolution.

Power is the rate of doing work therefore dividing the work per revolution by the time it takes to complete one revolution will give us the power of the system, which is 25344 ft lbs / 11.41 min = 2221.26 ft lbs /min = 50.2 Watts.

If we were to take the revolution rate as reported in the Mother Earth News article and assume full load capacity then we would get a power output of:

25344 ft lbs / 5 min = 5068.8 ft lbs /min = 114.5 Watts

These calculations reveal that this system is not a very feasible system. The cost of the system is high because of the large quantity of the low boiling point fluids that is used in the system. The system is also high in cost because of the shear size of the system. Yes it is low tech and like the basic dippy bird it would make an excellent decorative item for a science lab or one's desk. However, unless a simple and easy method is found for enhancing the thermal transfer of this system then this system is not worth building. I believe that the thin rectangular tank design above is a step in the right direction but am unsure if it is enough. More calculations will need to be done.

These conclusions are based on the assumption that the above calculations are not in gross error. Hopefully I have not made any major mistakes or overlooked anything. So in examining these calculations do try to verify that these are indeed correct. Do check to see if indeed these calculations are a proper model of the system. If you find that they are then please comment, however, if you find that this model is not representative of the basic Minto Wheel system then please correct the model and let us all know the correct model and its results.

Just completed a quick and dirty sample calculation of the thin rectangular system and using rectangular tanks of 3 feet X 5.5 feet X ¾ inches, with a 22 foot Minto Wheel system as above will give a maximum output of about 190 watts turning at a rate of one revolution every three minutes (RPM / 3 Min).

CONCLUSIONS

It should be readily apparent from the previous mathematical model of the **Minto Wheel** Device that **devices** based on these simple principles of natural convection in heat **are doomed to very low levels of power development.**

These devices will never be able to develop any significant amount of power in relationship to their size. The huge size for such limited power development makes these devices impractical for consideration in any application where power is the needed commodity. These devices would only be practical as novelty devices the same as the dippy bird novelty items.

The basic premise of these devices is valid, however, due to the extremely low coefficient of heat transfer in natural convection which the standard basic Minto Wheel type devices depend on, these devices will never be used as a practical alternative to present power systems.

If you want to make the basic premise of these devices work in a practical power system then you will have to develop a design that uses forced fluid flow heat exchange mechanisms.

I did check into this and found that a vastly improved system has been designed and patented. If you want to pursue this then you should read U.S. Patent 6,434,941 granted in August of 2002, invented by two Japanese inventors, titled “ORDINARY TEMPERATURE HEAT ENGINE”.

I have not done any calculations on this system, however from looking at the patent it is obvious that the system would be less costly to build. Also since the system does utilize forced flow heat exchangers, the system output should be capable of being at least a couple hundred times higher (or more) for a given size heat exchanger. This translates into a smaller system which would be cheaper to build and maintain with vastly superior power output development capacity. Perhaps we could call this the Stationary Minto System or the Stationary Dippy Bird System which ever you prefer.