Comparative analysis of two models of a bicycle pump using thermodynamics approach

Obiora Clement Okafor
Grundtvig Polytechnic

Journal of Engineering Science and Technology Volume 02, Issue 07 (2019) Pg No : 01-08

Content lists available at StemJournal

Journal of Engineering Science and Technology

Journal homepage : www.stemjournal.in/JEST

Comparative analysis of two models of a bicycle pump using thermodynamics approach

Okafor, Obiora Clement[1]

[1]*Department of Mechanical Engineering, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria.*
Corresponding Email : okaforobiorac@gmail.com

ABSTRACT

This study presents a comparative analysis of two different models of a bicycle pump using thermodynamics approach. The fixed factors of the pumps were all measured while the other needed parameters were determined using the relevant formulas. The discharge pressure, discharge temperature, mass of air inside the cylinder, polytropic index of compression, compression work and heat lost during the compression operation were all calculated for each of the pumps considered. The results showed that the pump with a bigger cylinder diameter gave a discharge pressure of 5378.5kPa, discharge temperature of 580.83k, compressive work of -87.5J and a heat loss of -43.23J. While the pump having a smaller cylinder diameter gave a discharge pressure of 3935.7kPa, discharge temperature of 502.6k, compressive work of -34.4J, and a heat loss of -17.2J. It was proven that the pumping operation of the bicycle pump is a non-adiabatic one with an approximate polytropic index of compression of 1.2. Sequel to that, the diameter of the cylinder affects the thermodynamic characteristics of the bicycle pump.

Keywords:- Thermodynamics, bicycle pump, adiabatic condition and polytropic index

1.0 Introduction

A bicycle pump is a type of positive-displacement air pump specifically designed for inflating bicycle tires. Positive-displacement pumps suck and raise fluids by actually displacing it with a piston /plunger that executes a reciprocating motion in a closely fitting cylinder. The amount of fluid delivered by the pump is equal to the volume displaced by the piston. The bicycle pump works by thermodynamically sucking air into the cylinder or barrel, compresses it before the delivery to the tire. During the downward stroke, air inside the cylinder is compressed and pushed down the tube of the pump and then into the tire through the valve, which is forced open by the pressure of the air. At the upward stroke, the handle is pulled up, the valve shuts off automatically so that air cannot escape from the tire, and new air is forced back into the cylinder and the cycle continues.

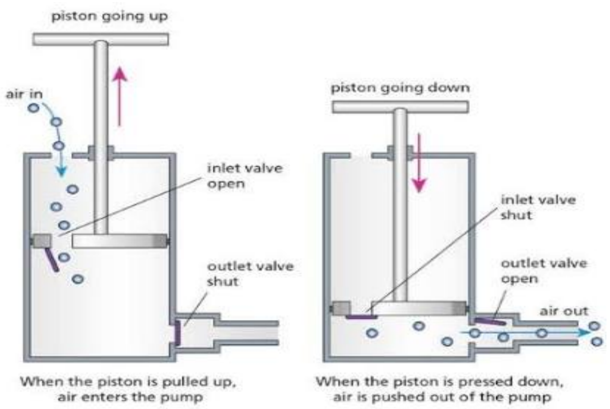

Figure 1: Operational mechanism of the bicycle pump.

During the pumping operation, some distinctive features are recognized. The cylinder of the pump is warm indicating loss of heat in the process as a result of friction between the air, the piston and the cylinder. Also, the pressure being delivered to the tire and thermodynamic work done on the bicycle system. These distinctive factors are imperative for an enhanced and effective design of a bicycle pump.

This study is focused on thermodynamic analysis of two models of a bicycle pumps geared towards a comparative study of their respective operational factors that influence their effectiveness.

AIR AND ITS PROPERTIES

Air is the homogenous mixture of gases. It contains oxyen (21% by volume and 23% by mass) nitrogen (79% by volume and 77% by mass) and others being water vapour, noble gases, impurities, which are of infinitesimal percentages.

The density of air decreases with an increase in altitude and it is affected by variations in temperature, pressure and humidity. According to International Standard Atmosphere (ISA), at 15 degree Celsius, the density of air is 1.225kg/ m^3.

Dry air density can be computed using the ideal gas equation:

$$\rho_{air} = \frac{P}{RT}$$

(1)

Where: $\rho_{air} = density\ of\ air$ in kg/m^3.

$P = absolute\ pressure\ in\ pascal$

$R = specific\ gas\ constant$ in J/kg. k

$T = absolute\ temperature\ of\ air\ in\ kelvin$. The table 1 below illustrates the effect of temperature variations on the air density at a pressure of 1atm. The computations were done using the equation for density stated above.

Table 1: Effects of Temperature Variations on the Air Density at a Pressure of 1atm

TEMPERATURE (°C)	AIR DENSITY (kg/m^3.)
35	1.1463
30	1.1768
25	1.1847
20	1.2049
15	1.2259
10	1.2475
5	1.2700
0	1.2932
-5	1.3173
-10	1.3424
-15	1.3684
-20	1.3954
-25	1.4236

From the table above, it will be observed that the density of air increases as the temperature decreases. For a greater output pressure to be delivered by a bicycle pump, air of higher density is required.

2.0 Materials and Method

Two bicycle pumps named pump model 1 and pump model 2 were used for this study. Some fixed factors like: height of the cylindrical barrel, length of the piston, external diameter of the barrel, thickness of the barrel , air temperature, suction pressure of air into the pump, diameter of the nozzle, internal diameter of the cylindrical barrel, radius of the cylindrical barrel, were all measured for each of the pumps.

Figure 2: **Pump 1** **Pump 2**

Factors such as: initial volume of the cylindrical barrel, final volume of the compressed air, area of the nozzle, area of the barrel, mass of air trapped in the barrel, discharge pressure, polytropic index of compression, exit temperature, compressive work and heat loss were all calculated for each of the pumps.

Table 2: Measurement of Fixed Factors for Each of the Pumps.

Factors	Pump 1	Pump 2
Height of the cylindrical barrel (H)	247mm	295mm
Length of the piston (L)	238mm	281mm
External diameter of the barrel	33mm	22mm
Thickness of the barrel	1mm	1mm
Diameter of the nozzle	1.94mm	2.3mm
Internal diameter of the cylindrical barrel,	31mm	20mm
Radius of the cylindrical barrel, r	15.5mm	10mm
Air temperature (°C), T_1	30°C	30°C
Suction pressure of air into the pump (P_1)	101.325kPa or 1.01325bar	101.325kPa or 1.01325bar

2.1 Determination of the Needed Parameters for Pump 1

Volume of the cylindrical barrel, $V_1 = \pi r^2 h$ (2)

Final volume of the compressed air, $V_2 = \pi r^2 \left[\text{barrel height} - \text{swept length}\right]$ (3)

Area of the nozzle, $A_2 = \frac{\pi d^2}{4}$ (4)

Area of the barrel, $A_1 = \frac{\pi d^2}{4}$

2.2 Thermodynamic Analysis of Pump 1

Mass of air in the barrel

Mass of air trapped in the barrel during the induction stroke of the piston,

m = density of air at 30 **°C** $\times$ *volume of the barrel*. (5)

The discharge Pressure of the Pump

The pressure rating of tires is usually stamped somewhere on the sidewall. This may be in psi (pressure per square inch) or bar. Inflating to a lower pressure range will increase traction and make the ride more comfortable. Inflating to the higher range will make the ride more efficient and will decrease the chances of getting a flat tire but a firmer ride must be expected. From experimental determination, an input force of 15.866N will cause a piston displacement of 238mm with the aid of a spring balance.

The delivery pressure of the pump system, P_2

$$= \frac{Applied\,force}{Area\,of\,the\,nozzle}$$

(6)

Polytropic Index of Compression (n)

Compression operation of a bicycle pump is a polytropic process whose operational parameters depend on the index of compression. The process is isothermal if the index of compression is of the value 1 and isobaric if the index of compression is 0. These conditions of operation are not possible since a temperature rise is noticed while using a bicycle pump and the delivery pressure is not the same with the suction pressure.

Using the relation: $$\frac{P_2}{P_1} = \left[\frac{V_1}{V_2}\right]^n$$

(7)

The polytropic index of compression can be determined.

Discharge Temperature of the Pump (T_2)

The process becomes almost adiabatic if the compression stroke was done slowly and as such no energy interaction will take place between the pump system and the environment. But as it is a common practice and observation that the compression process takes place very fast during the inflation of a bicycle tire. Hence, the process is a polytropic one and the energy interaction between the pump and the environment need to be calculated.

Using the ideal gas equation, the exit temperature of air T_2 can be computed.

$$P_2V_2 = mRT_2$$

(8)

R = specific gas constant = 0.2871kJ/kg K

This delivery temperature is actually very high, and it is almost the melting point of lead (600k). The value is actually in the range of road bicycle tire, so it's not surprising that a bicycle pump can get very hot when you are inflating a tire.

Compression Work Done BY the Pump System

Using the relation:

$$W = \frac{mR(T_1 - T_2)}{n-1} = \frac{P_1V_1 - P_2V_2}{n-1}$$

(9)

Heat Loss During the Compression Operation

This can be computed by applying the first law of thermodynamics to the pump system.

Heat loss, Q =

$$W + \Delta U = W + mC_V(T_2 - T_1)$$

(10)

m = mass of air

C_V = specific heat capacity at constant volume = 0.718kJ/kg K

2.3 Calculations of the Needed Parameters for Pump 2

Volume of the cylindrical barrel, $V_1 = \pi r^2 h$ (11)

Final volume of the compressed air, $V_2 = \pi r^2 [\text{barrel height} - \text{swept length}]$ (12)

Area of the nozzle, $A_2 = \frac{\pi d^2}{4}$ (13)

Area of the barrel, $A_1 = \frac{\pi d^2}{4}$

2.4 Thermodynamic Analysis of Pump 2

Mass of air in the barrel

The mass of air trapped in the barrel during the induction stroke of the piston,

m = density of air at 30 **°C** $\times$ *volume of the barrel.* (14)

Discharge Pressure of the Pump

Experimentally, an input force of 16.53N will cause a piston displacement of 281mm with the aid of a spring balance.

The delivery pressure of the pump system, $P_2 = \frac{Applied\, force}{Area\ of\ the\ nozzle}$ (15)

Polytropic Index of Compression (n)

Using the relation: $\frac{P_2}{P_1} = \left[\frac{V_1}{V_2}\right]^n$ (16)

Discharge Pressure of the Pump

Using the ideal gas equation, the exit temperature of air T_2 can be computed.

$$P_2 V_2 = mRT_2 \quad (17)$$

Compression Work Done by the Pump System

$$W = \frac{mR(T_1 - T_2)}{n-1} = \frac{P_1V_1 - P_2V_2}{n-1} \quad (18)$$

Heat Loss During the Compression Operation

This can be computed by applying the first law of thermodynamics to the pump system.

Heat loss, Q $= W + \Delta U = W + mC_V(T_2 - T_1)$ (19)

Table 3: Summary of the Calculated Working Parameters of the Pumps.

Parameters	Pump 1	Pump 2
Volume of the cylindrical barrel	$1.8643 \times 10^{-4} m^3$	$9.2677 \times 10^{-5} m^3$
Final volume of the compressed air	$6.8 \times 10^{-6} m^3$	$4.3982 \times 10^{-6} m^3$
Area of the nozzle	$7.0686 \times 10^{-6} m^2$	$4.2 \times 10^{-6} m^2$
Area of the barrel	$7.5477 \times 10^{-4} m^2$	$3.1416 \times 10^{-4} m^2$
Mass of air in the barrel during the induction stroke	2.194×10^{-4} kg.	0.00012kg
Discharge pressure	5378.5kPa.	3935.7kPa.
polytropic index of compression	1.1995	1.20065
Discharge temperature	580.83k	502.6k
Compression work	-87.5J	-34.4J
Heat loss during the compression operation	-43.23J	-17.2J

Note that the negative sign in the values of the compression work and heat loss for the two pump models only indicate that work was done to the system, which is a compressive one and heat was lost in the process.

3.0 Results & Discussions

From the performed experiment and analytical calculations, the model pump 1 gave an output pressure of 5378.5kpa at a temperature of 580.3k and performed a work of -87.5J at a heat loss of -43.23J. Also the model pump 2, gave an output pressure of 3935.7kpa at a temperature of 502.6k and performed a work of -34.4J at a heat loss of -17.2J. This proves that the pumping operation is non-adiabatic and the more the compression operation (that is increase in the number of piston strokes) the more the heat loss and pressure of air in the tire. Sequel to this, the delivery pressure of the pump depends on the suction pressure of the air, volume of the barrel, mass of the air trapped in the barrel, operating temperature, number of piston strokes and the nozzle diameter. Pump cylinder/barrel with a larger diameter (model 1) gave the largest output pressure while the other pump model whose barrel diameter is small gave a lower value though still a working value for the delivery pressure. Based on this note, the model pump 1 was designed to pump air into a bicycle tire, a wheel barrow and other machines which are compatible with the valve mechanism. Such an operation cannot be handled by the model pump 2 except for a bicycle tire.

Through the knowledge of analytical thermodynamics, the experiment considered the micro components that constitute the bicycle pump and the operational conditions, and a prove of a non- adiabatic condition of operation was actualized.

4.0 Conclusion

The cylinder diameter of a bicycle pump affects its thermodynamic functional parameters. This is so because, the volume of air trapped inside the cylinder which determines the amount of work done to the system, the heat dissipation quantity and the exit temperature of the pump is dependent on the cylinder diameter. Furthermore, the higher the cylinder diameter the greater the exit pressure, temperature, compressive work and heat loss of the pump and vice-versa. Thus, the pumping operation of the bicycle pump was proven to be non-adiabatic having a polytropic index of compression of 1.2 approximately.

References

1.https://en.wikipedia.org/wiki/Density_of _air.

2.Nelkon, M., (2009). Principles of physics, 9th Edition, Pearson Education LTD, England. pp. 136-138.

3.Rajput, R.K., (2013). Text book on thermal engineering, 9th Edition, Laxmi publication LTD, New Delhi. Pp.59-63,673-753.

4.Rajput, R.K., (2012). Fluid mechanics and hydraulic machines, 4th Edition, S. Chand & Company LTD, New Delhi. Pp.1241-1246.