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Evaluation of thermal characteristics of oscillating combustion

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Abstract

In view of the economy and environmental impacts of the energy utilization, most of the heat transfer industries such as steel mills, glass plants and forging shops, foundry process and furnaces are focusing on energy efficient strategies and implementing new technologies. Gas Technology Institute (GTI) and Air Liquide Chicago Research Centre (ALCRC) have applied Oscillating Combustion Technology (OCT) on high temperature forged furnaces and reheat furnace for melting steel. The oscillating combustion requires a new hardware to incorporate on the fuel flow ahead of the burner. Solid State Proportionate (SSP) valves were used to create oscillations in the fuel flow. Natural gas was used as fuel and the technology was applied with air-gas, oxygen-gas, and excess level of air during the oscillating combustion. The present work deals with the implementation of OCT on liquid fuels at ambient conditions for melting aluminum metal in a fuel-fired crucible furnace which is of importance to foundry. Also, carrying out a study over the enhanced performance characteristics of oscillating combustion and comparing its thermal effects with those of the conventional combustion mode. The oscillating device, developed by the author, unlike other oscillating valves used earlier is a cam operated electro mechanical valve cause oscillations on the fuel flow. Experiments were conducted at varying air-fuel ratio, aluminum stocks, frequency and amplitude of the oscillating valve. The results when compared to the conventional combustion led to low fuel and specific energy consumption, enhanced heat transfer rate, increased furnace efficiency with visibly low volumes of flue gases with reduced emissions. The increased heat transfer rate and furnace efficiency was found to be in agreement with the results of GTI and ALCRC experiments. The reasons for such improvements in performance characteristics were verified by conducting experiments in the furnace by measuring the temperature distribution at designated point and calculating the heat transfer rate both for conventional and oscillating combustion mode. The analyses presented in this paper are for two levels of air-fuel ratios above and below the stoichiometric ratio, three different loads at 10^0 & 20^0amplitude and 5 & 10Hz frequency of oscillating valve.

Key words: Furnace efficiency, fuel fired furnace, heat transfer, oscillating combustion, specific energy consumption

1. Introduction

Energy is one of the most critical input resources in the heat transfer industries requires new combustion concepts to increase the thermal efficiency with reduced emissions and alternate sources of energy (Im *et al*., 1996; Kim *et al*., 2002). The increased demand, depleted energy resources, rising cost of fossil fuels and considerable environmental impacts are to be viewed and attempts must be made for higher energy utilization of fuel and thermal energy (Fadare *et al.*, 2009). The furnaces which operate at high temperature produce large quantities of emissions are sometimes less productive and less efficient. The aim of steady state combustion technology is to enhance the energy efficiency and consequential fuel cost savings as well to reduce emission levels (www.energy.com). Industrial manufactures are to implement new technologies to increase the thermal efficiency and stringent pollution norms require development of new combustion concepts (Gupta, 1977). Oscillating combustion system is a low-cost, low NO_x, high efficient technology and can be integrated in any combustion system, whose principle is based on a cyclical perturbation of the gas line (Delabroy *et al*., 2001). Oscillating combustion sometimes referred as the derivative of pulse combustion. Pulse combustion occurs when fuel and oxidizer react chemically in the presence of a standing acoustic wave. Although fuel and oxygen generally admitted to the combustion can be applied to gaseous, liquid and solid fuels (Research in pulse combustion). Oscillating combustion is a retrofit technology that involves forced oscillations of the fuel flow rate to a furnace. The oscillations of the fuel create successive, fuel-rich and fuel-lean zones within the furnace. The fuel rich zone flames are more luminous and longer causes more heat transfer from the flame to the load. This act of increased heat transfer to the load is the result of break up of the thermal boundary layer (Energy matters, 2002). Oscillating flames results in lower peak temperature of the furnace since the fuel- rich and fuel-lean zones mix only when the thermal energy of the fuel rich zone flame transferred the heat to the load thereby causing low peak furnace temperature and reduction in additional NO_x formation (John C and Wagner, 2004). Modeling at Air Liquide by Wagner and John C showed that oscillation flames have lower peak temperature and longer length than non-oscillating flames, which corroborates the burner test results. OCT has led to increased heat transfer and the increased heat transfer results in improved furnace productivity and efficiency (Wagner, C John, 2002). In order to optimize the furnace few parameters are mentioned as amplitude, frequency, duty cycle and phasing (gti.osc.combus.com). Oscillating combustion can be applied to many types of furnaces used in steel and high-temperature process industries such as glass, petrochemical, aluminum, cement and metal heating. OCT has been extensively tested and evaluated by Institute of Gas Technology, Air-Liquide, Ceram Physics.Inc. Gas Research Institute, GT Development Corporation etc.(Energy matters, 2002). The tests have shown enhanced furnace efficiency in terms of low fuel consumption with visibly low volumes of flue gases.

The concept of heat transfer or so called film co-efficient was introduced by Newton which depends on the properties of flowing fluid, thermal conductivity, viscosity, density and specific heat are termed as transport properties which play crucial role for better heat transfer (Arora.).

When oscillations occur, the pressure amplitude is sufficient enough to produce significant variations in axial velocity within the nozzle annulus. These axial velocities can vary during the oscillating combustion. The swirl vanes on the surface of the fuel gun of the burner would provide a variation in tangential velocity. Due to this the flow around the nozzle's annulus is having high and low regions of tangential velocity convected along the main axial flow of the fuel. The magnitude of heat transfer in any furnace from hot gases to load depends upon the temperature distribution inside the furnace. Generally, the temperature distribution through out a body varies with location and time. Temperature distribution in the crucible of a furnace is an important operation variable that is a function of the materials used in construction, temperature in the metal-refractory interface etc.(Luis Felip Verdeja, Roberto Gonzales *et al*, 2002). Also, the amount of heat release depends upon the variations in the axial velocity of the fuel due to the oscillations introduced by the oscillating valve and the variations in the tangential velocity of combustion air. Oscillating combustion is a retrofit technology that involves forced oscillations of the fuel flow rate to a furnace. When temperature gradient exist within, it is experienced that heat is transferred from high temperature to the low temperature region and the heat transfer is proportional to the temperature gradient and the area normal to the direction of flow of heat. The heat flux to the load from the temperature distribution inside the furnace is analyzed and calculated for non-oscillating and oscillating mode of combustion.

During the oscillating combustion mode the turbulent flame travels rapidly upward in radial direction (in 'y' direction) greater than the axial direction ('x' direction towards the load) to the location of designated temperature points. When a load is heated up, generally its corners are heated faster than any other region. Heat penetrates into the load in all the directions or x, y, z directions. However, highest temperature spots are located at the corners of the load than in the inner area of the load surfaces. Therefore, the temperature gradient also exists in the surfaces of the load at different zones is due to the fast heating of the corners at the surface. In this mode of combustion, the radiation heat flux or the temperature of hot gases at the stack zone found to be less in comparison to steady state. It is because the load at its position has received large portion of radiation flux or heat from the gases and radiation from the furnace wall. Thereby the temperature found to be low at higher position. However the gases escape with high temperature into the stack. The cumulative heat transfer from hot gases to the load directly or indirectly via refractory to loads is a function of time. Higher velocity shortens the time for heat transfer to be accomplished within a given flow path length or furnace size.

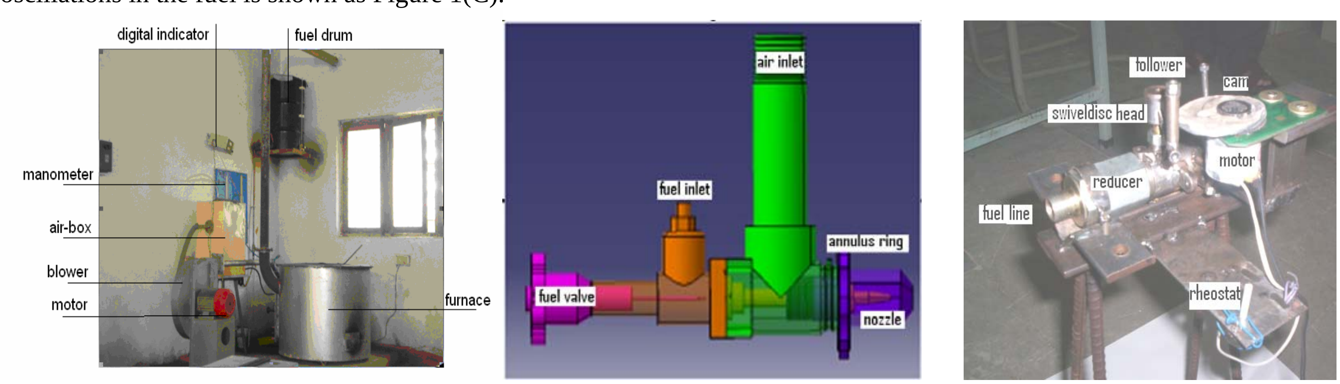
The radiation emitted by hot gases impinges on the furnace refractory brick wall as well as stock or load. Temperature gradient is the main cause for driving radiation flux from the furnace wall as well from the convective and radiative heat transfer from the hot gases to the load or stock. When large radiation flux is prevailing between hot gases and load it is understood that large heat flux is formed around the crucible or load. Since the thermal gradient between the load and hot gases is bigger than that of between furnace wall and hot gases, most of the radiation flux from hot gases flows into the load, thereby load heats up faster. So, the thermal gradient is found between the furnace wall and hot gases and hot gases and load. The oscillating combustion mode results in successive fuel-rich zone which enables to break up the thermal boundary layer developed around the furnace load due to thermal gradient between hot gases and load.

The main aim of the research is to implement the concept of "Oscillating Combustion Technology" on liquid fuels with ambient conditions on a crucible furnace installed with an "Oscillating Valve". The oscillating valve should be simple, low cost and highly reliable during the operation. It should be a retrofit into the furnace and should necessitate no major modifications. With the oscillating valve installed in the experimental setup exclusive analyses was carried out on temperature distribution and heat transfer for optimization of thermal efficiency with less emission.

2. Materials and methods

2.1. Description of the Experimental Equipment

The experimental setup shown in Figure1 (A) has a small furnace with different crucibles, a blower with motor and an air-box. Air-box is connected to 'U' tube manometer to calculate the amount of air flow in to the furnace. A gun type burner was used has an adjustment to vary the amount of fuel and air passing through the nozzle is shown as schematic Figure 1 (B). Test equipment is equipped with digital temperature indicators and thermocouples placed at different positions in the furnace to record the temperatures and to analyze the heat transfer rate from the experimental data by using the empirical equations. An oil drum located at approximately 2.5 m above the level of burner has a 3-way cock and piezometer tubes to measure the fuel consumption from time to time during the operation for consistent values. An oscillating valve installed on the fuel line ahead of the burner to create oscillations in the fuel is shown as Figure 1(C).



A **B** **C**

Figure 1. Experimental setup (A), Schematic of gun type burner (B), Oscillating valve (C)

2.1.1 Specifications of Instrumentation

Electrical ratings and settings:

Manufacturer: Lucky Industries, Model: 3 PH Induction Motor; Speed: 2880 rpm, Power: 2.2 kW, 3 HP, 4.5 A, 415 V.

Burner data: Manufacturer: Bajaj Engineering; Model: Gun Type

Blower data: Manufacturer: Bajaj Engineering; Nominal Motor Power: 2.2 kW

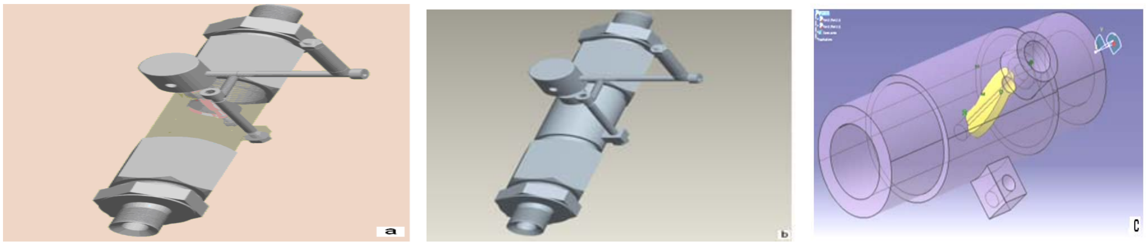
Furnace dimensions**:** i) Inner diameter of the furnace = 0.47m : ii) Height of the furnace (L) = 0.45m ; iii) Total inner volume = 0.0829 m^3

Fuel drum**:** Inner diameter = 0.457m : Area of cross section of drum = 0.164 m^2.

Chromel-Alumel (K-type) thermocouples used - Temperature range of -18^{0}C to 1372^{0}C; Accuracy = ± 0.5 % ; Sensitivity = 40 μV/^{0}C. These thermocouples have long life and low thermal conductivity and suitable for aluminum alloys. Digital temperature indicators are connected with the thermocouples measure and display the designated furnace temperatures All the thermocouples and sensing probe used in this instrumentation system are properly calibrated in the range of investigation.

2.1.2 Brief description of oscillating valve

The proposed oscillating valve which is simple, reliable, low cost, easily installed as retrofit has a swivel disc incorporated on the fuel flow pipe and the whole oscillating valve unit was installed in the fuel flow ahead of the burner is shown Figure 2 with different schematic views.



A **B** **C**

Figure 2. Schematic of oscillating valve in different views.

The axis of the swivel disc is perpendicular to the axis of fuel flow through the pipe. When the swivel disc is actuated, it rotates either side of its axis and controls the volume of the pipe. When the swivel disc is oscillated from its position, due to the cam and follower action it causes reduction in the volume. Thereby, restricts the fuel flow through the valve to the burner. When the cam resumes its normal position, the spring attached to the follower brings back the swivel disc to its original position or to its starting point. The swivel valve could open and close in $1/10^{th}$ of a second, and can vary according to the control by potentiometer. The oscillations of the swivel disc are adjusted electromechanically and the amplitude of the swivel disc is adjusted according to the size of the cam or cam profile. The motor consumes 4mA of current during its operation.

2.1.3 Description of experimental variables

1) Frequency (Hz): Number of oscillation cycles per unit time. The oscillating valve was operated at 5 and 10Hz of frequency.
2) Amplitude (Degree): The relative change in mass of fuel flow rate above or below the average flow rate. It is the magnitude of closing of the swivel disc from its initial position. Valve was operated at 10^0 and 20^0 of amplitude.
3) Load: Aluminum used (10, 15 and 20 kg.).
4) Air-fuel ratio: Above and below the stoichiometric ratio. Two levels of air- fuel ratios above and below the stoichiometric ratio.(!3:1,14:1. 15:1, 16:1 and 17:1)

2.3. Experimental procedure

The experimental work on oscillating combustion was carried out on liquid fuel fired crucible furnace. Prior to the testing of oscillating combustion, few modifications were carried out on the furnace and incorporated the oscillating valve in the experimental set up. Adjustment for variation of fuel flow into the burner is provided to set up required air- fuel ratios during the experiments. A custom valve control was used to oscillate the air-fuel ratio around the stochiometric ratio creating alternate fuel-rich and fuel-lean zones in the furnace during the oscillating combustion for any assumed air- fuel ratio. Initially, experiments were carried out on conventional mode of combustion. Tests include different air-fuel ratios, mass of stocks or loads. Oscillating combustion experiments were carried out with the same parameters with the oscillating valve incorporated as retrofit system. The data gathered during the experiments were used to find out the fuel consumption, specific energy consumption, melting time, temperature distribution, heat transfer rate and thermal efficiency for 13:1 and 15:1 air fuel ratios. Since the thermal characteristics were found to be good during the oscillating combustion at 13:1 air fuel ratio, 20^0amplitude, 5 Hz frequency and 20 kg load, the results were compared with those of stochiometric air fuel ratio i.e. 15:1(approx.). Analysis is made with the available experimental data for such improvements in the performance characteristics.

2.4. Measurement of experimental parameters.

The consumption of air supplied during the combustion was measured with an air box measurement apparatus. For consistent measurement of fuel consumption during the operation a three way cock burette was used. Also a piezometer tube fixed to the fuel drum provides the fuel consumption. Aluminum melting time was recorded by logging it with starting to melting time at equal intervals of time. Thermocouples, sensing probe with digital temperature indicators were used to measure the temperature at designated points in the furnace. A weighing machine was used to weigh the aluminum load for the experiments.

3. Results and discussions

Experiments were performed for conventional and oscillating combustion mode for the evaluation of thermal characteristics. The oscillating valve was operated at different air-fuel ratios, at 13:1, 14:1, 15:1, 16:1 and 17:1. Optimum results were found at 13:1 and 15:1 air-fuel ratio for both modes of combustion. This can be explained as the higher heat release rate around the stoichiometric ratio resulting higher thermal energy available in the furnace. The temperature variation at the aluminum load at 13:1 and for stoichiometric ratio (15:1 appx.) for conventional and oscillating combustion mode was observed and presented. The effect of varying temperatures on the fuel consumption, specific energy consumption, thermal efficiency of furnace and reasons for such improvements due to the enhanced heat transfer rate for both modes of combustion was analyzed. The results and discussions are broadly based on 13:1 and 15:1 air-fuel ratio at different parameters. They are discussed here and are shown in as graphical representations.

3.1 Temperature Profile at Load in the Furnace

Here the manifestation of temperature distribution for the stock of 20 kg load inside the furnace at stoichiometric ratio and at a fuel rich condition of air-fuel ratio 13:1 is represented in the Table 1 and shown as Figure 2 for 20^0 amplitude and 5 Hz frequency. From the Figure 3 for 13:1 air-fuel ratio the point $T_{1,}$ the oscillating combustion mode shows increase in the temperature magnitude than the non-oscillating mode and the higher temperature is observed at the end of 40 to 50 minutes of operation. The temperature difference between oscillating and non-oscillating mode found to be around 130^0 C at the end of 20 minutes of operation and 76^0 C after 40 minutes of operation. It shows that the maximum difference prevails till the point the furnace attains steady state and high radiant condition. The difference is decreased at the end due to the minimum thermal gradient at the position irrespective of the combustion mode. However, the temperature obtained during the oscillating mode must have ensured the process operation of melting the aluminum due to increased heat transfer and thermal conductivity in the load.

T1= Temperature measured at the load during melting operation

Table 1.Temperature profile at the Load (T1)

Air-fuel ratio	Condition-(Temp.^{0}C)	Time interval (minutes)				
		After 10 min.	After 20 min.	After 30 min.	After 40 min.	After 50 min.
13:1	Without Oscillation	205	375	553	625	705
15:1	Without Oscillation	197	342	480	578	650
13:1	With Oscillation	302	505	648	701	--
15:1	With Oscillation	288	474	612	680	723

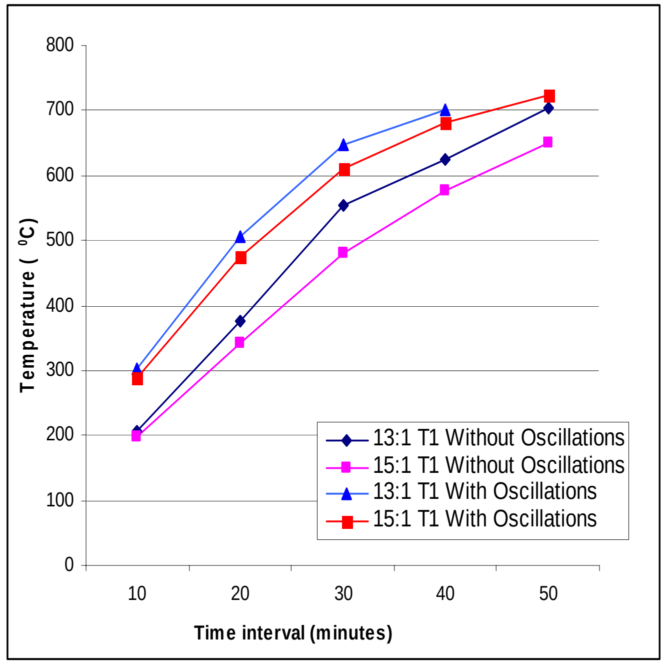
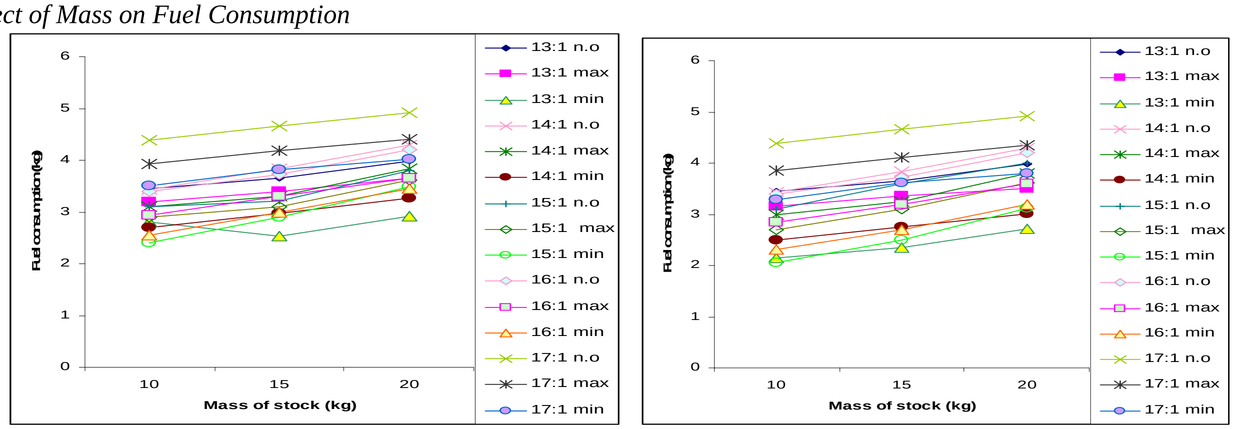


Figure 3. Graphic display of factors effects on temperature distribution

The temperature distribution and heat transfer in the furnace can be seen from the Table I and Figure 3 for 15:1 air-fuel ratio that the temperature point T_1 is in increasing trend during the oscillating combustion mode. There is a spurt in the temperature for both modes of operation during the time interval of 20 to 30 minutes. The magnitude of temperature at the load found to be greater in the oscillation mode. The temperature difference was around 140 ^{0}C after 20 minutes of time interval and gradually reduced after 40 minutes of time interval. The maximum difference in T_1 prevails till the point in the furnace attains radiant condition. The high degree of temperature during the oscillating combustion mode is an indication of high thermal gradient between the gases and load resulting greater absorption of heat by the load especially due to the fuel-rich flame. As the fuel-rich zone flame is more luminous and longer in length enhances heat transfer to the load. It can be seen that for any assumed interval of time the magnitude of temperature was found to be higher during the oscillating mode than the steady state mode for both air-fuel ratios. This can be attributed that enhanced heat transfer rate depends upon the temperature gradients inside the furnace which are generally found that the top surface temperature always stays higher than the bottom surface temperature. Oscillating combustion is a novel retrofit and efficient method makes use of oscillating flow field with different zones of flames thereby enhanced heat transfer to the load. This causes decrease in energy consumption and can directly reduce the emission levels.

3.2 Effect of Mass on Fuel Consumption



A **B**

Figure 4. Graphic display of factor effects on fuel consumption at 10^{0}amplitude (A) and 20^{0}amplitude (B)

From Figure 4(A), it can be seen that conventional mode of combustion the fuel consumption tends to increase marginally at higher loads. Optimum fuel consumption was observed at 15:1 air-fuel ratio for 10 kg, 15 kg, and 20 kg of aluminum load stocks. The same trend was continued for other air-fuel ratios but the melting time was found to be longer. In the oscillating combustion mode the fuel consumption came down drastically for 10^0 of amplitude operation at 10 Hz & 5 Hz frequency. Low fuel consumption was observed among the oscillating combustion for 13:1 air-fuel ratio for a 20 kg of load. However, there is only marginal increase in the fuel consumption for other air-fuel ratios for any given load. This can be considered to be a minor factor. The fuel consumption during the conventional mode of combustion for the same 13:1 air-fuel ratio and 20 kg was found to be 3.98 kg when compared to the oscillating mode fuel consumption which was 2.92 kg. A variation of almost 1.0 kg of fuel was less consumed. This can be discussed as heat is always lost from flame to the furnace walls and the propagation of the flame becomes slower as the flame gets closer to the quenching position and the flame velocity is reduced with the reduced flame temperature. Gradually heat is lost to the furnace walls during the steady state combustion mode. In the oscillating combustion mode, within a reasonable short time the furnace wall temperature becomes more or less uniform because time scale of the flame propagating is less and its velocity is faster due to more luminous flame from the fuel-rich zone of the flame. Fuel consumption tends to become low due to less time taken for the load to melt.

Figure 4(B) shows the fuel consumption during the oscillating combustion mode for 20^0amplitude for all air-fuel ratios and especially at 5Hz frequency operation was found to be at its lower value. The restriction of fuel passage by the swivel valve of the oscillating combustion valve at 20^0amplitude plays an important role in creating greater amplitude with lower frequency. The lower frequency gives enough time to match the higher amplitude in perturbing the fuel flow to introduce oscillations. This causes the air-fuel ratio to oscillate above and below the stoichiometric ratio, thereby producing alternating fuel-rich and fuel-lean zones in the flame. This increases the heat transfer rate from flame to the load, hence significantly less fuel consumption

3.3. Effect of Mass on Specific Energy Consumption (SEC)

Specific energy consumption (SEC) is the ratio of quantity of fuel or energy consumed to the quantity of metal processed. Furnace utilization factor and standby losses plays important role in achieving the low SEC. Utilization has a critical effect on SEC and is a factor that is often neglected. If the furnace is at a temperature then standby losses of a furnace occur whether or not a product is in the furnace. Energy is also lost from the charge or its enclosure in the way of heat.

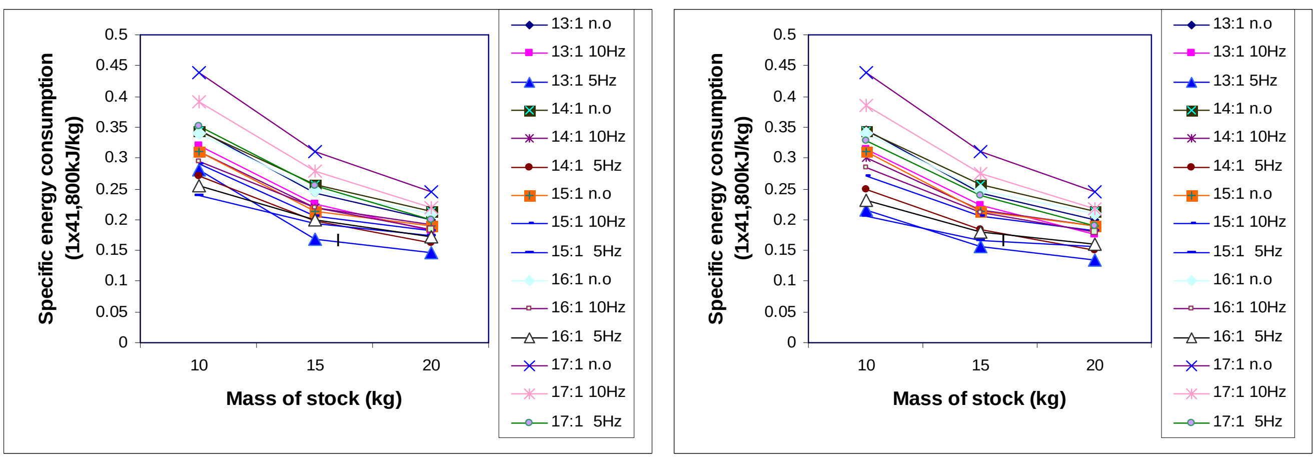
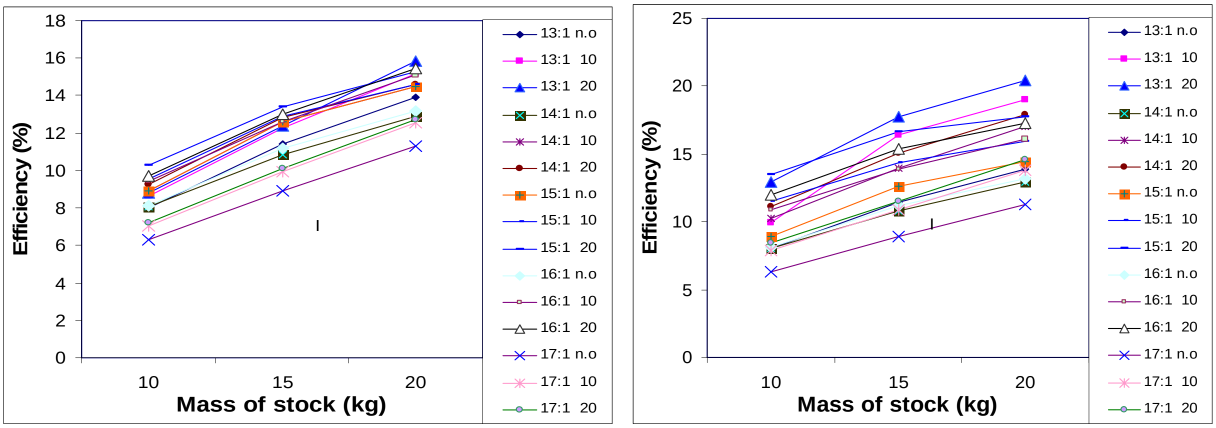


Figure 5. Graphic display of factor effects on specific energy consumption at 10^0amplitude (A) and 20^0amplitude (B)

The effect of oscillations on SEC for different air-fuel ratios and loads has been shown in Figure 5(A). For the steady state combustion mode without oscillations the SEC was found to be more for the rich mixtures and in decreasing trend for lean mixtures. But when compared for the same air-fuel ratio for different loads the SEC was lower for higher loads and lean air-fuel ratios. However the time taken for the melting operation for these low SEC loads was marginally higher during the steady state mode operation. But when compared the same with oscillating mode combustion, the SEC has dramatically found to be at its lower side and especially for 20kg of load i.e. 0.146 kJ/kg at 5 Hz frequency at 13:1 air-fuel ratio and 0.163 kJ/kg at 5 Hz frequency at 14:1 air-fuel ratio. The significant reduction in oscillating combustion can be stated as the oscillated fuel, creating successive fuel-rich and fuel-lean zones during which the heat transfer rate from the flame to the load is maximum for a higher load and due to maximum utility of the furnace.

Here, the effect of oscillations especially during the oscillating combustion mode for all air-fuel ratios and loads operating at 20^0 amplitude and 5 Hz frequency is seen in Figure 5(B). SEC has been low among the oscillating combustion for all air-fuel ratios. This was due to the enhanced rate of heat transfer to the loads due to radiation and convection of hot gases to load and internal conduction in the load during oscillating combustion. Noticeable difference was observed in SEC at 15:1 air-fuel ratio. This was found to be low among the oscillating conditions i.e.0.156 kJ/kg. Significant reduction in SEC was observed from steady state to oscillating combustion from 0.400 kJ/kg to 0.156 kJ/kg. However for all other air-fuel ratios the SEC was found to be less at 20^0 amplitude operation. At 20^0 amplitude the restriction of the fuel quantity was more and due to smaller frequency of the swivel disc operation causing more time for the restricted fuel to flow with oscillations to the burner. This resulted in optimum release of energy during the fuel-rich zone and higher heat transfer. There was a slight variation among the oscillating mode of operation but the difference was significant when compared to the steady state combustion.

3.4 Effect of Air-fuel ratio on Efficiency

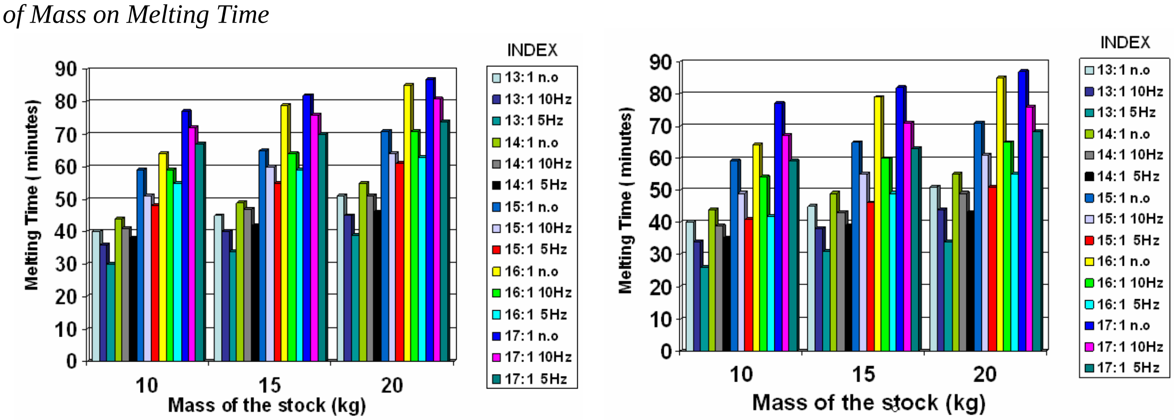


A **B**

Figure 6. Graphic display of factor effects on efficiency 10Hz (A) and 20Hz (B)

The relation between air-fuel ratio and efficiency for different mass of stocks at different amplitudes and frequencies with and without oscillations has been shown in Figures 6(A) & (B). For oscillating modes the efficiency was found to be increasing from 13:1 to 15:1 and there is marginally decreasing for lean air-fuel ratios. This is due to the release of optimum energy at nearly stoichiometric ratio and further the mixture was lean which tend to decrease the efficiency at 16:1 and 17:1 air-fuel ratios. But the efficiency was on the increasing trend for the higher loads due to the maximum utility of the furnace capacity and absorption of heat energy. In the same oscillating modes of operations, again it was demonstrated that the efficiency was in increasing trend up to 16:1 air fuel ratio and higher loads. The efficiency was found to be remarkable at air-fuel ratio 13:1 and 20° amplitude, 5 Hz frequency and 20 kg of load during oscillating combustion.

3.5 Effect of Mass on Melting Time



A **B**

Figure 7. Graphic display of factor effects on melting time 10^0amplitude (A) and 20^0amplitude (B)

The effect of different loads of mass of stock on melting time is shown in Bar Chart as Figure 7(A) for 10° amplitude at different air-fuel ratios and frequencies with and without oscillations. Melting time for all the masses was found to be less for lower frequencies. It took less time for 10 kg at 13:1 air-fuel ratio but marginally took more time for 15 and 20 kg for the same 13:1 air fuel ratio. Though, the time taken for melting 10 kg of mass was less than 15 and 20 kg but the maximum heat energy available in the furnace due to oscillating combustion could not be used. However, the melting time for other masses was marginally high but processed larger amounts of mass

The relation between mass of the stock and melting time at 20°amplitude is shown Bar Chart as Figure.7 (B) at different air-fuel ratios and frequencies with and without oscillations. Different air-fuel ratios gave different melting times. It is seen that the time taken for melting different masses was reduced further due to oscillations of lower frequency at 20°amplitude. This was again due to the radiant heat which was existing already and the optimum use of available heat energy in the furnace. In oscillating modes of operation the oscillating valve is able to open and close steadily at higher amplitude and lower frequency facilitating break up of thermal boundary layer which shortens heat up time.

4. Conclusions

Experimental investigation was performed to investigate the temperature distribution and radiative heat transfer characteristics of aluminum loads in a fuel fired crucible furnace with conventional and oscillating combustion modes of operations at different parameters. The temperature measurements inside the furnace at load were recorded using thermocouples with digital indicators and the data has been used to analyze the heat transfer rate inside the furnace. Thermal boundary layer was a major concern during the normal combustion mode in a furnace. It has ill effect on the heat transfer rate to the load. The break up of thermal boundary layer is the result of increased heat transfer rate in the oscillating combustion from hot gases to load.

Oscillating combustion results were compared with conventional combustion results. The results showed that due to oscillations in the fuel flow by the oscillating valve there are improvements in the performance characteristics in the oscillating combustion. Also, the oscillating combustion results were compared with the work carried out by the GTI and ALRC. The results were found to be in good agreement in terms of furnace efficiency, heat transfer rate and fuel costs. The results obtained during the oscillating combustion are promising**.**

- 2% to 6% increase in efficiency,
- 7% to 27% of fuel savings
- reduction in specific energy consumption (SEC) from 16.5% to 32%
- reduced melting time and increased productivity rate with reduced flue gas volumes

It can be concluded that successful testing of oscillating combustion which recorded improvements in the performance characteristics would directly facilitate the deployment of this technology in the process industries, heat transfer industries.

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Biographical notes

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