Electrical Analogy of Liquid Piston Stirling Engines

Aman GUPTA[1], Sunny NARAYAN[2]

[1] Indus University, bharadwaj1717@gmail.com

[2] Indus University, rarekv@gmail.com

Abstract: *The use of fossils for of heat and power generation is a cause of concern due to emissions which are a great threat to human life. Solar and geothermal energy can be harnessed as renewable sources. According to second law of thermodynamics, theoretically maximum thermal efficiency is of Carnot cycle. However there are other cycles having advantages which includes liquid piston engine. This device is able to convert low-grade heat into hydraulic work. The basic principle of a Fluidyne is similar to a Stirling engine. This work deals with the dynamic modeling of liquid piston engines which is type of Stirling engine. Similarities between this device and an RLC electric circuit were considered. Pressure oscillations in engine were analyzed analogous to charging and discharging of a RLC circuit.*

Keywords*: Engines, Pumps*

1. Introduction

Use of fossil fuels is a concern due to emissions which are a great threat to human life. Solar and geothermal energy can be harnessed as renewable sources [1]. According to second law of thermodynamics, theoretically maximum thermal efficiency is of Carnot cycle [2]. However there are other cycles having advantages which includes liquid piston engine. This device is able to convert low-grade heat into hydraulic work. The basic principle of a Fluidyne is similar to a Stirling engine.

A gas when heated expands and if its expansion is confined, its temperature rises. This can be understood more easily by following operations [3]:

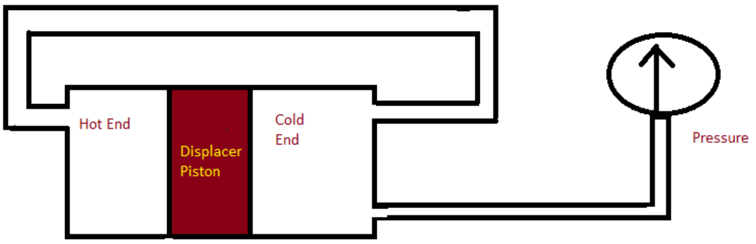

Fig. 1. Motion of a displacer piston in cylinder

A thermal engine is a device which converts heat energy into mechanical energy. The operation of a heat engine can be described by a simple thermodynamic cycle as follows:

Initially the displacer piston is at centre, with half of the gas in hot side and other half of gas in cold side of cylinder. The pressure gauge is neutral.

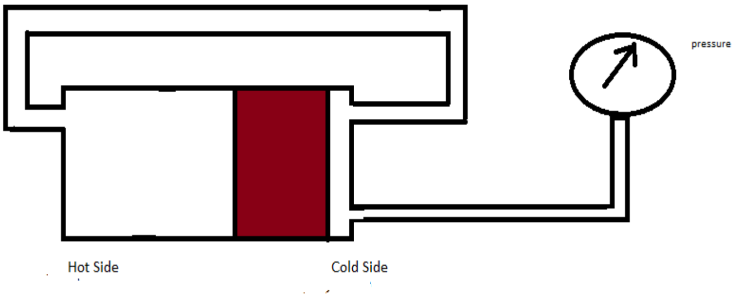

Fig. 2. Motion of displacer piston towards cold side

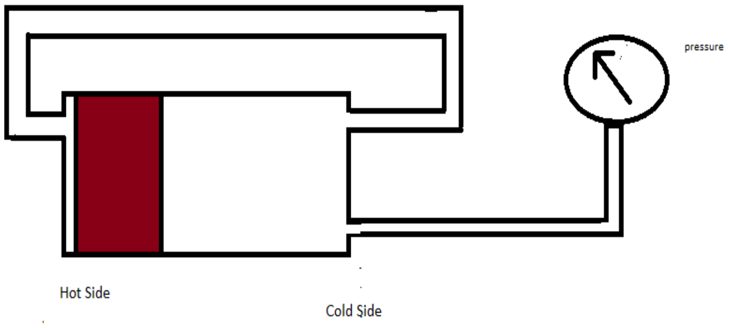

Fig. 3. Motion of displacer piston towards hot side

As the displacer piston moves towards the cold end, the gas is displaced towards the hot end by the connecting tube, its temperature and hence pressure goes up as indicated by the gauge.

As the piston moves towards the hot side, the gas is displaced towards the cold end, its temperature and hence pressure falls. The changes in the displacer pressure can be used to drive another piston known as the power piston. When the gas pressure is high, the power piston moves towards the open end of cylinder, hence doing some work which can be used to pump water or rotate a crankshaft.

Pumps are the most important mechanical devices that play an important role in our daily lives. They have been used in the form of Persian wheels or water wheels since ancient times for irrigation purposes. They cause displacement of the working fluid by adding energy to it.

2. Pumping setups

There are several available setups wherein pressure variations can be used for pumping water. Commonly used pumping configuration involves a T piece at the end of output tube and two non-return valves. On the outward stroke, the fluid is forced through the upper valve whereas during the inward stroke, the fluid is drawn through the lower non return valve. However this setup has some drawbacks.

Above a certain pumping head, the work needed to pump the fluid becomes greater than the volume change in the engine.

Another configuration uses the pressure variations in the working gas. When the pressure of gas is low, the fluid is drawn up from lower valve and as it rises, the fluid is expelled.

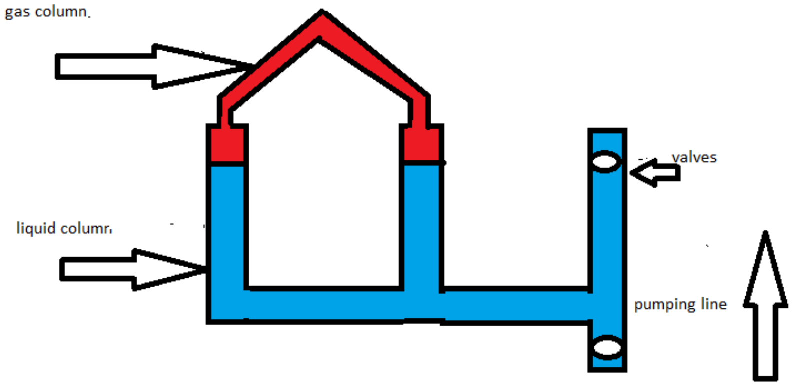

Fig. 4. Pumping configurations (a)

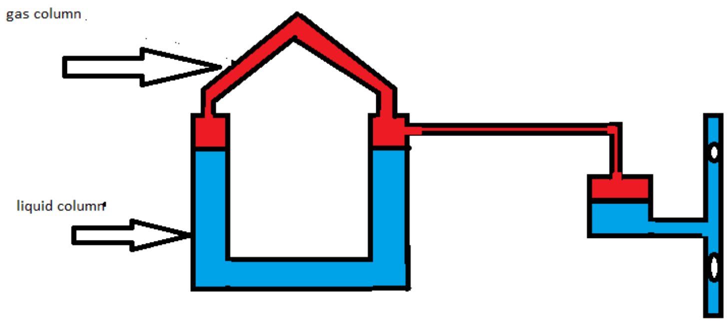

Fig. 5. Pumping configurations (b)

3. Electrical analogy

The modeling methodology of this device is explained in [4– 8]. Each component of Fluidyne is represented by a RLC circuit wherein resistors are attributed to heat transfer and viscous/form drag effects, capacitors denote gravitational/hydrostatic and vapor compressibility effects and inductors describe the effects of inertia.
Pressure (*Pi*) difference across a physical device component in the fluid domain is represented by a voltage (Ei) difference across an equivalent analogous electrical component. Volumetric flow rate V'(t) is represented by the current (I) flowing through the corresponding electrical component. In the thermal analysis a temperature (T) difference across is represented by a voltage (V) drop and the resulting entropy flow rate (S) may be represented by an analogous current (I) flowing through the electrical component.

The operation of Fluidyne engine can be represented in terms of following two operations similar to charging of an electrical circuit:

During the suction phase which is analogous to charging of RLC circuit we have:

$$\mathrm{ZI}+\frac{\mathrm{q}}{\mathrm{C}}=\mathrm{V_{in}} \tag{1}$$

Differentiating on both sides we have:

$$\mathrm{ZC}\frac{\delta^2\mathrm{q}}{\delta^2\mathrm{t}}+\frac{\delta\mathrm{q}}{\delta\mathrm{t}}=0 \tag{2}$$

Electrical analogous equations for this phase may be written as:

$$\mathrm{ZC}\frac{\delta^2\mathrm{V}}{\delta^2\mathrm{t}}+\frac{\delta\mathrm{V}^{\cdot}}{\delta\mathrm{t}}=0 \tag{3}$$

Applying Laplace on both sides we have:

$$\mathrm{ZC(D^2V')+DV'} = 0 \tag{4}$$

$$\mathrm{ZC[S^2F(S)]+[SF(S)\text{-}V'(0)]} = 0 \tag{5}$$

$$\mathrm{F(S)=V'(0)}\left[\frac{1}{\mathrm{S}}+\frac{1}{\mathrm{S}+\frac{1}{\mathrm{ZC}}}\right] \tag{6}$$

Taking inverse Laplace we have:

$$V'(t) = V'(0)[1-e^{\frac{-t}{ZC}}] \tag{7}$$

$$V'(t) = V'(0)[1-e^{\frac{-t}{\zeta}}] \tag{8}$$

Where ζ=ZC
When t=ζ we have

$$V'(t) = V'(0)[1-e^{-1}] = 0.63\,\mathrm{V}'(0) \tag{9}$$

Hence this phase may be represented graphically as:

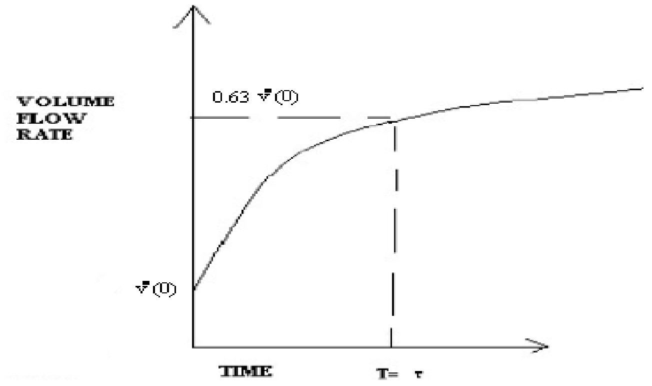

Fig. 6. Suction phase

During the discharge phase which is analogous to charging of RLC circuit we have:

$$ZI+\frac{q}{C}=V_{in} \tag{10}$$

Differentiating on both sides we have:

$$Z\frac{\delta q}{\delta t}+\frac{q}{C}=0 \tag{11}$$

Electrical analogous equations for this phase may be written as:

$$Z\frac{\delta V'}{\delta t}+\frac{V^{\cdot}}{C}=0 \tag{12}$$

Applying Laplace we have:

$$ZC[SF(S)\text{-}V'(0)+F(S)]=0 \tag{13}$$

$$F(S)=\frac{V'(0)}{S+\frac{1}{ZC}} \tag{14}$$

$$V'(t)=V'(0)[e^{\frac{-t}{\zeta}}] \tag{15}$$

Where ζ=ZC
When t=ζ we have

$$V'(t)=V'(0)[e^{-1}] = 0.36\,V'(0) \tag{16}$$

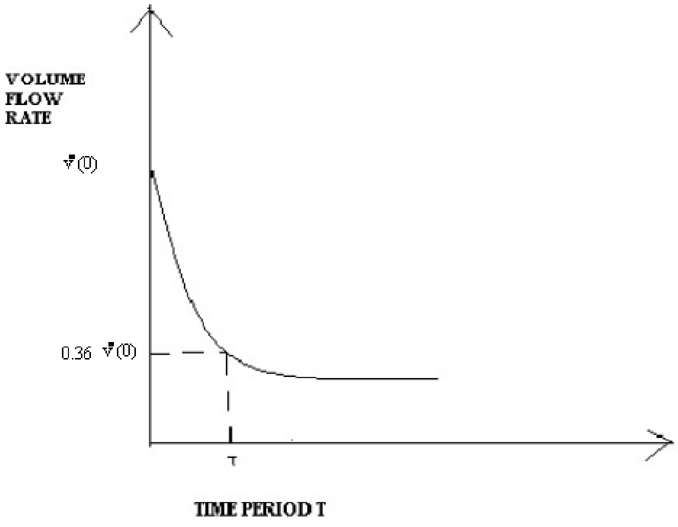

Fig. 7. Discharge phase

When suction volume equals discharge volume we have:

$$V'(t)=V'(0)[1-e^{\frac{-t}{ZC}}]=V'(0)[e^{\frac{-t}{\zeta}}] \tag{17}$$

$$\frac{t}{\zeta}=0.693 \tag{18}$$

Hence t=0.693ζ

$$V'(t)=0.5\ V'(0) \tag{19}$$

This may be represented graphiclaly as:

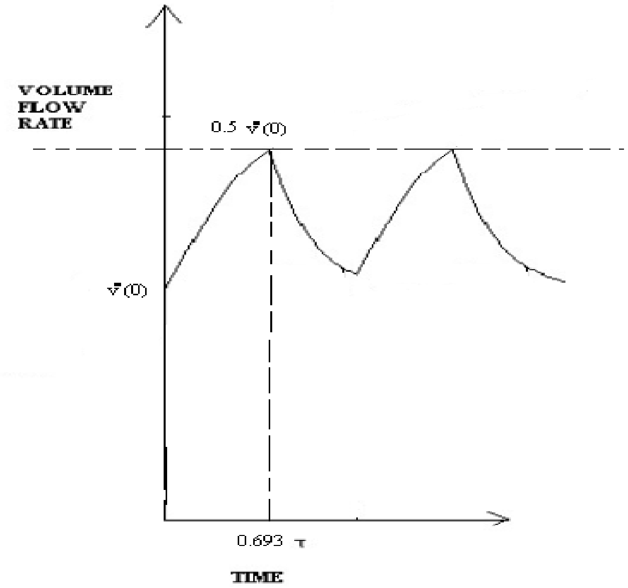

Fig. 8. Neural phase

4. Conclusions

In this work motion of a liquid piston engine has been analyzed. An electrical analogy was designed for the physical device in which both suction and discharge phase were studied similar to a RLC circuit [9-15]. Further improvements in this device may be done by use of regenerator or bigger tubes to improve heat transfer rate.

Nomenclature
V Voltage
t Time
S Stroke length
ρ Fluid density
Q,V' Fluid Flow rate
C Capacitance
Z Impedance
q Charge flow rate
I Current

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