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Optimal Design and System Control in an Oscillating Combustion by Electromechanical Link Based Valve

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ABSTRACT

This paper aims at design and fabrication of an electromechanical butterfly valve drive system based on a four bar linkage mechanism proposed and developed by the author as a retrofit to conventional combustion system to study and investigate oscillating combustion technology in a crucible furnace. However, there are several challenges to transform by oscillating combustion concept into an attractive product especially achieving oscillations in a fuel flow to create fuel rich and fuel lean zones in a flame. This technique promises a substantial improvement in fuel economy, furnace efficiency, heat transfer coefficient, heat transfer and controls the melting time, emissions, specific energy consumption. Presently the various properties were investigated in a crucible furnace at different Air-fuel ratios, frequency, amplitude at different temperatures, and time intervals.

Keywords: Oscillating Combustion, Butterfly Valve, Crucible Furnace, Frequency, Amplitude

INTRODUCTION

Oscillating combustion is a simple, innovative, low-cost technology can be applied as a retrofit in the heat transfer industries such as steel mills, glass plants, forging shops and foundry process furnaces to enhance the performance characteristics [1]. Clean energy combustion systems, Inc. has developed environmental friendly technologies that are used to burn a wide range of fuels. OCT is a revolutionary approach to the combustion of fossil fuels. Delabroy *et al* described that oscillating combustion system is a low-cost, low NOx, high efficient technology and can be integrated in any combustion system whose principle is based on a cyclical perturbation of the gas line [2]. Gupta has enumerated the need in the present scenario that researchers focus is on energy conservation opportunities in gas, liquid-fuel fired combustion systems, which can be designed to achieve clean and efficient combustion with enhanced performance and productivity rate by reducing the heat losses [3]. There is a need to develop a technology that reduces emissions while increasing thermal efficiency for any furnace. John and Wagner, in his NOx emission reduction by oscillating combustion technology urged industries to make their furnaces less polluting and more productive, whether they are firing with ambient-temperature, pre-heated air, oxygen enriched air, or oxygen [4]. The oscillating combustion technology requires only that a new fuel flow control valve be installed on the fuel line ahead of each burner and the gas supply pressure be adjusted appropriately. A custom valve control system is then used to oscillate the air-fuel ratio above and below the stoichiometric ratio, thereby producing alternating fuel-rich and fuel-lean zones in the flame. Since combustion under both fuel-rich and fuel-lean conditions produces low levels of NOx, the NOx formed in each zone is significantly lower than that which would occur if the combustion took place without fuel oscillation but at the same overall average fuel flow rate. When the fuel-rich and fuel-lean zones eventually mix in the furnace, after heat has been transferred from the flame to the load and the flame temperature is lower, the resulting burnout of combustible gases occurs with little additional NOx formation. Additionally, the increased flame luminosity resulting from the fuel-rich combustion zones combined with the increased turbulence created by the flow oscillations provides increased heat transfer to the furnace load [5]. Climate change and ‘Greenhouse effect’ have been subjects of interest for many years due to their importance in achieving a ‘greener’ planet with energy efficiency and less GHG emissions. New technologies are enthused to be developed to succeed in this mission and as a result, different renewable power generation technologies have evolved over time. Wind energy, hydro power, solar thermal systems, solar photovoltaic systems, biomass and fossil fuels, geothermal energy are some of the popular ones among those new technologies which are in action [6].

BACKGROUND AND MOTIVATION OF OSCILLATING VALVE

In 1980 the GTI (Gas Technology Institute) was developed solenoid valve or solenoid based EGR (Exhaust Gas Recirculation) valve, while AL's early tested rotary plug valve. These valves had drawbacks which are not suitable for industrial applications. The solenoid valve will not give the long life time and rotary plug valve was expensive. These valves were not suitable for oscillating amplitudes (adjustable high and low flow rates). In 1994 the Ceram Physics Inc (CPI) of Westerville developed a valve which is meeting the requirements of low cost and long life. This valve name is known as solid state proportioning (SSP) valve. It has a flow rate of 40 SCF/h and is operated at high frequency at 20 HZ and produces fairly square flow rate pulses.

In the SSP valve the electrostrictive actuator is used a SS device that increases the length when a voltage is applied. The actuator acted on a wedge which is applied the magnitude of length and compressed the elastomer disc in the vertical direction. Due to conservation of volume the elastomer expands horizontally into open space along its edge, this restricts the fuel flow in the valve. When the voltage releases the elastomer will regain its original shape due to its elastic property. The valve operation fuel releases and restrictions will be completedin1/20th of second. So that the oscillating amplitudes is adjustable electronically. After SSP valve design, the CPI people was redesigned the SSP valve. The revised SSP valve will be featured on inductive (solenoid type) actuator and an annular space for the gas flow. It can be operated at 24 to 60 volts depending upon the application. The annular space allows the much higher valve capacities. Ceram physics and GTI scaled up the valve capacities from 500 SCF/h to 3000SCF/h. The GT Development Corp (GTDC) of Seattle, Washington was designed and developed a modern valve which is known as cyclic valve. It is driven by motor that covers and uncovers holes in aperture plate to generate the oscillating pulses. The amplitude of the oscillations was controlled mechanically instead of electrically as with e SSP valve. It is somewhat less flexible than SSP valve but easier scale up to industrial sizes. GTI and AL people were extensively tested the cyclic valve from 1200 SCF/h to 4500 SCF/h. The NOx reduction was very similar to that of SSP valve which was tested with the same burner. Later on an Electromechanical CAM operated valve (shown fig 1) was designed and developed by Govardhan, India [1]. Which is controlled he 12v DC motor. It was noise free and have long life and suitable for large industrial applications.

In this current project the author developed an electromechanical link based robust valve shown in fig 2. which can operate the 15° 30° 45° 60° 75^0 and 90^0 amplitudes by adjusting the stroke length of the valve and also most suitable for the different frequencies like 3Hz, to7H$_Z$ of the frequency. The butterfly valve which works on a crank lever mechanism. It is easy to operate, reliable, economic, long life, and most suited for industrial applications.

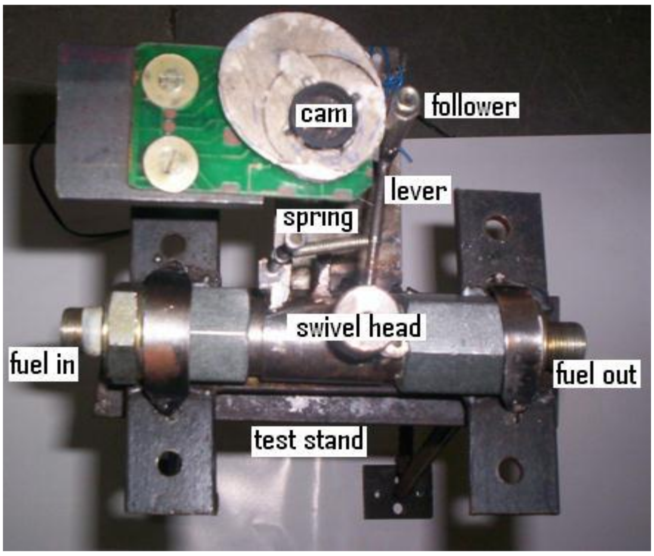


Fig.1 CAM Operated Valve [1]

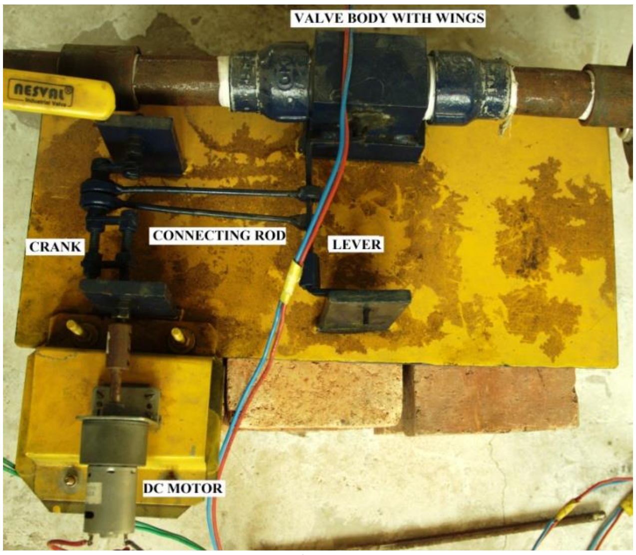


Fig.2 Butterfly Valve Design

RESEARCH METHODOLOGY AND RETROFIT DESIGN

Installation of the fuel flow control valve 'Oscillating Valve' on the fuel line ahead of the burner and the supply of fuel to the burner is one of the main requirements to create oscillation. The oscillating valve is required to oscillate the air-fuel ratio above and below the stoichiometric ratio. Designed and fabricated the 'Oscillating Valve' to incorporate in the test setup as retrofit. Performed series of experiments to gather the information of performance characteristics. The quantity of fuel flow is maintained constant before and after the installation of the oscillating valve as retrofit. Performed series of experiments to gather the information about the performance characteristics and the metallurgical effects during conventional and oscillating combustion modes.

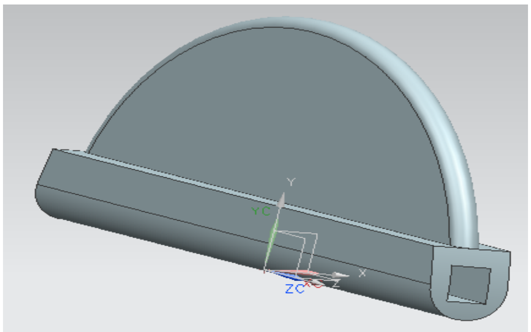


Fig.3 Butterfly valve wing

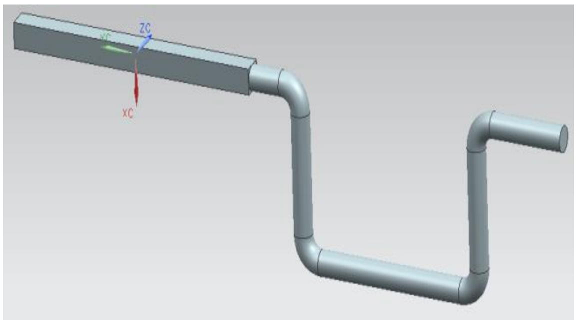


Fig.4 Butterfly valve Lever

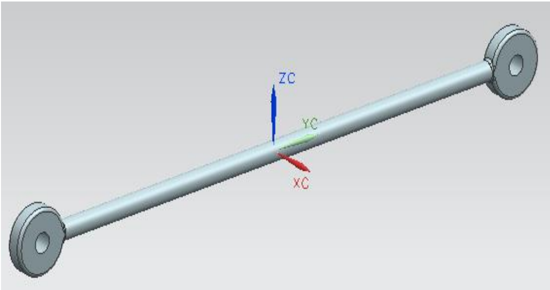


Fig.5 Butterfly valve Connecting rod

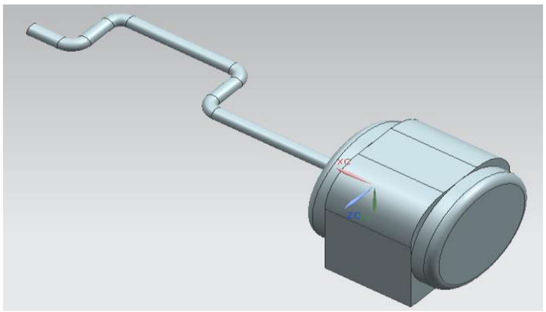


Fig.6 Butterfly valve crank with motor

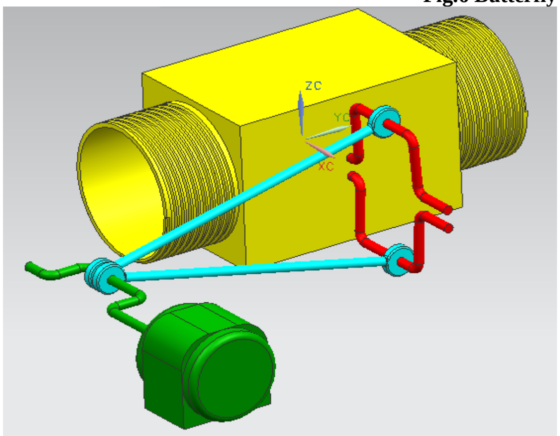


Fig.7 Butterfly Valve assembly

CONTROL DESIGN

A link based electromechanical valve consists of two semi-circular wings hinged to a square rod that permits fuel flow only in one direction. Wire cut method was used to provide square holes on the semi-circular wings. The circular holes have made on body by using electro chemical method to get the accuracy and straightness. The links have been designed to get the amplitudes of 15^0, 30^0, 45^0, 60^0, 75^0, 90^0would depend on stroke length by using the below relation.

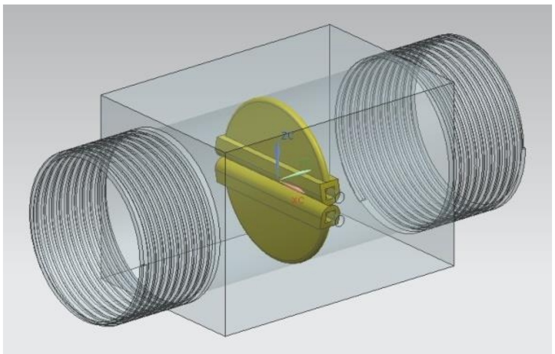
$$l = r\theta \tag{1}$$

Arc length $$s = r\theta \quad (\theta \text{ Must be in radians}) \tag{2}$$

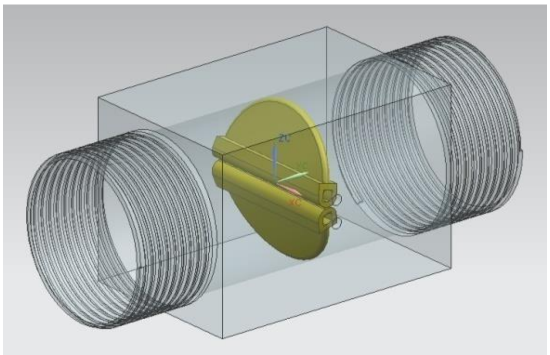
Arc length of sector $$s = \frac{centralangle * \pi * r}{180}$$

A 500 RPM DC motor is attached to run the valve to create the oscillations during fuel flow. Generating 3 Hz, 5 Hz and 7 Hz frequencies by regulating the motor speed using the Pulse Width Modulation (PWM) module controlled method.

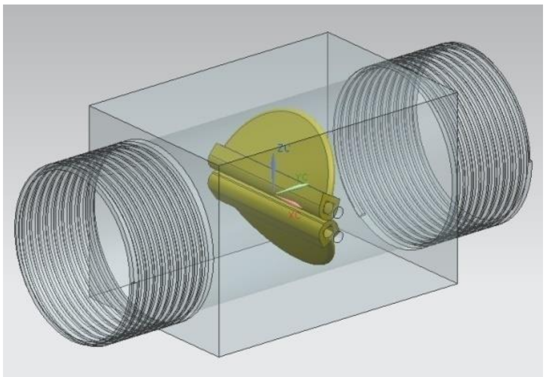
The burners firing time was proportional to the heat demand from the burners. With time proportional firing, the gas is turned on and off during oscillating combustion. Time proportional firing maximizes convective heat transfer by maintaining the maximum velocity of gases from the burners. This is beneficial in low temperature furnaces but virtually insignificant in a reheat furnace. With modulating control, more fuel regulation is required to maintain proper, turbulent mixing of the air and fuel ratios. The proper air fuel ratios can be achieved by regulating the fuel velocity by using regulator.



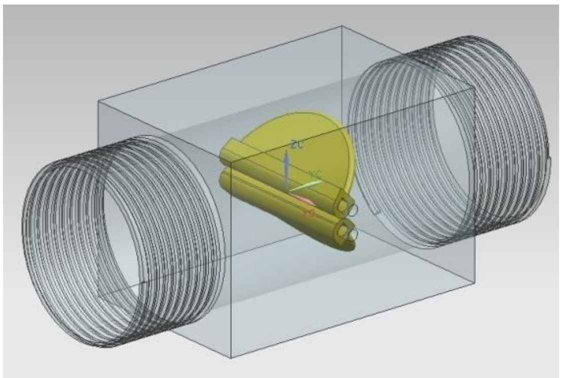
0^0 OPENING



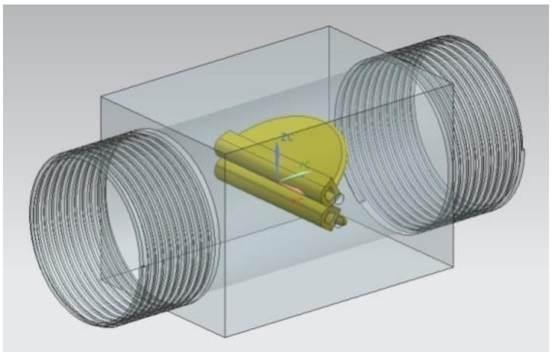
15^0 OPENING



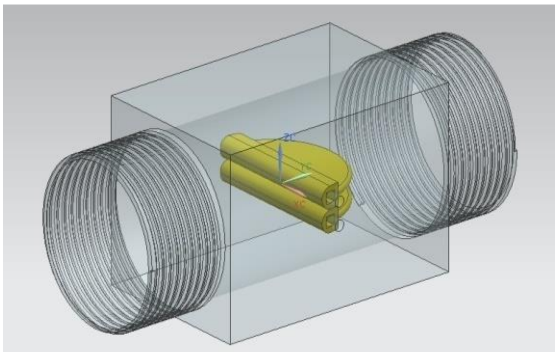
30^0 OPENING



45^0 OPENING



60^0 OPENING



90^0 OPENING

Fig.8 Butterfly Valve at Different openings (amplitudes)

QUADRIC CYCLE CHAIN

When number of links are connected in space such that the relative motion of any motion of any point on a link with respect to any other point on the other links follows a law the chain is called kinematic chain. This type of motion is called completely constrained motion or successfully constrained motion.

Application of quadric cycle chain is oscillatory motion or crank and lever mechanism. By properly proportioning the lengths of links we can obtain an oscillatory motion. It can be easily seen from the figure 2 that O_1A the crank is able to rotate completely but the follower O_2B, can only oscillate from B_1 to B_2, B_1B_2 being the maximum arc of oscillation.

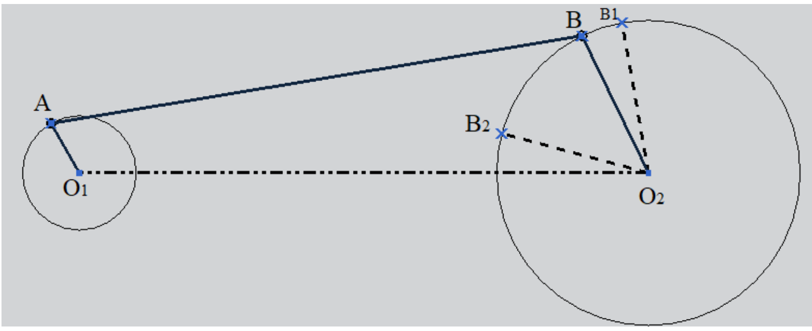


Fig.9 Crank Lever Mechanism

GRUBLER'S CRITERION FOR CONSTRAINT OF A PLANAR MECHANISM WITH LOWER PAIRS

Consider link 2 having relative motion with link 1 as shown in Fig 10. The coordinate system oxy is fixed in link 1. To refer to link 2, we need three coordinates x_p y_p and θas illustrated in fig 2.13. Therefore, the maximum degree of freedom f_{max} of link 2 is given by f_{max}=3

At point P, if link 2 is connected by a turning pair, x_p and y_p become invariant and the degrees of freedom f of link 2 reduce to f=1

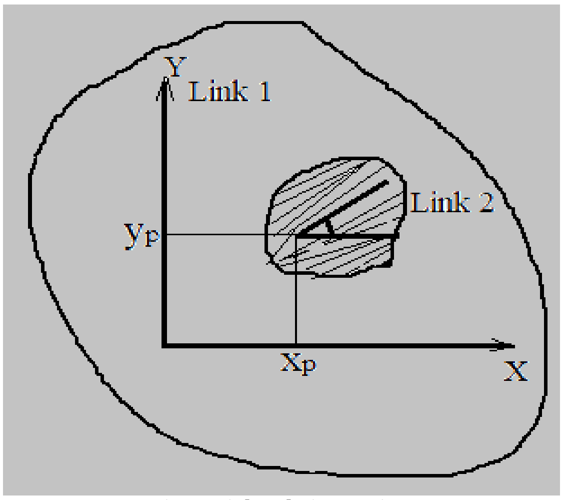


Fig.10 Link Relative Motion

Now consider a chain with n links, connected by j turning pairs, having a total degrees of freedom equal to F. since there are n links, the total number of degrees of freedom is 3n, since each link has initially f_{max} = 3.

If chain links under consideration forms a mechanism, one link is fixed, and therefore the number of degrees of freedom is 3(n-1). Further, two degrees of freedom are lost for each turning pair, i.e., 2j. Hence

$$F=3(n-1)-2j \qquad (3)$$

It should be noted that when a kinematic chain is made up of different types of links, such as those shown in Fig.2.2(c), then the number of joints, j, of a kinematic chain is computed as follows

$$j = \frac{1}{2}\left(2n_2 + 3n_3 + \ldots\ldots + in_i\right) \qquad (4)$$

Where n_2 = number of binary links, N_3 = number of ternary links and n_i = number of links with I hinged joints

Then $n= n_2+n_3+\ldots..+n_i$

For constrained motion f=1, therefore, Eq2.1 becomes

$$2j-3n+4=0 \qquad (5)$$

Equation (5) is true for all lower pairs and is known as Grubler's criterion for the constraint of planar mechanism with lower pairs. If the kinematic chain contains higher pairs, Equation (5) modified as follows.

Let h be the number of higher pairs in the chain. For each higher pair only one degree of freedom is lost, and therefore (3) is

$$F=3(n-1)-2j-h \qquad (6)$$

Hence, the constraint criterion for planar mechanism is

$$2j-3n+h+4=0 \qquad (7)$$

Where F=number of degree of freedom of freedom of chain, J= number of lower kinematic pairs, h= number of higher kinematic pairs, n= number of links

When F=1, the linkage is called a mechanism. In a mechanism, any one of the movable links can be driven by an external force. The remaining movable links will then have constrained motion. When f=0, the linkage forms a structure. That is, an application of external force does not produce relative motion between any links of a linkage.

When F>1, the linkage will require more than one external driving force to obtain constrained motion. When F<1, there is one redundant member and that the chain is a statistically interminate structure.

Inversion

A mechanism has been defined above as a kinematic chain in which one of the link is fixed. Four different versions a mechanism obtained by fixing any one of the links 1, 2, 3 or 4. Many a time, particular inversion of a mechanism may give rise to different mechanisms of practical utility, when the proportions of lengths of the links are changed.

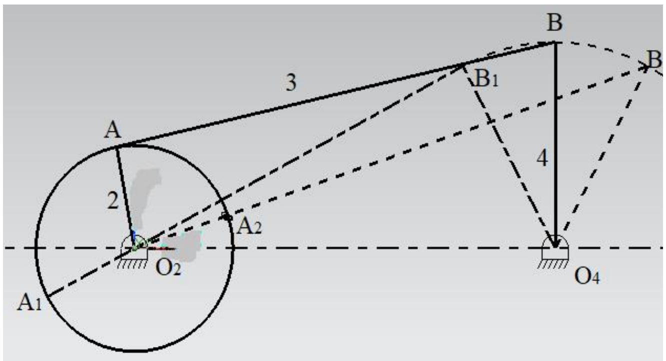


Fig.11Crank-Lever Mechanism

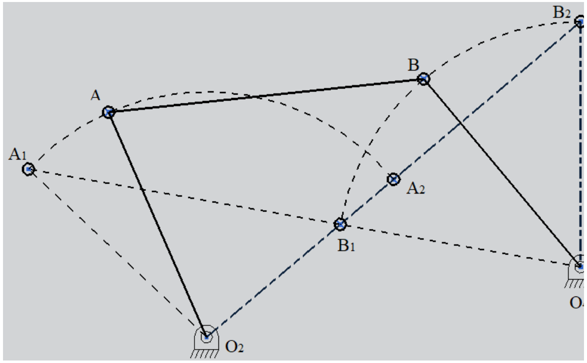


Fig.12 Double Lever Mechanism

Inversion of Quadric Cycle Chain

Kinematically speaking, all four inversions of the quadric cycle chain are identical. By fixing links 1, 2, 3, and 4 one by one are identical. However, by suitably altering the proportions of length of the links l1, l2, l3, and l4 of links 1, 2, 3, and 4 respectively, several forms of the quadric cycle chain can be obtained.

Crank lever mechanism the mechanism is shown in fig.11.Here for every complete revolution of link 2 (called as crank), the link 4 (called as lever) makes a complete oscillation. Proportions of the links are

$$(l_2+l_3) < (l_1+l_4) \quad (8)$$

$$(l_3-l_2) > (l_1-l_4) \quad (9)$$

When the crank is very short, this mechanism can be used as an eccentric, in which case the connecting link or rod 3 is called the eccentric rod.

Double Lever Mechanism

In this case both the links 2 and 4 can only oscillate. The extreme position of the levers with the connecting rod 3 is shown in fig.12. The double-lever mechanism must satisfy the following relations

$$(l_3+l_4) < (l_1+l_2) \quad (10)$$

$$(l_2+l_3) < (l_1+l_4) \quad (11)$$

When the links 2 and 4 are of equal length and $l_1 > l_3$ this mechanism forms an automobile steering linkage.

MODELING ANALYSIS

A link based electromechanical valve system incorporated in the path of fuel flow consists of two wings the axes of the butterfly wings are perpendicular to the axis of the fuel line. Two wings are fixed on the square rod which acts as link and is connected to connecting rod and this connecting rod is connected to rotary link acts as crank which works on the principle of crank lever mechanism.

When the wings oscillate from vertical to inclined position, it increases the volume of the gas at different position like 15^0, 30^0, 45^0, 60^0, 75^0, 90^0 of openings respectively. The oscillations of the butterfly wings like frequency, amplitude, duty cycle are adjusted by the crank which run by Pulse Width Modulation (PWM) module controlled DC motor. The air fuel ratios can be varied with adjusting the flow velocity of a fuel; here the flow velocity of a air can be kept constant. The heat release inside the furnace depends upon the variation in the velocity of the fuel flow due to variations in the frequency, amplitude and duty cycle of the oscillations which are created by oscillating valve. The oscillations created by the butterfly valve would produce a fuel rich and fuel lean zones inside the furnace and these fuel rich zone would heat up the load faster.

Table -1 List of Parameters Controlled and Monitored During Oscillating Combustion Testing

Controlled	
Frequency	the number of oscillation pulses per second
Amplitude	the relative change in gas flow rate above or below the average flow rate
Exhaust Gas Temperatures and Compositions (NOx, CO, O_2, and CO_2)	
Natural Gas Pressures and Flow Rates, Furnace Temperatures, Specified Product Temperature and Processing Time	

VALVE DESIGN AND CONTROL CONSIDERATION

The different views of the experimental setups are like temperature measuring apparatus, oscillating valve and butterfly wings positions at different openings like 15^0, 30^0, 45^0, 60^0, 75^0 and90^0.The butterfly valve works on the principle of crank lever mechanism the crank will rotates and the lever will swivel from 0^0 to 90^0 at different angles on this axis of the lever two wings are attached in the fuel line to control the fuel input to the burner. This crank lever mechanism which is attached to a 12 V motor of 500 RPM. The motor speed is controlled by Pulse Width Modulation (PWM) module to get the different frequencies like 3Hz, 5Hz and 7Hz in an oscillating combustion mode. There are some important points in the design of oscillating combustion valve.

- The flow regulations in the fuel line are keenly monitored the amount of fuel discharge will be same in before and after installation of valve.
- After installing the valve there is slight pressure drop in the fuel line and it was covered by adjusting the regulator.
- The sophisticated oscillating valve is designed with help of qualified technicians to avoid the gas leakages and unwanted noise during the operation.
- The friction between the links will be minimized to get smooth operation at variable speeds like 180, 300, and 420RPM.

RESULTS AND REFLECTIONS

Air fuel ratio plays a vital role in furnace combustion. In this present work the experiments are conducted on three air fuel ratios like 16:1, 17:1 and 18:1 fuel rich, stoichiometric and fuel lean air fuel ratios respectively. Fig 13shows the relation between amplitude and discharge (AFR) for fuel rich, stoichiometric and fuel lean air fuel ratios respectively. The discharge of the oscillating combustion technology is calculated at different amplitudes of the oscillating valve. The discharge was calculated by using the relation $Q = av$. The discharge is directly proportional to area of opening at the different amplitudes. It can be seen from Fig 13 that the rise in discharge of 16:1 is slightly higher than that of remaining air fuel ratios (17:1 and 18:1). The discharges at different openings create successive fuel rich and fuel lean zones in the flame. The load heats up faster due fuel rich zones $Q_{fuel\ rich} > Q_{stoichiometric} > Q_{fuel\ lean}$ In $Q_{\text{fuel rich}}$ zone the heat transfer is more, low melting time and increased productivity.

The stroke length which is directly proportional to the amplitude ($l = r\theta$)is shown in Fig 14. For every one revolution of the crank the lever oscillates from 0mm to 47.1204 mm of the stroke length and 0^0 to 75^0 of the amplitude. With the direction pointed out by the analysis, calculated the stroke lengths with respect to the amplitudes. The oscillations of the butterfly wings are controlled electromechanically and the amplitudes of the butterfly wings are adjusted according to the stroke lengths of the valve. The magnitude of the flame length depends upon the variations in the amplitude and frequency of oscillations introduced by oscillating valve. The load heats up faster in the oscillating combustion compared to steady state combustion due to more luminous fuel rich zones, high turbulence and more luminous flames created by flow oscillations and breakup of the thermal boundary layer.

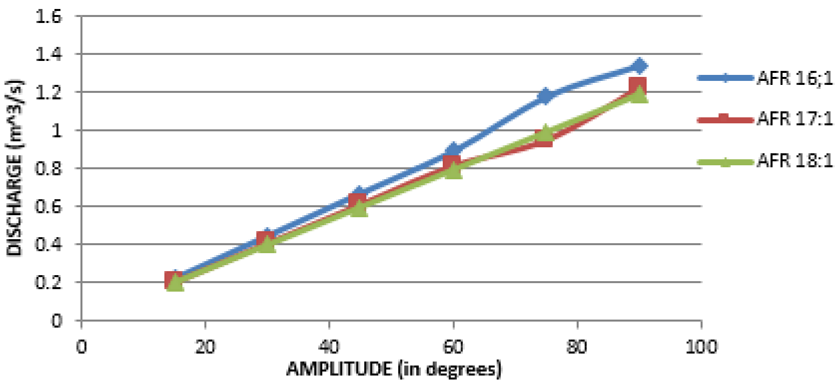


Fig. 13 Comparison of different AFR

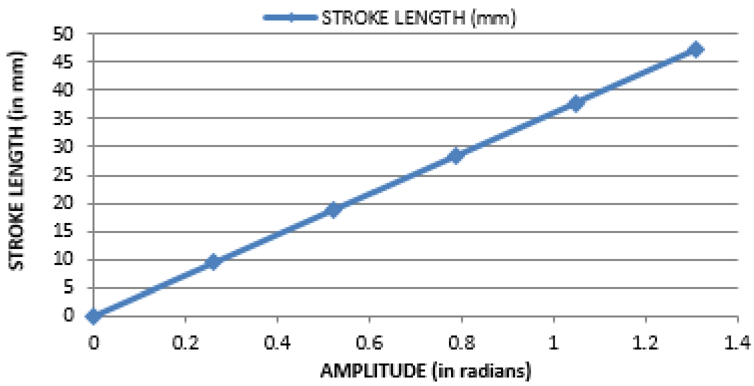


Fig.14 Relation between amplitude and stroke length

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