# The Micro Steam Car, a practical and theoretical design project

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## INTRODUCTION

Many educational project competitions have come and gone in design classes around the world. Structures have been made with various restraints, machines have been configured to move with certain objectives and projectiles have been launched to meet all sorts of criteria. While each is a useful learning exercise, few have embraced more than one or two mechanical engineering disciplines and few have endured long enough to establish a resemblance of the theory and experience that guide virtually all engineering design.

A design class project launched in 1990 at the University of Natal was found by accident rather than intent, to involve all aspects of the profession. Called the Micro Steam Car, participants design and build an inexpensive vehicle about 40 cm long powered by an ethanol heated tin can boiler, a pin-sized nozzle and a turbine. The objective is fuel efficiency as measured by the distance covered on the smooth floor of an athletics hall using the allowed 20 ml fuel.

Competitors fill their boilers with the minimum possible amount of water and load their burners with the carefully measured fuel volume. A few minutes after light-up, steam pressure builds up and the car struggles off, under a full load of water and fuel, between marked lines roughly 2 m apart.

At the end of each crossing of the hall, the contestants turn the car around. If the car runs off course, direction corrections may be made. Rather than to bend down to a car, a rod can be used to nudge the car in the right direction.

In addition to becoming an annual student event, it was seen to hold the potential to attract both school pupils and fully qualified engineers and thus a two-level national competition was launched. The distances achieved increased from the pioneering 175 m of the first student winner to around 5500 m for the current open event champion, with scholars right behind at 5300 m. Finally, the direct visibility of the concepts and the economy and availability of the materials, has led to certain standard designs being published to enable individuals or groups to build cars in a matter of hours for education or fun. The simplicity of the formula does not detract from the technical challenge involved and probably does much to enhance it since new ideas are so easily implemented.

It is hoped that this paper will convey some of the excitement of being able to design and build a complete heat engine and vehicle and of seeing both young and old, the experienced and the novice, taking part in designing, inventing and learning.

A basic design is presented to illustrate the main concepts. It is hoped that it will stimulate rather than limit the creative process. Some elementary theory is given to establish the main working principles, relationships and constraints. The paper is concluded with some ideas regarding the achievement of high performance.

## NOMENCLATURE

*(Values for a sample data set are included)*

| | |
|---|---|
| $C_n$ | component of absolute velocity normal to the tangent ≈ 260 m/s |
| $C_1$ | absolute turbine inlet/nozzle exit velocity ≈ 600 m/s |
| $C_2$ | absolute turbine exit velocity |
| $C_d$ | drag coefficient of car ≈ 1.0 |
| $C_{\theta 1}$ | tangential component of velocity $C_1 \approx 540$ m/s |
| $C_{\theta 2}$ | tangential component of velocity $C_2 \approx 310$ m/s |
| $D_{turb}$ | turbine diameter ≈ 0.045 m |
| $D_{shaft}$ | turbine shaft diameter ≈ 0.0015 m |
| $Q_{evap}$ | heat absorbed by steam during evaporation only = $m_{\mathrm{evap}}(h_0 - h_f)$ |
| $Q_{fuel}$ | heat in fuel ≈ $500 \times 10^3$ J |
| $q_{fuel}$ | heating value of fuel ≈ $29\,732 \times 10^3$ J/kg ethanol |
| $h_0$ | enthalpy of steam at nozzle inlet ≈ $2750 \times 10^3$ J/kg (sat. vap. at 4 bar abs.) |
| $h_f$ | enthalpy of saturated liquid at boiler pressure ≈ $605 \times 10^3$ J/kg at 4 bar abs. |
| $h_l$ | enthalpy of cold liquid used to fill boiler ≈ $105 \times 10^3$ J/kg |
| $h_{1is}$ | enthalpy after isentropic nozzle expansion ≈ $2505 \times 10^3$ J/kg |
| $k_w$ | wind friction coefficient of turbine ≈ 0.019 |
| $k_b$ | belt-induced bearing turbine friction coefficient ≈ 8.8 |
| $k_d$ | drag proportionality constant for car ≈ 6.5 |
| $m_{fuel}$ | mass of fuel ≈ 0.017 kg ethanol (20 ml) |
| $m_{steam}$ | mass of steam evaporated ≈ 0.08 kg |
| $m_{resid}$ | residual mass of liquid left in boiler at flame-out ≈ 0.03 kg |
| $\dot{m}_{evap}$ | steam evaporation rate ≈ 0.08 kg/2220 s ≈ $3.6 \times 10^{-3}$ kg/s |
| $t_{burn}$ | total burn time of fuel ≈ 2700 s |
| $t_{warmup}$ | time to bring boiler up to pressure ≈ 480 s |
| $U$ | blade speed ≈ 10 m/s floor test, 21 m/s wheel up test, 28 m/s belt off test |
| $V$ | car speed ≈ 1.5 m/s |
| $V_r$ | transmission velocity ratio $U/V \approx 10$ |
| $\dot{W}_{turb}$ | power transfer from steam to blades ≈ 0.3 W |
| $W_1$ | velocity at inlet relative to blade ≈ 510 m/s |
| $W_2$ | velocity at exit relative to blade ≈ 420 m/s |
| $w_{turb}$ | specific work transfer from steam to blades ≈ 8500 J/kg |
| $a_1$ | nozzle angle ≈ 64° |
| $b_1$ | angle of inlet relative velocity ≈ 60° |
| $b_1$ | average exit blade angle ≈ 50° |
| $h_{boiler}$ | boiler efficiency ≈ 39% |
| $h_{comb}$ | efficiency of combustion process ≈ 100% |
| $h_{nozzle}$ | aerodynamic efficiency of steam nozzle ≈ 75% |
| $h_{blade}$ | aerodynamic efficiency of turbine blades ≈ 52% |

## MATERIALS, LAYOUT AND DETAILS OF A SIMPLE MICRO STEAM CAR

In order to explain the concept and to provide a basis for the theory presented later, Fig. 1 presents an example of a Micro Steam Car. Apart from being illustrative, this design is of particular interest because it was created to be an educational tool in classrooms and in the home. To have the widest possible application, expensive tools, equipment and materials were ruled out. The steps of construction had to be sufficiently simple so that, under instruction, relatively unskilled participants could perform most tasks successfully at the first attempt.

These were not easy objectives to achieve. All mechanical products rely on the almost unlimited availability of machine tools, operator skill and materials. When all of these are severely restricted, new solutions to virtually every standard method of manufacture are needed. The design shown represents many hundreds of hours of research and innovation in which all aspects were exposed to successive work groups and then revised to reduce or eliminate problem areas. The materials are supplied in kit form at cost price to schools and individuals all over South Africa. The university and other institutions conduct many courses for groups of from 10 to 30 participants. The project is valuable not only to education in general but it also serves to attract able and motivated young people into mechanical engineering. The use of the design has not been restricted to young people and it has been used in many family and other social groups.

The tools of construction were limited to a pair of scissors, two pairs of pliers, various-sized pokers to create holes and such items as could be made by the participants themselves. The materials selected were those readily available as scrap, such as tin cans, items that can be obtained economically in bulk, such as tin lids, and certain specialized material custom-made for the project, such as the silicon rubber tubing for the safety valve. Other materials, such as PTFE thread tape, paper glue sticks and silicon rubber adhesive are also used. Anyone interested in the kit or more information regarding the design should contact the author.

The car is not very efficient and achieves about 1000 m which leaves plenty of scope for improvement. It illustrates the kind of three-wheel single-stage belt transmission that has become common with competitors. Because extensive use is made of tin cans, for flat sheet, for disks and for boilers, locally available products will determine the way a design pans out, particularly for group activity where large numbers of identical items are needed. In South Africa and in Europe, steel body beverage cans are available which are essential for soldering in the copper nozzle and safety valve tubes.

Apart from high thermal performance, it is essential for a Micro Steam Car to be light, to use heat-resistant materials, to be dismantled for repair and modification and to be relatively easily made with a minimum of tools. Historically, the original rules forced participants to use only scrap materials and allowed no machine tools. These restrictions were lifted when it became obvious that there was little advantage in using expensive new material and when complex cars made by skilled machinists were radically outperformed by designs made in student dorms. The burden of policing the application of the rules was also lifted.

With a three-wheel layout, a flexible suspension is not needed to ensure that the wheels will always touch the floor even if the chassis is distorted or the surface uneven. The third wheel, most often the front, usually becomes the final drive pulley. Thus all wheels run free on their axles which eliminates the need for fixing a hub for torque transmission.

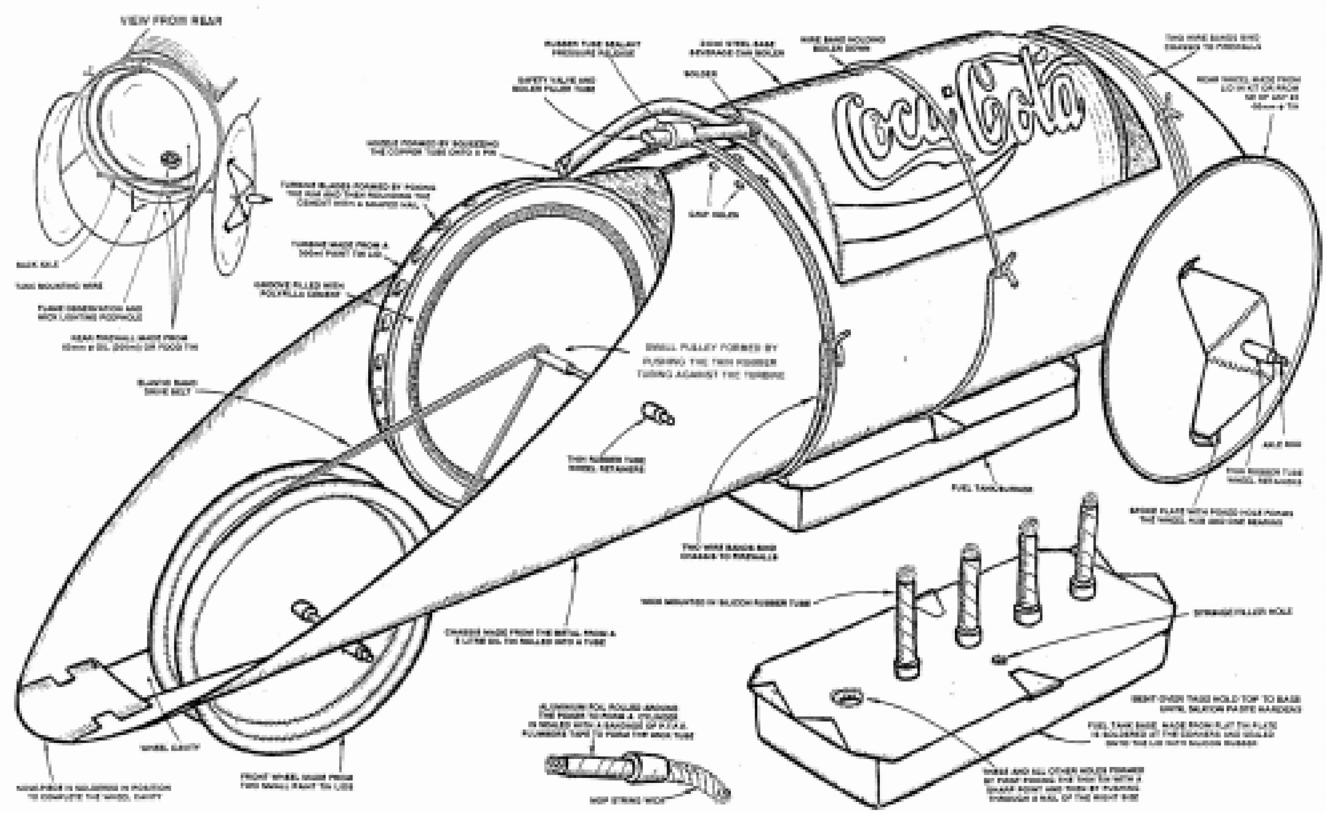


Fig. 1. A basic Micro Steam Car design.

## The chassis

To achieve the maximum simplicity, the chassis must be more than a platform and in the example it forms the firebox, the smokestack, the boiler mount, the turbine base, the turbine bearings and part of the burner. The flat sheet of tin from a 1-gallon oil or solvent tin is cut to shape and rolled into a tube before a wire-strapping tightly to two segments of 85 mm diameter food tins which become the firewalls.

## Axles, wheels and bearings

Any thin straight rod will make an axles. Welding rods work well and, if straight enough, bicycle spokes are ideal. For large groups, a wire or spring manufacturer can normally supply straightened wire cut to length.

The lids of tin cans, which can be easily and cleanly sliced off with a pocket knife, make ideal almost ready-made wheels. Bearing hubs have been made from blind rivets, from epoxy moulded around the shaft or from holes poked into the thin metal using a sharpened axle stub. The poking action deforms the steel plate into a short tube to form the bearing.

This method of poking holes is important because it eliminates the need for drilling and makes a better hole in thin steel plate. A hardened steel masonry nail ground to a sharp point and mounted in a rounded wooden handle becomes not only an essential tool for the Micro Steam Car but will soon become indispensable in the workshop.

To form the hub using poked hole bearings, the hemispherical base of a beverage can may be epoxied onto the disk or a star can be cut from tin and bent to form spokes. To align the hub at right angles, those without a drill press or lathe may like to use a tin can with both ends in place. As shown in Fig. 2, a central hole in each lid will perfectly align a shaft with the end faces.

There are many creative ways to use the lids and bases of tin cans to form the notch around the rim of the pulley wheel. In the example shown, two identical single-seal tin lids

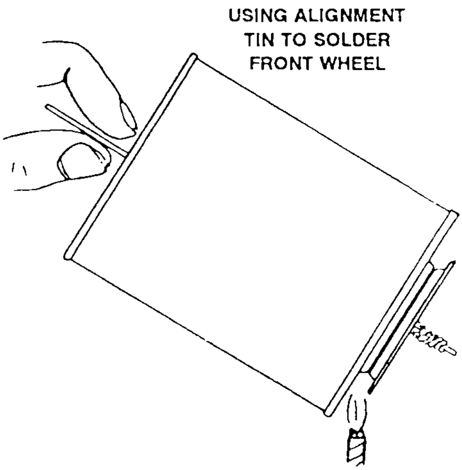


Fig. 2. The alignment tin and shaft.

are soldered together, as shown in Fig. 2. The soldering flame, identical to that described later for the burner, is a useful way of eliminating the need for a soldering iron in groups or in the home.

All the wheels must be retained on their shafts firmly and with the correct clearance. String knotted tightly around a shaft is a simple solution while the core of an electrical ‘chocolate block’ connector is perhaps more elegant. In the present example, retainers consisting of short lengths of thin silicon rubber tubing are slid onto the shaft and carefully adjusted for clearance.

## The turbine

To achieve a reasonably high boiler pressure the micro turbine has one very small nozzle and thus the turbine must be partial admission impulse. Theoretically, the rotor should be only 2 or 3 mm in diameter and should run at over 100 000 rpm. Even if it were possible to make such a small turbine, the high-speed bearings would carry a large friction penalty and the drive system would be very complex. Consequently, micro turbines tend to be as small as the craftsman can manage.

To guide those unskilled in turbomachinery, a successful micro turbine depends on five basic rules:

(1) the nozzle jet must be as close and as tangential as possible
(2) the blades must have a razor-sharp edge that faces directly into the flow without ‘incidence’
(3) after receiving the flow, the blades must turn or bend the flow as much as possible
(4) the turbine must have a low wind-resistance
(5) the turbine should operate at the best rim or blade speed. This is a trade-off between power extracted from the jet and wind friction, both of which increase with speed.

To best meet these rules, especially the fourth one, a number of designs have been handmade with ‘Pelton’ type bucket-shaped blades formed completely or partly within the rim of the disk so that the blades do not scoop air to create wind friction.

The shape of these blades depends on how they are made, and here the ingenuity and skill of the craftsman comes into play. One way is to create sawtooth-shaped notches around the rim and then to close them off with a disk of thin sheet metal on either side.

Rounded cavities have been hand-carved into a 30 mm diameter wheel under a binocular microscope. When magnified, aluminium looks and carves like lead. If the craftsman is patient and is prepared to practice and to grind specially shaped gouges and chisels, the resulting cavities can even be polished with a toothpick and grinding paste. Alternatively, a rounded punch can be used to tap hemispherical notches into the rim of a soft aluminium disk.

In the design described here, the rim or opening of the bucket-shaped Pelton blades are made by drilling or poking holes around the cylindrical perimeter of a double-seal paint tin lid. The drill bit or poker is then inserted into each hole and rotated as far as possible in order to orientate the opening to face tangentially. The bucket-shaped blade cavity is completed by filling the groove around the tin lid with a stiff mix of household plaster and then gently pushing in a rounded nail to create the hemispherical shape.

As on the rear wheels, a hemispherical or spoked hub can be used. As shown in Fig. 3, the pulley is formed by sliding a 10-mm length of the thin retainer rubber tube onto the shaft and pushed firmly against the turbine. This forces the shaft to rotate with the turbine and thus

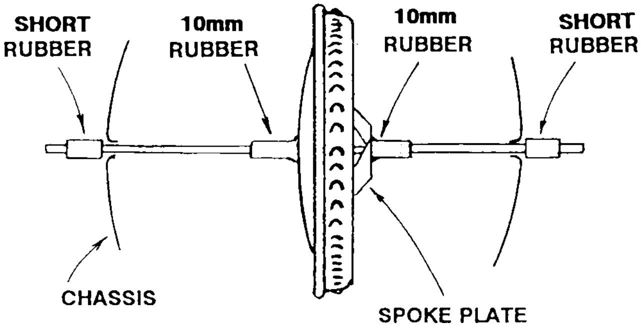


Fig. 3. The turbine hub, pulley and shaft.

the bearings are formed by sized holes poked into the tin chassis. Pulley flanges are not needed and the elastic drive belt will find its own natural position if the turbine and front wheel are properly positioned. The turbine should be statically balanced by resting the shaft on straight edges and either removing or adding weight appropriately.

## The boiler, nozzle and filler/safety valve

Short lengths of 1/8″ or 3.2 mm OD copper tubes, flame-soldered into the base of the steel body beverage can boiler, form the basis of the nozzle and of the filler and safety valve combination.

A nozzle is a fairly sudden and smooth constriction in the steam flow that allows the steam velocity to increase and jet onto the turbine in a tangential direction. As far as possible, sharp corners and parallel sections should be avoided. In the example, the nozzle is formed at the end of the copper tube that feeds steam from the boiler. The easiest way to make a nozzle is to select the correct diameter steel wire, needle or pin and then to carefully squeeze the soft copper tube onto it.

The combined filler and safety valve effectively eliminates the need for a threaded closure and a spring-loaded accurately turned release valve. The end of a copper tube is closed off, with a side cutter or by soldering, and a lateral hole is drilled. A short length of 3 mm ID silicon rubber tube is slid onto the copper to cover the hole. When the steam pressure exceeds the elastic force of the rubber, steam will be released. The release pressure can be raised by sliding a wire rod in between the rubber and the copper to increase the elastic force. To fill the boiler, the rubber is pushed beyond the hole and water is forced in with a larger rubber tube or by mouth.

Because of the importance of safety, a pre-drilled copper tube and the correct silicon rubber should be supplied to all participants by the organizers of a competition or group project.

## The burner and fuel tank

The simplest way of burning alcohol is using a cotton wick dipping into the reservoir of fuel. It is believed that the wide clear blue flame achieved when the tip of a wick is about 5 mm from the heated surface is more efficient than a long orange flame which completes its combustion before contacting the boiler

Because of the proximity of the store of fuel to the hot combustion zone, a major problem is to avoid heating the fuel which eventually boils and makes the burn rate uncontrollable. The design shown in the example prevents excessive heat flow by firstly using the chassis as a heat shield, the wicks penetrating from below into the combustion zone through vent holes just large enough to allow draught airflow to the flame. This airflow also ensures cooling of the zone where heat tends to flow. The second barrier to heat flow lies in the conductivity of the wick tube material. Glass tubes have been widely used. Thin shim metal also works well but needs to be sealed to prevent fuel from weeping out and burning in the wrong place. In the example, waste ‘pie dish’ aluminium foil is rolled into a tube around a nail and then sealed with a bandage of PTFE tape. The wick material comes from a kitchen mop and each tube is pressed into the tank with a stubby length of 3 mm ID silicone rubber tube.

The rectangular fuel reservoir is designed so that it can easily be made from two pieces of flat sheet metal. The base is bent into a box shape and the corners flame-soldered to avoid all leaks. The upper lid section has poked holes for the wicks and is glued onto the base with silicon rubber sealant. The ends are bent up so that the correct clearance is formed when the completed tank/burner is drawn tightly up against the bottom of the chassis with the mounting wire.

### Further details

For anyone wanting more details of this design, the plans are available from the University of Natal with a free length of safety-valve rubber.

## BASIC MICRO STEAM CAR THEORY

The intention of this section is primarily to provide an understanding of the processes involved. It will, however, also show how simple measurements and experiments can be carried out to point the way to future designs and to adjusting the existing car for improved performance.

Since a turbine is involved, the starting point is the Euler equation for specific work transfer ($w_{turb}$) and power transfer $(\dot{W}_{turb})$ from the steam to the turbine wheel. Note that the useful power output from the turbine wheel will be less than this quantity owing to wind friction, bearing loss and vibration loss.

$$w_{turb} = U(C_{\theta 1} + C_{\theta 2}) \quad \text{and} \quad \dot{W}_{turb} = \dot{m}_{evap} U(C_{\theta 1} + C_{\theta 2})$$

where the quantities are defined in Fig. 4.

Before going further, some of the peculiarities arising from the nature of the micro steam turbine are discussed.

The steam mass flow $\dot{m}_{steam}$ involved is minute and making a small rotor to match is virtually impossible. This means that a practically sized turbine must be a partial admission impulse design with all the expansion in the nozzle and no pressure change in the rotor blades. What makes the turbine special is that, relative to the rotor and blades, the nozzle is smaller than normal partial admission machines by at least two orders of magnitude.

There are two implications of this micro-sized nozzle. Firstly, the steam jet, instead of filling the volume between two or more blades, is so small that it strikes a vane at one point only, as shown in Fig. 5 thus making what is known about efficient aerofoil shapes of little use.

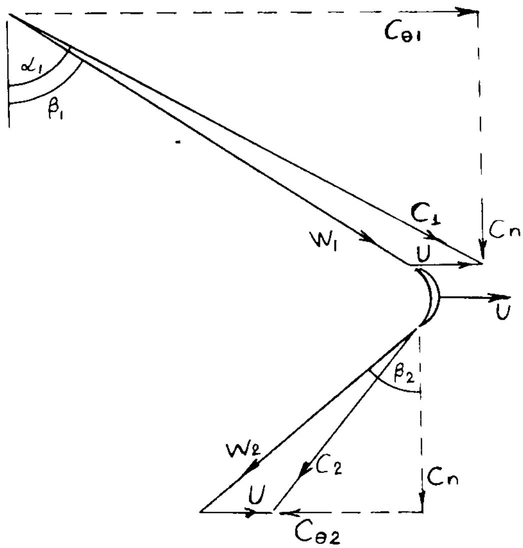


Fig. 4. The turbine velocity triangle.

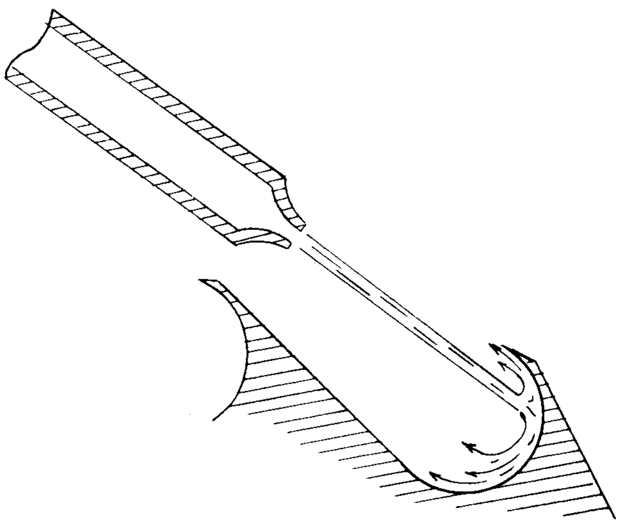

Fig. 5. A micro steam jet interacting with a macro turbine blade.

Secondly, since the power output $\dot{W}_{turb}$ from a rotor is in the region of 100 times less than a conventional turbine of the same diameter, the power will be of similar magnitude to the normal bearing and windage friction power. Since windage friction power follows the cube of the blade speed (*U*), net positive power outputs are found at speeds far below those normally expected for small turbomachines, at around 10 m/s instead of 300 m/s. Typical rotational speeds are around 5000 rpm instead of 150 000. Vibration can also be a significant absorber of the microwatts produced.

Because the specific work $w_{turb}$ depends on the blade speed, the result is a much lower than normal value which means a lower than normal efficiency. This is even further reduced by friction power being of the same order as the power produced.

As shown in Fig. 4, the exceptionally low blade speed means that the relative velocity is almost the same as the absolute velocity in both magnitude and direction. The blade angle can therefore be made the same as the nozzle angle.

The above realities are fortunately not all bad news. The low speed simplifies the bearing design, power transmission design and material selection to the extent that excellent turbines can be very easily designed and made by the non-specialist. The dominance of wind friction has also led to 'Pelton' type radial inflow, radial outflow blades that are believed to have less friction because they are wholly or partly buried within the turbine disk and 'scoop' or pump less dead fluid. Such blades are very much easier to hand form than normal axial flow designs.

After some thought it should become obvious that the two major variables are the burn time, which affects the steam mass flow, and the effective 'transmission' ratio of turbine blade speed over floor speed (or drive wheel rim speed). These are often flexible enough to be regarded both as design variables and as operational variables which can be fine-tuned on a finished car for optimum performance.

The transmission must be designed to allow the turbine to run at a speed which maximizes the power output by minimizing the effects of wind and bearing friction. Fortunately, the maximum power is that which drives the car the fastest and can thus be readily found experimentally, provided some gear ratio adjustment is possible.

Because tip speed dictates turbine performance, large turbines will have roughly the same blade speed as small turbines but will rotate at different speeds. The same concept applies to the drive wheel. For the same floor speed, a large front wheel rotates slower than a small front wheel. Therefore, instead of a gear ratio that relates rotational speeds, the most useful parameter is the ratio between the blade speed and the floor speed of the car. Current values lie in the range 8–12 and within reach of a single-stage belt drive.

The burn time is fairly easily changed via the length and number of wicks. A short burn time increases the steam mass flow rate and the power output and tends to drive the car faster, perhaps even faster than the walking pace of 1.5 m/s considered safe for steering and turn around.

The pressure in the boiler has not yet been mentioned. The steam pressure and density will always increase until the nozzle mass flow exactly balances the steam evaporation rate. Thus, if the burn time is changed without changing the nozzle diameter, the pressure will be low and inefficient for long burn times. For very short burn times, steam may vent uselessly through the safety valve.

Returning now to the turbine power output equations, the velocities, mass flow and angles will be found from boiler data and turbine dimensions. After that, the losses will be subtracted to obtain the nett power output from the turbine. When this is equated to the useful power absorbed by the car, the speed and distance enter into the argument to provide indications of optimum settings and to perhaps point the way to an improved design.

The following are found from assumed boiler pressure and from turbine data. The approximate numerical values quoted are by way of example using typical data listed in the nomenclature.

$$C_1 = \sqrt{2\eta_{noz}(h_0 - h_{1is})} \approx 600 \ \text{ m/s}$$

$$C_{\theta 1} = C_1 \sin\alpha_1 \approx 0.9 C_1$$

$C_{\theta 2}$ can be found from the following sequence

$$C_n = C_1 \cos\alpha_1 \approx 260 \text{ m/s}$$

$$W_1 = \sqrt{C_n^2 + (C_{\theta 1} - U)^2} \approx 510 \text{ m/s}$$

$$W_2 = \sqrt{\eta_{blade}} \quad W_1 \approx 420 \text{ m/s}$$

$$C_{\theta 2} = W_2 \sin\beta_2 - U \approx 310 \text{ m/s} \approx 0.5 C_1$$

$$\therefore \quad \dot{W}_{turb} \approx 1.4\, U\, C_1\, \dot{m}_{evap}$$

The steam mass flow rate ($\dot{m}_{evap}$) is the total steam evaporated (which can easily be measured), divided by the evaporation time ($t_{burn} - t_{warmup}$), which is either measured or deliberately selected and which is almost the same as the run time. Thus

$$\dot{W}_{turb} \approx \frac{1.4\, U C_1\, m_{steam}}{(t_{burn} - t_{warmup})}$$

The mass of steam evaporated ($m_{steam}$) is dependent on the heat available from the fuel and the boiler efficiency. The efficiency is defined in terms of the total heat absorbed by the steam and residual liquid. This emphasizes the effects of excess residual liquid at the end of the run and concentrates on the primary objective which is to produce vapour. For zero residual liquid, a 100% efficient boiler at a 4 bar bs. boiler pressure will produce 0.189 kg steam.

$$\eta_{boiler} = \frac{Q_{absorbed}}{Q_{fuel}} = \frac{m_{steam}(h_0 - h_l) + m_{resid}(h_f - h_l)}{\eta_{comb} m_{fuel} q_{fuel}} \approx 39\%$$

The above equation can also be used to calculate the boiler efficiency from measurements. Thus finally

$$\dot{W}_{turb} = \frac{1.4 U C_1 \left[\eta_{boiler} \eta_{comb} m_{fuel} q_{fuel} - m_{resid}(h_f - h_l)\right] / (h_0 - h_l)}{(t_{burn} - t_{warmup})}$$

The turbine power output is absorbed by its own losses (windage, vibration and belt tension induced bearing friction) and in driving the car against drag and rolling resistance. Thus

$$\dot{W}_{turb} = \dot{W}_{windage} + \dot{W}_{bearing} + \dot{W}_{vib} + \dot{W}_{drag} + \dot{W}_{rolling}$$

A drastic reduction in useful power output can occur if a turbine vibrates. While the effect of this may be very serious at high speeds when for example a turbine is run free without any load, the effect at normal running speeds may well be negligible. It is assumed here to be negligible both at the normal running speed and at higher speeds.

The rolling resistance is believed to be small for a well-made Micro Steam Car and this is also assumed to be zero.

If the drive belt is removed, the friction induced in the bearing by belt tension falls away as does the drag on the car. If the remaining bearing friction due to the weight of the turbine is assumed negligible compared to the windage loss, a measurement of the free speed enables an estimate of the wind friction constant $k_w$ to be made as well as to incorporate the diameter of the turbine into the calculations. The windage loss is similar to other viscous aerodynamic power loss and will be proportional to area and velocity cubed.

The belt-off test gives

$$\dot{W}_{turb} = \dot{W}_{windage} \propto Area_{turb} U^3 = k_w D_{turb}^2 U^3$$

If the belt is now connected and the drive wheel allowed to run free (the ‘wheel up’ test), an estimate of the bearing friction induced by belt tension can be determined. The bearing is assumed to be film lubricated with a friction torque proportional to shaft diameter which makes the power absorbed proportional to diameter and velocity. Thus

$$\dot{W}_{bearing} \propto D_{shaft} U = k_{bearing} D_{shaft} U$$

or

$$\dot{W}_{turb} = k_w D_{turb}^2 U^3 + k_{bearing} D_{shaft} U$$

The final term is the only ‘useful’ power output. It is that used to overcome wind drag on the car and can be found by simply measuring the floor speed of the car. The drag power is also proportional to the velocity cubed and depends also on the frontal area and the drag coefficient. Thus

$$\dot{W}_{drag} \propto C_d A_f V^3 = k_d C_d A_f V^3$$

In the absence of accurate drag coefficient data, it will be helpful to regard unstreamlined shapes as having a value of unity and a perfectly streamlined teardrop-shaped body as around 0.25 to at least enable an estimate to be made of the value of improving or of not bothering about streamlining.

The final power equation is

$$\dot{W}_{turb} = \frac{1.4UC_1\left[\eta_{boiler}\eta_{comb} m_{fuel} q_{fuel} - m_{resid}(h_f - h_l)\right] / (h_0 - h_l)}{(t_{burn} - t_{warmup})}$$

$$= k_w D_{turb}^2 U^3 + k_{bearing} D_{shaft} U + k_d C_d A_f V^3$$

If the blade speed, $U$, is now replaced by the velocity ratio ($U = VV_r$), the above simplifies to:

$$\frac{1.4C_1\left[\eta_{boiler}\eta_{comb} m_{fuel} q_{fuel} - m_{resid}(h_f - h_l)\right] / (h_0 - h_l)}{(t_{burn} - t_{warmup})} = k_w D_{turb}^2 V^2 V_r^2 + k_{bearing} D_{shaft} + k_d C_d A_f V^2 / V_r$$

Solving for the car velocity, $V$, gives:

$$V = \sqrt{\frac{\dfrac{1.4C_1\left[\eta_{boiler}\eta_{comb} m_{fuel} q_{fuel} - m_{resid}(h_f - h_l)\right] / (h_0 - h_l)}{(t_{burn} - t_{warmup})} - k_b D_{shaft}}{k_w D_{turb}^2 V_r^2 + k_d C_d A_f / V_r}}$$

Finally, since $Distance = V \times (t_{burn} - t_{warmup})$, the parameters can be varied and the optimum found for any given combination. For example, changing the burn time from 45 min to 50 min will increase the distance from 3295 m to 3322 m. Changing the velocity ratio from 10 to 8 improves performance to 3414 m but does not affect the best burn time which remains 50 min. Decreasing the turbine diameter to 35 mm increases distance to 3710 m and requires a velocity ratio of 9.

All this is for a fixed nozzle velocity which assumes that the boiler pressure is constant as the burn time is varied. Although this will not strictly model a car being run with a constant nozzle diameter, the calculations will correctly indicate to the user the best burn time after which the nozzle diameter may be adjusted appropriately.

The calculation of the nozzle diameter is simplified by the fact that for a reasonable performance, the pressure ratio will be supercritical, the jet will be supersonic and the nozzle will have a convergent/divergent shape with a throat. Because the absolute temperature of steam does not increase dramatically in the pressure range of interest (2 bar abs. to 5 bar abs.), and because the critical pressure ratio is constant, the throat velocity is virtually constant at around 400 m/s. The throat density is also a constant 1.57 time less than the boiler density. Thus:

$$\dot{m}_{evap} = \dot{m}_{nozzle} = C_{throat}\eta_{throat}A_{throat} \approx 400 \times 1.57\eta_{boiler}A_{throat}$$

$$A_{throat} \approx \frac{\dot{m}_{evap}}{400 \;\; 1.57\eta_{boiler}} \approx 6.5\times10^{-8} \; m^2 \approx 0.29 \text{ mm } \varnothing$$

If a nozzle is convergent only, the throat diameter becomes the exit diameter. Most nozzles to date have been convergent only because the small diameter makes it difficult to form the divergent section and, if the divergence is too large, any possible gain in efficiency could be offset by normal shock losses.

The above procedure with an interactive data input is also available from the University of Natal on disk.

## TUNING AND DESIGNING FOR DISTANCE

As already stated, the car described in detail above was designed for power rather than efficiency. Any car should be adjusted and tuned for maximum distance before components are remade or a new car is designed.

Since friction is the enemy of steam car performance, it should be obvious that all bearings should be oiled and have sufficient clearance. The turbine should be balanced and the drive belt should have the minimum tension to just avoid slippage.

The first rule of tuning is to select the pulley ratio for the maximum floor speed. This will ensure that the maximum distance will be achieved for the selected burn time. The sample design allows for the turbine pulley to be easily dismantled and the pulley diameter changed. Because of the relatively large power output, a well-made version tends to go faster on pulleys larger than the 3 mm suggested for a group of varying talent. Unless drastic changes are made to the burner, it is unlikely that such a small turbine pulley will be called for that will point towards a redesign with a layshaft double-belt two-stage transmission.

If the speed of the car is above the maximum of 1.5 m/s (a fast stride) that is safe and comfortable for steering and turning at the ends of the track, it means that the power and burn rate are too high and should be reduced as discussed below.

Once the pully ratios have been selected, the only major variable is the burning rate of the flame and can be changed by adjusting the length of the wick protruding from the tubes or by reducing the number of wicks used.

The boiler pressure is radically affected by burn rate. In the design example presented, an especially low boiler pressure was chosen for safety (about 0.5 bar) and thus any serious builder of this design should load the valve rubber in case higher pressures are achieved.

The burn time giving the longest distance should be chosen. Here having the calculations computerized and the data for a particular car entered would help in the selection process.

When changes to the structure of the car are called for, this tends to be called a redesign. The most obvious component to re-make is the nozzle to achieve a more efficient boiler pressure. For a high-performance car, the pressure should be above 2 bar gauge and if possible even higher. Although beverage and aerosol cans are good up to 8 or 9 bars, it is very difficult to make a nozzle small enough for even 4 bars.

Other items that can readily be redesigned are the turbine size (including the blade spacing and breadth), boiler and combustion zone insulation and the overall streamlining of the car. Not quite so obvious are those factors that reduce friction, especially on the turbine. Here belt tension must be a minimum and the shaft diameter must be as small as possible. Some designers believe that gear transmissions present less reaction force on the high-speed turbine bearing than to belt drives. Turbine vibration must be eliminated.