

EFFICIENCY EVALUATIONS OF A BALLOON POWERED CAR

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Abstract

The present paper is an investigation on the efficiency of cars powered by an air-filled toy balloon in which contributes propulsion. The causes of energy loss have been investigated theoretically and several precise experiments have been made to determine the amount of energy loss that occurs for different causes. Experiments were done using image processing techniques, measuring the volume of the balloon and its changes in several cases and leading to energy analysis. It will be shown that about 50% of the energy will be lost as a result of the Moulin's effect, and a variable amount will be lost as a result of the head loss.

Introduction

The main method design we will emphasize in this paper on, is by attaching the filled balloon to the car pointing the installation of a filled balloon on the car, backwards and emptying freely in the air with its end pointing towards the back of the car, emptying freely in the air.

In this case, because of the momentum of the outgoing air jet, a force will be exerted to the car, forcing it to move. There are other methods designs which could use utilize a balloon to move a car as a source of energy to mobilize the car as used in the Balloon Car Contest at NASA's Jet Propulsion Laboratory, many of which do not fill the balloon with air but use it as a rubber band instead. Another method design is releasing the air slowly to chronically release the outgoing air jet into a turbine-like structure and use the energy to rotate the wheels. This way, the efficiency may increase because due to the head loss decreases when velocity decreases resulted by the velocity decrease, however;- w We neglected studying this approach because of for complexity.

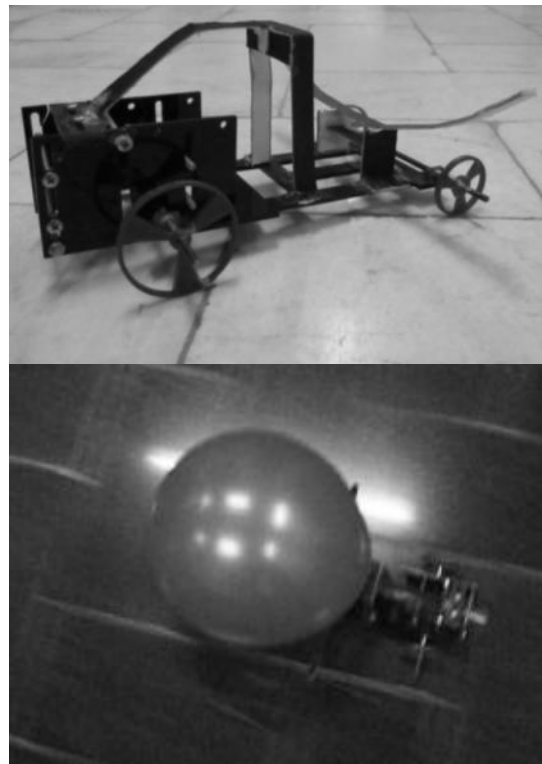


Figure 1: The Model Car

In our case, the balloon is attached to a cylindrical nozzle and deflates through it (Figure 1). In this case three forces are exerted to the car; the motivational force which is exerted to the balloon due to the momentum of the outgoing air flow, and two resistive forces which are: Aerodynamic drag force and the friction forces applied to the car. Regarding the conservation of momentum, the motivational force could be calculated as a function of the relative velocity of the outgoing air flow.

According to the Work and Energy Theorem, the total work done by all the external forces exerted to the car must be equal to its alterations of kinetic energy. Since the initial and final kinetic energies of the car are of zero value (initial and final velocities are zero), the total work done by all the forces exerted to the car must be zero.

Thus the amount of work done by the motivational force equals to the work done by the resistive forces. It is desired to maximize the work done by the motivational force, since our definition of efficiency is the ratio of the work done on the car by the motivational force to the energy needed to fill the balloon.

Considering In view of –the motivational force to be much larger greater than the resistive forces (since it functions in a much shorter time and does the same amount of work) the work done by the motivational force is independent to from the resistive forces. The energy released by the balloon air flow will be divided into two main parts compartments; the energy which moves the car and the energy which moves the air. The input energy given to the car will be would mainly wasted in two main ways (other than the kinetic energy of the air). First Initially, a fraction of the energy will be lost when the balloon during the inflationes process because due to of the balloon's plastic deformation deformation it makes. In the case of rubber material, T this phenomenon is known entitled as the “Moulin’s Effect. Note that a filled and emptied balloon will be larger than the initial balloon. This means that a part of the energy given to a balloon while when inflatinflationing will be used to deform the rubber material, which is not given back when it deflates.

The other second form of energy loss occurs when the fluid is in speedy rapid motion during the emptying process deflation. This energy loss is widely known as “Head Loss”, and has two main factors: Head Loss caused by the viscous friction forces with the inner walls walls of the balloon, and the head loss because of resulted by the turbulent motion which arises from because of the high velocity. Both of these factors the head losses are proportional to the velocity square and the proportions are functions of the system’s size and geometrical properties (in our case, the head loss coefficient changes alters with during time and is not useable as a cannot be considered as a constant.)

In the following, we will determine the amount of these energy losses.

Several factors were to be experimented physically, mainly to measure the constants in the system and the amount of energy losses in different steps. The physical experiments wouldere also in charge to approve the theoretical assumptions. During the

experiments, each balloon was used only once to avoid changes in the results because of the Moulin's Effect. About 200 balloons were experimented totally.

Initial Energy and Moulin's Effect

The first set of experiments was designed to measure the amount of energy needed to fill the balloon and the amount of the restorable energy. To do so, our method was to find the relation between the internal pressure of the balloon and its volume.

To find the Pressure-Volume relation in emptying and filling stages, ~~the method was to attach~~ the balloon was attached to a leak-proof valve-pipe system which could simultaneously fill ~~it the balloon~~ with an air pump with a known small flow rate and ~~show demonstrate~~ the internal pressure at the same time (Figure 2). A ~~u-shape pipe manometer gauge filled~~ with inked water ~~in it~~ was used to ~~show signify~~ the internal pressure and two valves were attached ~~to in that make it possible to detach the pump and slowly empty the balloon and visualize~~ the pressure alteration during deflation or inflation would visually materialize, also while getting empty. The process was filmed by a camera far enough to minimize the effect of the perspective view, and Subsequently, both the volume of the balloon and the pressure were calculated in each frame by a program

using MATLAB™ image-processing. The balloon volume was calculated assuming axial symmetry about the z-axis (As demonstrated in Figure 2), and the internal pressure was calculated measuring the difference of water elevation in the two sides of the manometer gauge u-shape pipe automatically. (Figure 3). In order to provide $P - V$ diagrams in the case of inflation (Figure 3), the experiment was reversely accomplished so that both valves were initially opened and the balloon's inflation was recorded along with the changes in internal pressure and was ultimately analysed by the program. Using these techniques, the Pressure-Volume diagrams could be achieved.

While measuring the Pressure, there were some errors caused by the dynamic motion of the water in the tube, particularly in the inflation process which the discharge could not be smaller than a specific amount. Therefore, at the beginning of the inflation process, where there is no maximum point for the pressure, the dynamic behaviour of the water would not seem to be crucial, since it is the integration of the $P - V$ diagram which will be used later, and this oscillation does not have a significant effect.

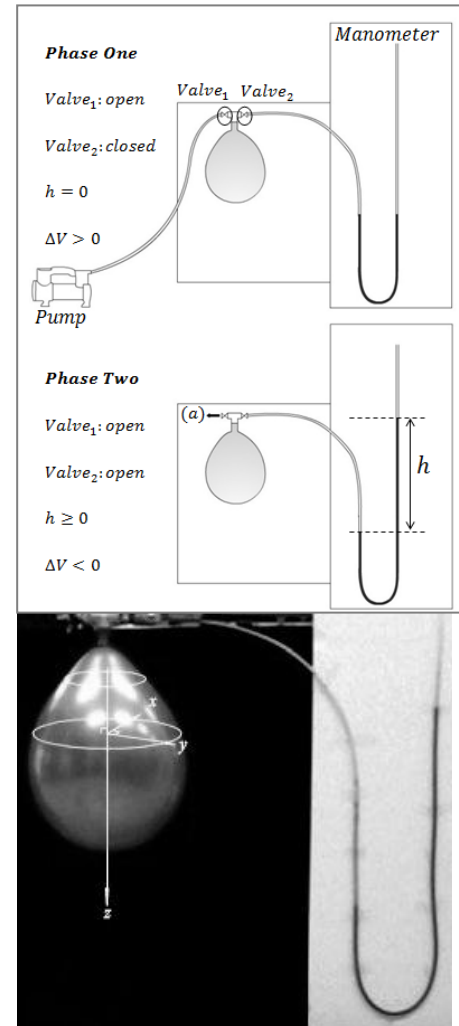


Figure 2: The $P - V$ Experiment Setup Illustration (Note: $h < 0$ thus flow rate (a) was dramatically minimized.)

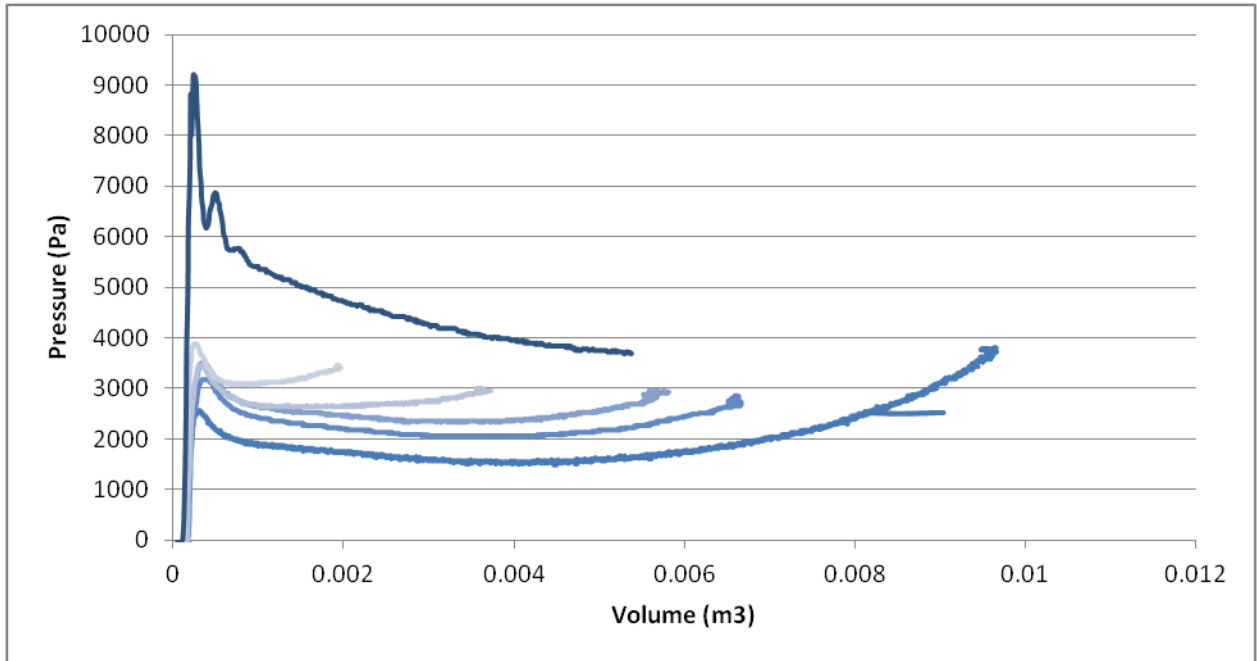


Figure 3: The P-V Diagram for Several Deflation Cases and an Inflation case (the Top Curve) Each Curve is consisted of about 1000 Points outputted from the Image Processing.

Having the $P - V$ graphs for [filling inflation](#) and [emptying deflation](#) from different initial volumes, the energy was to be calculated. To inject an infinitesimal volume dV of a gas to a container with a pressure of P , the energy [needed required](#) is PdV . ~~so~~ Thus, the energy to fill the balloon is the integration of pressure which is a function of volume:

$$E = \int_{V_0}^V P(V)dV \quad (1)$$

~~It is t~~The same [occurs](#) for the [emptying deflation](#) process. ~~So~~Hence, the energy needed to fill the balloon was calculated by numerical integration. ~~Also~~Moreover, the restorable energy was calculated by integrating the relation for the [emptying deflation](#)-case.

Our results illustrate that about half of the work

[needed required](#) to fill a balloon is not restorable, (Figure 4) ~~This means that this in other words~~; 50% of the energy is used to cause the plastic deformations among the rubber-like material.

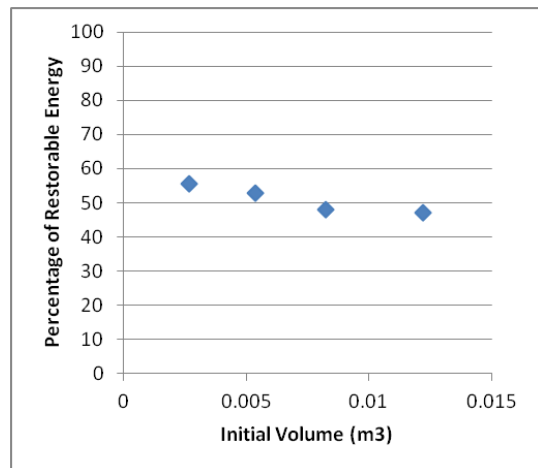


Figure 4: The Ratio of the Restorable Energy to the Total Given Energy

Fast Emptying Deflation Process and Dynamic Head Loss

All the entire energy loss is not because of limited to the Moulin's effect. Some other energy will be lost because of due to the dynamic of the outgoing fluid during the fast deflation, e.g. the viscose force between the fluid layers will do some negative work, converting the mechanical energy to heat. Flow turbulence also wastes some energy[3]. We must determine the amount of the energy lost during the deflation process, which is of course a function of the initial volume of the balloon's initial volume, varying the emptying deflation velocity and emptying deflation time. In order to investigate the reproduced energy by the balloon, we attach the balloon to a cylindrical nozzle (similar to the ones used on in the car) and let the air exit freely it deflate. A high speed video was captured from the deflating balloon, and again using the image processing, the volume of the balloon was found as a function of time (Figure 5). This was done for several initial volumes, and the experiment reproducibility was also checked by repeating the experiments.

It was observed that the rate of volume change (flow discharge) remains nearly slightly constant during the emptying time. The discharge is plotted against the initial volume, and a decreasing behaviour is observed (Figure 6). This behaviour is logically acceptable, since the average internal pressure of the balloon also has a decreasing behaviour regarding the initial volume. Note that the discharge was interpolated to be used for countless un-experimented points. The interpolation was made by fitting a logarithmic trend to the data, and the only reason of using a logarithmic function (and not a linear curve for

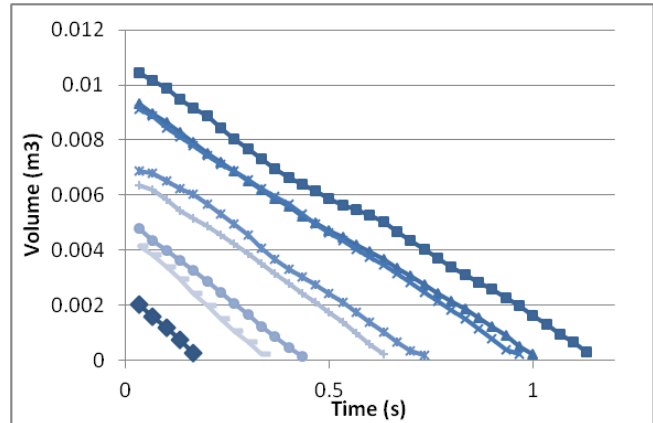


Figure 5: Some Emptying Diagrams

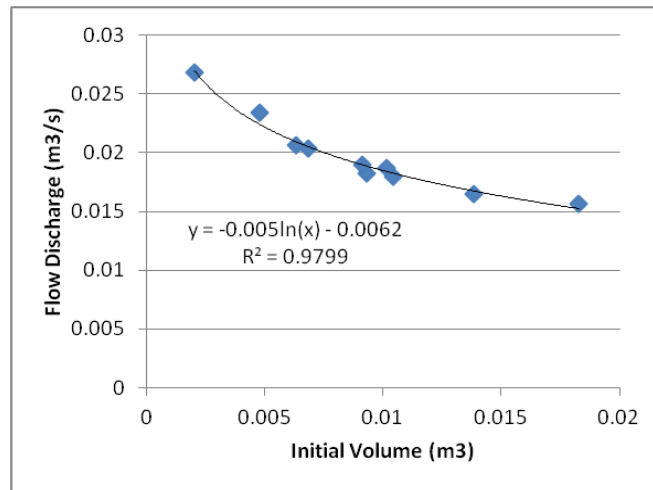


Figure 6: Flow Discharge

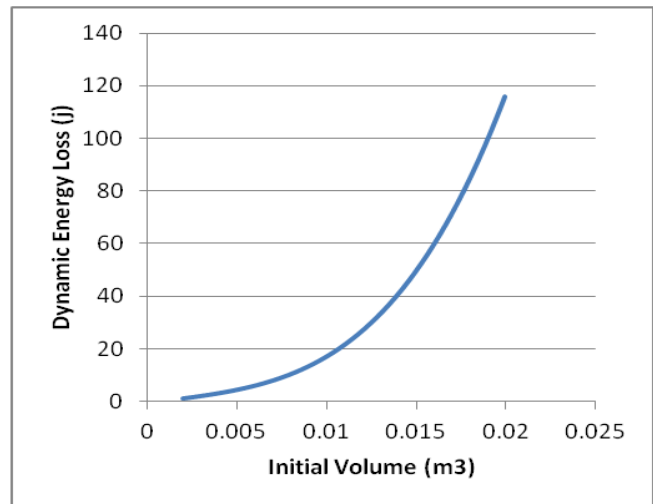


Figure 7: Dynamic Energy Loss

instance) was that it could give a better prediction for un-experimented points. Using the discharge, the emptying velocity and time can also be calculated for a known initial volume.

In this case, the energy released by the balloon is equal to the sum of the kinetic energy of the outgoing air. By calculating the mass and velocity of the outgoing air, the following formula equation would be achieved:

$$E_{released} = \frac{1}{2}(\rho Av \Delta t)v^2 = \frac{1}{2}\rho Av^3 \Delta t \quad (2)$$

Where v is the relative velocity of the jet air flow. Using the experimental data, the amount of energy loss because of resulted by fluid flow was calculated in different initial volumes of the balloon. (Figure 7)

Car Motion Investigation

Until this point, the total energy released by the balloon has been investigated, as well as the discharge of the outgoing flow. Now it must be specified what portion of this energy is transferred to the car as its kinetic energy, and the overall car motion must be investigated. According to the momentum conservation for the Car-Air system, the force exerted to the car can be calculated regarding the velocity of the outgoing flow:

$$F = \rho Av^2 \quad (3)$$

Experimentally, we built a car and attached the balloon to its end, the balloon was filled with using an air pump and knowing the with a known discharge of the pump and the time of and filling time, consequently, the initial volume of the balloon was known calculated. The car was set on the floor which's its tiles textures made it possible to find the distance travelled by the car. Films Videos were captured with a camera chasing

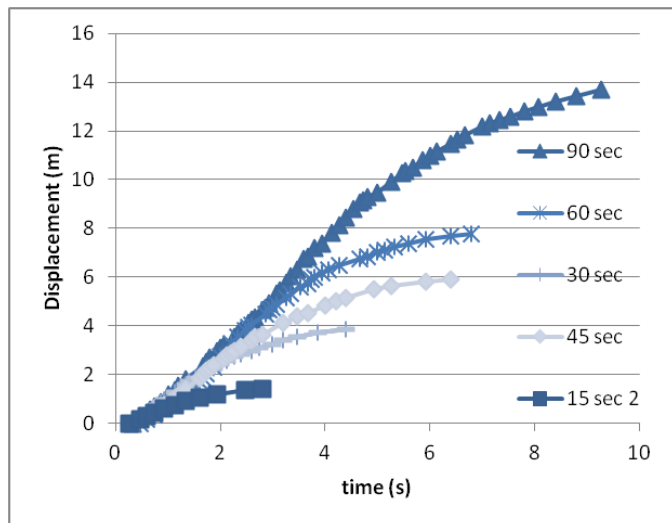


Figure 8: Motion of the Car

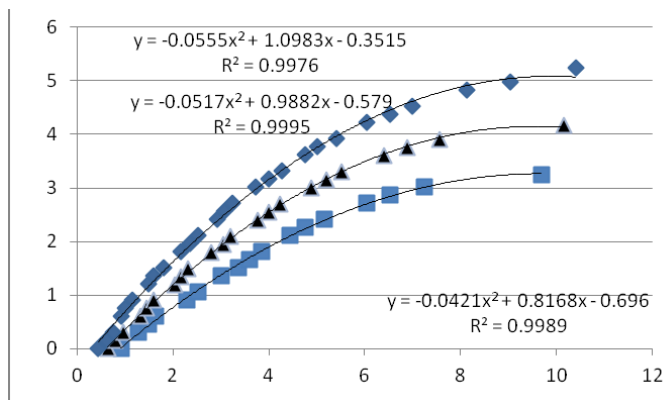


Figure 9: Friction Measurement

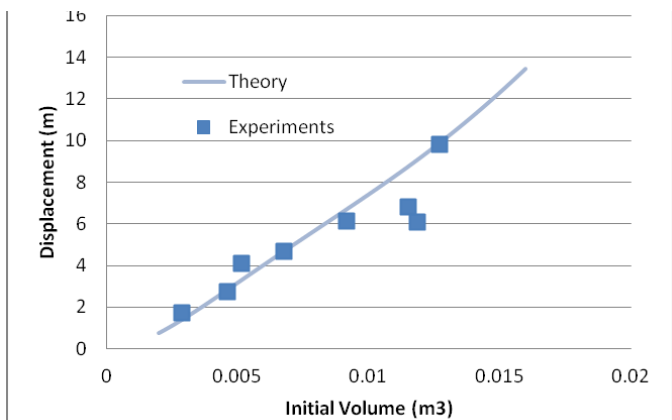


Figure 10: Distance Travelled by the Car, Theory and Experiments

the car from the top, and the motion diagrams were obtained (Figure 8). Furthermore, the total distance travelled distance was also measured. (Figure 10)

To find the friction forces, a the car was released pushed forward with varying velocities and its acceleration was measured (Figure 9).

Since the outgoing velocity and duration is known as a function of the initial volume, the motivational force can be calculated based on formula (3) and since the resistive force is experimentally measured (Figure 9), the total force applied to the car in each phase of motion (increasing velocity and decreasing velocity) is known and the acceleration can be calculated as F / m , so theoretically the motion of the car can be simulated. The total displacement of the car, predicted by the theory, was compared with the experiments; showing evincing an acceptable agreement concurrence. (Figure 10)

Conclusion

Using the theory discussed above, it could be shown that the amount of the released energy which will be the kinetic energy of the car, obeys this formula equation:

$$\frac{E_{car}}{E_{released}} = \frac{\rho A v \Delta t}{m} \quad (4)$$

Where m is the car mass and Δt is the emptying time.

Conclusion

In this investigation we tried to determine the sources of energy loss and describe the behaviour of each cause. We suggested three sources of energy loss: One caused by the plastic deformation of the rubber material, known as the Moulin's effect, and the energy loss caused by the dynamic fluid as a result of viscosity and turbulence which is known as head loss, and at last a small portion of the remaining energy will be used to move the car, and the rest will be transferred to the air.

Note that the plots and numbers can only be applied to our specific model and materials. As if the balloon changes, the $P - V$ diagrams will change since it is a function of the shape and material of the balloon.

~~The released energy its self is not all the energy that has been spent to fill the balloon. It was shown that 50% of the energy given to the balloon will be wasted because of the plastic deformation, and more than 40% of the remaining will be wasted because of the fluid head loss while getting empty. This amount was shown to be a function of the initial volume, and was extracted from experimental data. Thus, the overall efficiency of the car system as a function of the initial volume of the balloon could be calculated. As shown in figure 11, there is a specific initial volume of the balloon which has the maximum efficiency overall. However, according to Figure 10, there is no maximum for the total distance travelled by the car, unless a maximum possible volume for the balloon exists.~~

By measuring the Pressure and Volume in the inflating and deflating balloon using image processing (Figure 3) and integration, to find the energy needed to fill the balloon and the reproducible energy, the ratio of the energy lost as a result of the Moulin's effect

was calculated (Figure 4). The results suggest that about 50% of the energy needed to fill the balloon will be lost as a result of this effect.

Next the amount of energy lost by head loss was to be estimated. The discharge of the inflation of the balloon was measured using the same image processing technique, and it was used to calculate the kinetic energy released by the balloon. As shown in Figure 5, the discharge decreases as the initial volume increases, and this is because of the decrease of the mean internal pressure of the balloon as in Figure 3. The difference between the total reproducible energy and the kinetic energy produced during the deflation and the energy loss, as a result of head loss was found as in figure 7.

The flow discharge, as a function of initial velocity, as interpolated in figure 6, was then used to compute the motion of the car theoretically. So after estimating the friction force (figure 9), the total difference travelled by the car as a function of the initial volume of the balloon was measured experimentally and was compared with theoretical predictions (figure 10).

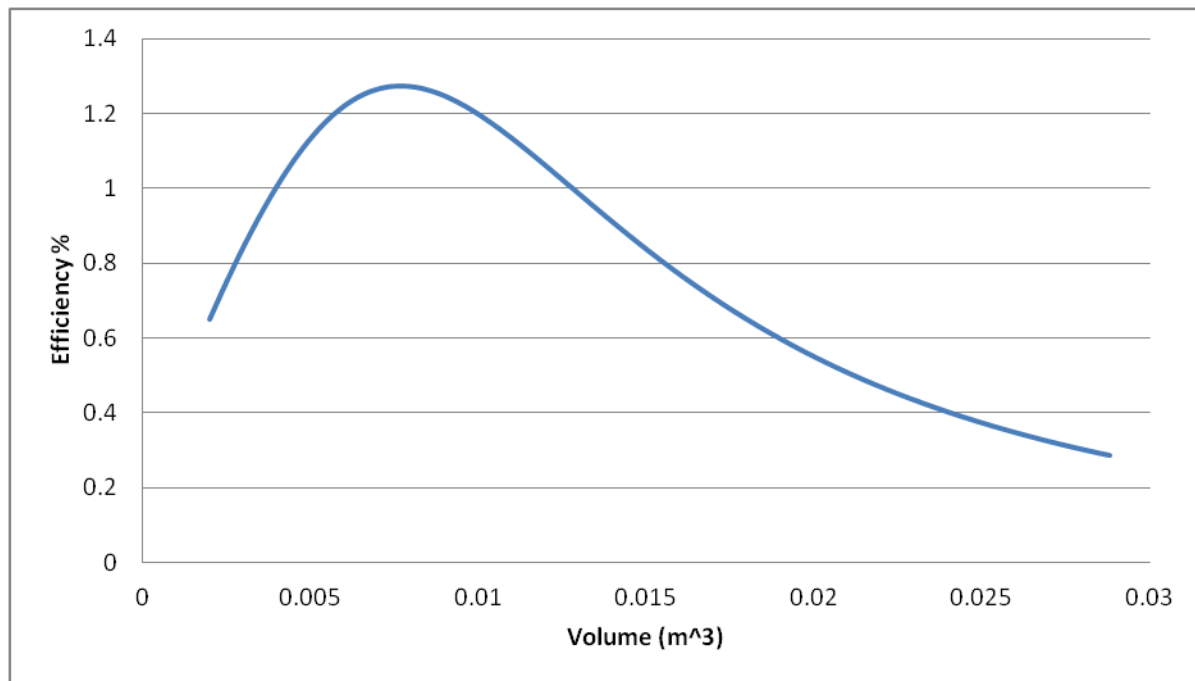


Figure 11: The Overall Efficiency of the Car

In conclusion, the overall efficiency of the car system as a function of the initial volume of the balloon could be calculated. As evinced in figure 11, there is a specific initial volume of the balloon which has the maximum efficiency overall. However, according to Figure 10, there is no maximum for the total distance travelled by the car, unless a maximum possible volume for the balloon exists.

References:

- [1] Balloon Car Contest at NASA's Jet Propulsion Laboratory, http://balloonhq.com/balloon_car/balloon_car.html
- [2] Treloar L R G 2005 *The Physics of Rubber Elasticity*, Oxford University Press.
- [3] Shames I H 2003 *Mechanics of Fluids*, McGraw-Hill.