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Influence of Oscillating Combustion on Thermal Boundary Layer in a Diesel Fired Crucible Furnace

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Abstract

The results of an experimental investigation on a diesel fired crucible furnace associated with thermal boundary layer are presented. Oscillating combustion technology is innovative and simple process employed to study its influence on thermal boundary layer, requires an oscillating valve to be incorporated on the path of fuel flow to create oscillations. This paper represents an effort to explain the enhancement in the heat transfer rate in the furnace load and improvements about the performance characteristics such as melting time, specific energy consumption and thermal efficiency. Tests were conducted on the furnace in non-oscillating and oscillating combustion mode and comparisons have been made to verify the significance of the oscillations which influences the breakup of thermal boundary layer formation during the non-oscillating mode of combustion. It has been observed from the experimental data that the different temperatures recorded during the pragmatic tests are sufficient to understand the enhancement in heat transfer rate from flame to the load is due to the more luminous fuel-rich zone and breakup of the thermal boundary layer.

Key words- melting time; oscillating combustion; specific energy consumption; thermal boundary layer; thermal efficiency.

1. Introduction

Oscillating combustion is being increasingly used in different branches of industry. Oscillating combustion is a type of combustion with periodic variation of parameters in time and space. Delabroy O, Louedin O. *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 [1] The focus of researchers and industrial manufacturers now a day, in the heat transfer industries is on energy efficiency improvement strategies and to implement new technologies to increase the thermal efficiency and stringent pollution norms which require development of new combustion concepts [2]. Some combustors are especially designed for the situation in which the combustion is the responsible for the excitation of the acoustic oscillations. On the other hand, for conventional combustion chambers, an external actuator is necessary to induce the oscillations, such as speakers strategically positioned in the burner or on the chamber wall. The external actuators can also be used in chambers where the flame is sufficient to induce the oscillation. [3]. Laboratory testing on many types of industries, burners and limited field testing in steel mills, glass plants and forging shops have shown that oscillating combustion technology is an innovative, retrofit and is relatively simple process employed to improve the efficiency and reduction in pollution levels. Steady state combustion technology is generally used in the heat transfer industry to obtain higher energy efficiency and consequential fuel cost savings and also reduces emissions. According to Sang Heon Han *et al.* mathematically temperature field of a slab or load is governed by the following transient heat conduction equation

$\rho\ c\ \partial T/\partial t = \partial/\partial x\ (\lambda\ \partial T/\partial x) + \partial/\partial y\ (\lambda\ \partial T/\partial y) + \partial/\partial z\ (\lambda\ \partial T/\partial z)$ where ρ, c, λ are mass density, specific heat and thermal conductivity of slab or load.[4] Heat transfer is extremely important in a wide range of materials processing techniques. Therefore, it is important to understand these flows and develop methods to minimize and control their effects [5]. A boundary layer exists with both streamline and turbulent flow. This is a stationary film on the solid surface where friction is at its greatest. The boundary layers acts as an insulating barrier. The thickness and thus the insulating effect is dependent on the fluid velocity. In general applications this is negligible with turbulent flow created by forced convection. It is observed that if the heat transfer rate of any combustion mode is increased it tends to enhance the thermal efficiency further and its production capacity.

The present paper describes the experimental study of oscillating combustion mode which is relatively a new concept to steady state combustion mode by installing an oscillating combustion valve on the path of fuel flow in a diesel fired furnace to improve the thermal energy transfer to the load and helps in furnace energy optimization by the breakup of thermal boundary layer which forms around the load during steady state combustion [6]. There are several alternative solutions for the optimization of furnace and fuel economy but one of the main factors is enhancing thermal efficiency by breakup of thermal boundary layer in the furnace [7]. The valve oscillates the air fuel ratio above and below the stoichiometric ratio, there by producing alternating fuel- rich and fuel-lean zones in the flame. Tests were conducted both at low oscillations amplitudes that avoided fuel–rich conditions and at high oscillation amplitude that caused the flame to alternate between fuel rich and fuel lean conditions which is the normal mode of oscillating combustion. The fuel-rich zone provides more luminous and larger flame [8]. The thermal conductivity of more luminous flame with long flame is greater there by acts as neutralizer to breakup the thermal boundary layer results in the load heats up faster since the rate of heat transfer increases from flame to the load. Also, the increased turbulence resulting from the fuel oscillations contributes to breakup of the thermal boundary layer [9]. Due to the breakup of thermal boundary layer typical improvements were realized include thermal efficiency, increased process rates and furnace productivity with visibly apparent reduced flue gas volumes and reduced pollution emissions. Results showed 2 to 6% increase in efficiency and 7 to 27% of fuel savings and considerable rate of enhanced heat transfer rate. The heat transfer rate increased which shortens heat up time there by increasing the furnace efficiency. The experiments were conducted at different air-fuel ratios, amplitudes and frequencies with the oscillating valve at different loads to study the breakup of thermal boundary layer for the energy efficiency improvement strategy to optimize the thermal efficiency of the furnace. For the optimization of a diesel fired furnace, optimization of combustion air and improvements in efficiencies by heat waste recovery methods are more important methods for energy conservation [10]. K. Kurpisz had applied inverse heat conduction method to determine temperature distribution by measuring temperatures at some selected points to overcome the difficulties generally found in any numerical method which demands information about all boundary conditions. It is also assumed that the temperature distribution within the region under consideration satisfies the Fourier-Kirchoff equation [11]. Modeling at Air Liquide by Wagner, John C. showed that oscillation flames have lower peak temperature and longer length than non-oscillating flames, which corroborates the burner test results. Oscillating combustion technology has led to increased heat transfer and the increased heat transfer results in improved furnace productivity and efficiency [12]. Kazuhito Ishimaru worked to know the temperature distribution in a reactor furnace, the mathematical model was applied using total gas flow, material charge condition and boundary conditions as input. The temperatures calculated by mathematical model were compared with that of measured temperature and gas volumes for its validity [13]. The objective of this work was to study the effect of the combustion mode by recording statistical temperature distribution and the differences at different positions of the furnace around the load and observed results on different parameters as mentioned in the paper. If the thickness of the thermal boundary layer is reduced around the load then the heat transfer rate could be improved.

2. Literature review

During the normal mode of combustion a thermal boundary layer will develop, if the surface temperature of the load and the free stream temperature of hot gasses flowing are different. The fluid particles coming in contact with the surface of the object or load would exchange thermal energy with those neighboring layers and a thermal gradient is set up. With the increasing vertical distance from the surface of the load the fluid temperature approaches free stream temperature. The effect of heat transfer penetrates further into free stream resulting in growth of thermal boundary layer. This is the region over which the variation of temperature takes place in a thermal boundary layer. Here, the rate of heat transfer from the hot gases to the load is reduced due to the development of thermal boundary layer between the load and hot gases. We know that the thickness of the thermal boundary layer depends on the speed of the hot gases, the distance from the front end of the surface and viscosity or thermal conductivity of the fluid and the thermal diffusivity of heat. These quantities can be combined to form

Reynolds Number (Re). $Re = ux / \gamma$,
where u = velocity of fluid in m/s,
x = distance from the leading edge in m. and
γ = kinematic viscosity of fluid in m^2/s.

In accordance with the Prandtl's theory, a high Re.No. flow past a rigid body has to be subdivided into two characteristic regions. The main part of the flow field or hot fluid may be treated as in viscid and for all Re. No. exists a thin region near the wall, which is termed as thermal boundary layer.

The thickness of the boundary layer (∂_t) would vary with Re No. as $(\partial_\gamma / x) \sim Re^{-1/2}$. The exponent (-1/2) on Reynolds is typical of all laminar flows and for a high turbulent boundary layer $(\partial_\gamma / x) \sim Re^{-0.2}$ ((γ = kinematic viscosity of fluid). During the experiments it was recorded that the peak temperature of the flame drops to low temperatures on one side and relatively high temperature on the other side. The difference of temperature was found to be very high. This data indicates the formation of the thermal boundary layer which can be denoted as:

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2} \qquad (1)$$

The thermal boundary layer equation can be solved using the knowledge of velocity boundary layer solution. The relevant boundary conditions for temperature are:
Thermal boundary layer

$$\text{at} \quad y = 0; \quad T = T_s \quad \frac{\partial^2 T}{\partial y^2} = 0 \qquad (2)$$

$$\text{at} \quad y = \partial_t; \quad T = T_\infty, \quad \frac{\partial T}{\partial y} = 0 \qquad (3)$$

Where, ∂_t is thermal boundary layer thickness which is defined as the distance required for the temperature T to reach 99 percent of its free-stream value T_∞. Here the ∂_t is found to be in a smaller value of thickness found from the temperatures obtained. $\partial_t = 5x / \sqrt{Re_x}$. It is seen that ∂_t increasing with the distance from leading edge of the load but decreasing with the free stream velocity of the fluid. The important point found that the velocity of fluid was around 14.5m/s before the entry of nozzle and changes to 58m/s at the exit of the nozzle and results in a turbulent flow and the thickness of the boundary layer was found to be at its minimum. According to Prandtl's theory the kinetic energy of the fluid particles inside the boundary layer appears to be less than that of the outer edge of the boundary layer.

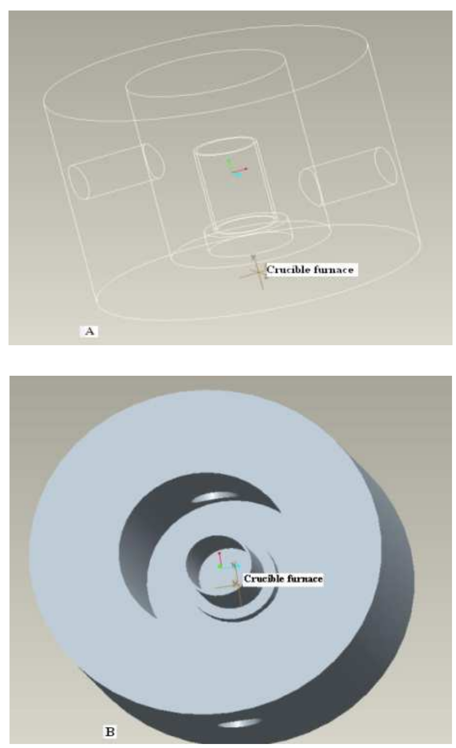
Prandtl's No. ($C_p\mu$ / k) and Nusselt No. hx / k plays important roles in the development and separation of thermal boundary layer around the load. Note that for P_r = 1, the thermal boundary layer is exactly the same as momentum boundary layer for zero pressure gradient. As the P_r no. is increased, the thermal boundary get smaller and vice-versa. This has an effect on the temperature gradient and correspondingly on the heat transfer rate. This concept is valid for some Re. No. for the laminar flow, but when the flow changes to turbulent for some critical value of Re. No. the theory may not be valid. However if the thermal diffusivity of heat is increased or oscillations are induced in the flow of fluid due to pressure amplitude variation to produce significant variations in axial velocity of the fluid can result in the variations of heat release and subject to develop fuel-rich and fuel-lean zones which breakup the thermal boundary layer and enhance the heat transfer rate to the load and increase its thermal efficiency.

3. Materials and Methods

3.1. Experimental description

The experimental setup is shown as Figure 1. Combustion occurs in a refractory lined crucible furnace shown as Figure 2 having a total volume of 0.0829 m^3 with capacity of melting 30kg of aluminum per hour. An oscillating combustion valve installed on the fuel line ahead of the burner is shown as Figure 3. A gun type burner is mounted in the furnace. The experiments were conducted in the test rig without and with fuel oscillations at different air-fuel ratios varying either side of stoichiometric ratio in the oscillating mode and non-oscillating mode. 10, 15 and 20kg of aluminum loads were chosen for melting operations.

Figure 1. Furnace test rig.



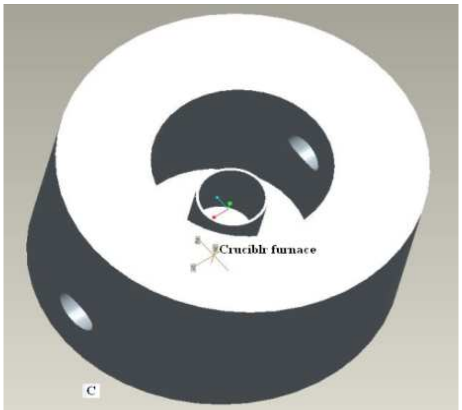


Figure 2. Schematics of crucible furnace in different views (A, B and C)

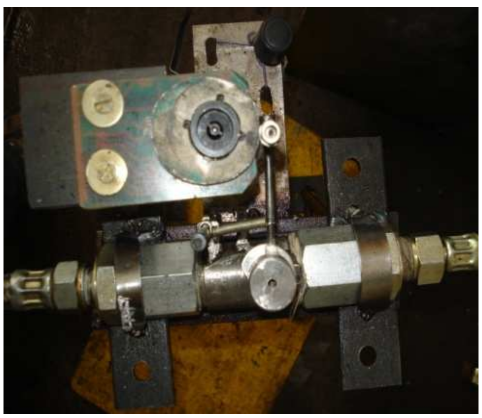


Figure 3. Oscillating combustion valve

3. 2. Description of experimental variables.

Aluminum was used for the experimental investigations. Different loads of aluminum of 10, 15 and 20kg were placed into the furnace and subjected to different air-fuel ratios of 13:1, 14:1, 15:1, 16:1 and 17:1. The oscillating valve was operated at 10° and 20°amplitude and at 10 and 5Hz frequency for the assumed air-fuel ratios. Experiments were conducted to study the temperature distribution and heat transfer rate, breakup of thermal boundary layer and the effect on performance characteristics of the oscillating and non-oscillating combustion mode.

3. 3. Experimental procedure

The experimental work on oscillating combustion was carried out on liquid fuel fired crucible furnace. 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 temperature distribution, heat transfer rate, fuel consumption, specific energy consumption, melting time and thermal efficiency for 13:1 and 15:1 air fuel ratios. 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 hence, the results were compared with those of stochiometric air fuel ratio i.e. 15:1(approx.). Analyses is made with the available experimental data for such improvements in the performance characteristics

3. 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. 5. Characterization of oscillations

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 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

4. Results and discussions

The essential factors affecting the efficiency are:
Incomplete combustion, in-correct heat distribution, heat losses from furnace openings and high stack or flue gases,

incorrect amount of furnace draught, low utilization capacity, refractory losses due to improper insulation and thermal boundary layer formation. The factors if controlled properly can enhance efficiency of the furnace. The data collected from the experiments and the calculations reveal the magnitude of the above factors for the optimization of the furnace. However, the impact of the formation of thermal boundary layer around the load is studied carefully and an analysis has been made and discussed.

4.1. Temperature distribution inside the Furnace

The improvement of combustion technique is importance to the sustainable development. Experimental investigations were performed to investigate the temperature distribution and radiant heat transfer characteristics of aluminum loads in a fuel fired furnace with steady state and oscillating combustion modes of operations at different parameters.

When a 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.

Figure 4 shows the schematic of crucible furnace where the heat transfer takes place from the flame to the load. The furnace was divided into three zones. Low, middle and top zone. Chosen two designated points in the middle zone and one at the top zone. With the help of measuring instruments temperatures were recorded at regular intervals and calculations were carried out by using the empirical correlations. The thermal gradient values obtained at the furnace walls and hot gases and hot gases to the load are shown in Table 1.

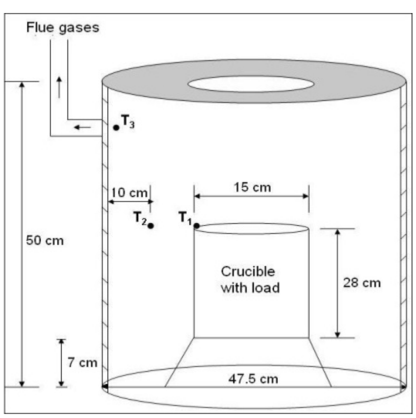


Figure 4. Schematic Temperature distribution in the furnace

Conditions:

A/F ratio = 13:1 ; N.O = No oscillations

Load = 20 kg ; W.O = With oscillations

Amplitude = 20^0 ; Frequency = 5 Hz

T_1 = Temperature of the aluminum load in the crucible during the melting operation

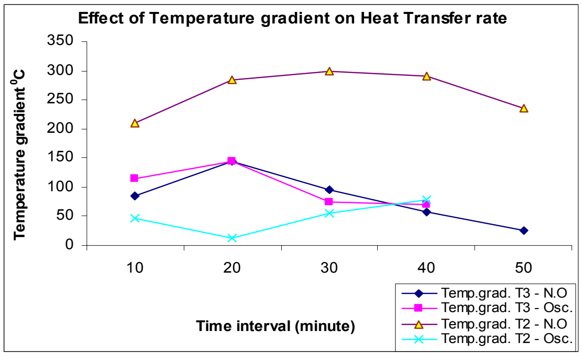
T_2 = Temperature of the hot gases 10 cm away from the inner walls of the combustion chamber of the furnace.

T_3 = Temperature of the hot gases at the entry of the stack.

$$\Delta T_2 = (T_2 - T_1) \quad : \quad \Delta T_3 = (T_3 - T_2)$$

Table. 1. Temperature gradient in the furnace

Time	Condition	ΔT_2 (^oC)	ΔT_3 (^oC)
After 10 minutes	With out Oscillations	210	85
	With Oscillations	46	114
After 20 minutes	With out Oscillations	285	145
	With Oscillations	13	145
After 30 minutes	With out Oscillations	299	95
	With Oscillations	56	74
After 40 minutes	With out Oscillations	290	57
	With Oscillations	79	70
After 50 minutes	With out Oscillations	235	25
	With Oscillations	---	---



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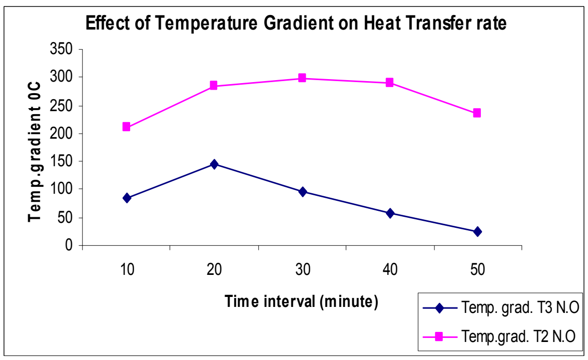

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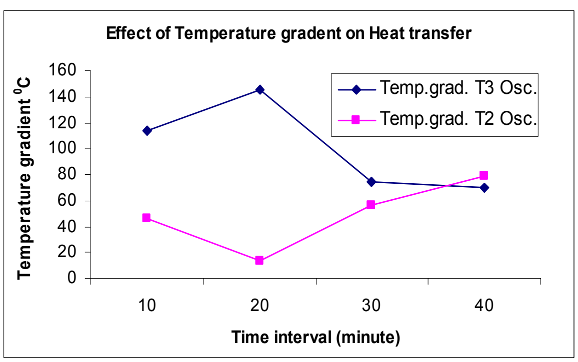

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Figure 5. Effect of temperature gradient on heat transfer

The rate of heat transfer from hot gases to load depends much on the existing thermal gradients in the furnace in and around the crucible and load.

From the Figure 5a, the temperature gradient ΔT_3 between furnace walls and hot gases was found at 85° C and ΔT_2 between hot gases and aluminum load was 210° C. There exists high temperature gradient between load and hot gases than the former one during the non-oscillating combustion mode. The difference in temperature gradient is reduced during the oscillating combustion mode. This is due to the oscillations in the fuel creating alternatively successive fuel-rich and fuel lean zones in the flame thus the absorption of heat energy by the load and also due to the high turbulent hot gases near the load resulting small temperature gradient.

During the non-oscillating combustion the ΔT_2 found to be increasing at the designated points and even after 40 minutes of operation the temperature gradient still found high. When ΔT_2 found to be large it can be stated that the valuable thermal energy is lost into atmosphere i.e. flue gases leaving with higher temperature. There is a significant decrease in temperature gradient when observed the ΔT_2 during the oscillating combustion mode. It is an indication that the thickness of the thermal boundary layer was either reduced or breakup of thermal boundary layer by the oscillating combustion resulting enhanced heat transfer rate.

From Figure 5b, the temperature gradient during non-oscillating combustion mode ΔT_3 found to be at low temperature gradient than ΔT_2. It can be explained that during the non-oscillating mode of combustion there was huge difference in the temperatures of the designated point T_2, temperature of hot gases and T_1 aluminum load. The heat transfer to the load was disturbed due to the thermal boundary layer formation around the load. This causes huge temperature gradient which is undesirable and lowers thermal energy transfer of the hot gases in melting the aluminum load. The temperature gradient at ΔT_3 was observed lower than the ΔT_2. Initially, ΔT_2 was low up to 20 minutes of operation indicating that heat transfer rate to the load was high and than slows down later due to the thermal boundary layer. The kinetic energy of the hot gas particles becomes less and moves slowly thus disturbing the energy transfer

From Figure 5c it can be noticed that during the oscillation combustion mode the temperature gradient at ΔT_2 is smaller than ΔT_3. It indicates that large amount of thermal energy was transferred for melting the load. The difference was found to be very small after 20 minutes of time interval. At this stage maximum heat energy was absorbed by the load. As the load heats up the temperature difference was found to be increasing, stating lower rate of heat transfer. At the end of the process both ΔT_2, ΔT_3 are found to be converging.

4.2. Effect of mass on melting time

Table 2 Mass and Melting Time at 5 Hz Frequency

Air-fuel ratio	Condition	Frequency (Hz)	Amplitude (degree)	Melting time (minute) at different loads		
				10 kg	15 kg	20 kg
13:1	Without Oscillation	--	--	40	45	51
	With Oscillation	05	10	30	34	39
			20	26	31	34
14:1	Without Oscillation	--	--	44	49	55
	With Oscillation	05	10	37	41	46
			20	34	39	43
15:1	Without Oscillation	--	--	50	58	65
	With Oscillation	05	10	34	47	50
			20	28	40	42
16:1	Without Oscillation	--	---	64	69	73
	With Oscillation	05	10	47	56	61
			20	42	48	55
17:1	Without Oscillation	--	--	77	82	87
	With Oscillation	05	10	67	70	74
			20	59	63	68

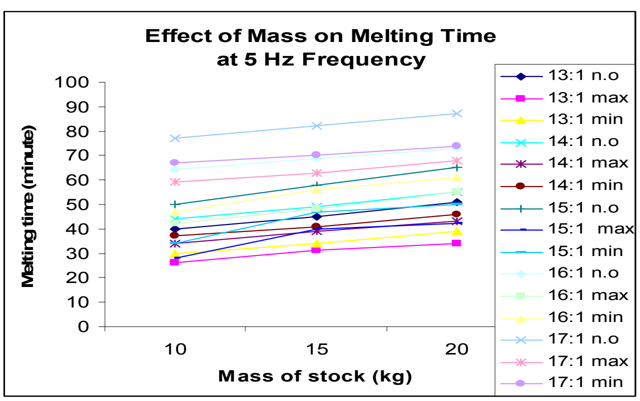
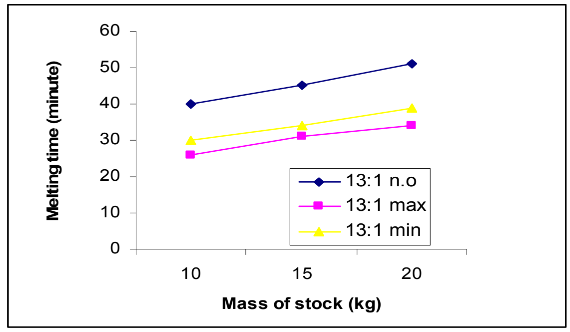


Figure 6. Effect of mass on melting time



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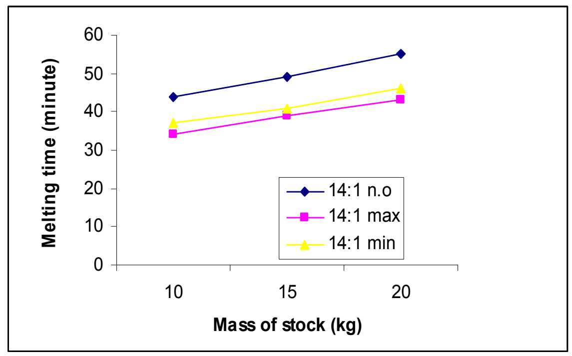

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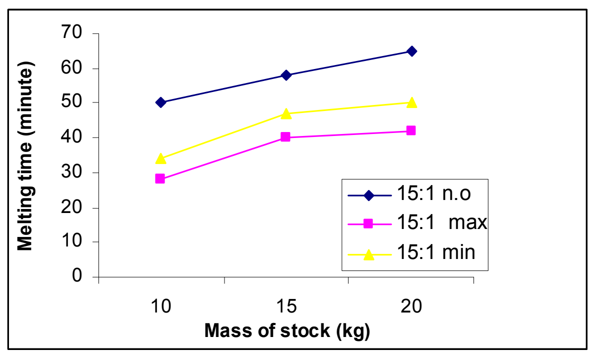

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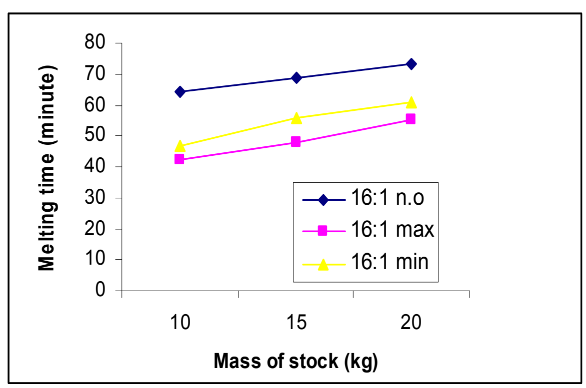

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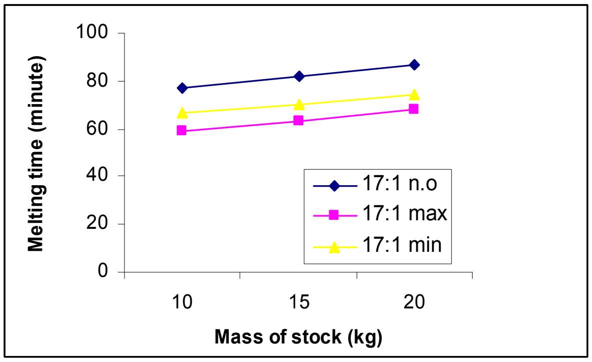

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Figure 7. Effect of mass on melting time at each a/f ratio

It is clearly evident from the Figure 6 and Table 2 that the melting time for the given load was found to be very low when compared from steady state combustion to oscillating combustion mode for all the air-fuel ratios. The 13:1 air-fuel ratio signifies low melting time than the other air-fuel ratios. It is also observed that the time taken for melting for different masses is further reduced due to oscillations at lower frequency and higher amplitude. This is because in oscillating modes of operation the oscillating valve is able to open and close steadily at higher amplitude and lower frequency facilitating to increase the rate of heat transfer which shortens heat up time. The difference of melting time was found to be 8 to 15minutes from steady state combustion to oscillating combustion mode in some cases.. The reason for the decrease in melting time during the oscillating combustion mode is due to the breakup of thermal boundary layer which existed in the steady state combustion mode by the high intense luminous and high turbulent flames. The increased rate of heat transfer results in low melting time and low fuel consumption. It also depicts the increase in thermal diffusivity of the flame to the load.

Figure 7 depicts the melting time for aluminum loads for each air-fuel ratio, “a → e”. It can be seen clearly from the figures that the melting time for any assumed air-fuel ratio during the non-oscillating mode was found to be higher than oscillating combustion mode. Low melting time was observed at maximum amplitude with minimum oscillations. As, the mixture tends to be lean the melting time increases.

4.3. Effect of mass on specific energy consumption

Table 3. Mass and SEC at 5 Hz Frequency

Air-fuel ratio	Condition	Frequency (Hz)	Amplitude (Degree)	Specific energy consumption (1*41800 kJ/kg) 10 kg	15 kg	20 kg
13:1	Without Oscillation	--	--	.34	.24	.19
	With Oscillation	05	10	.28	.16	.14
			20	.21	.15	.13
14:1	Without Oscillation	--	--	.34	.25	.21
	With Oscillation	05	10	.27	.19	.16
			20	.24	.18	.15
15:1	Without Oscillation	--	--	.31	.36	.40
	With Oscillation	05	10	.24	.19	.17
			20	.20	.16	.15
16:1	Without Oscillation	--	---	.34	.24	.21
	With Oscillation	05	10	.25	.20	.17
			20	.23	.18	.16
17:1	Without Oscillation	--	--	.43	.31	.24
	With Oscillation	05	10	.35	.25	.20
			20	.32	.24	.19

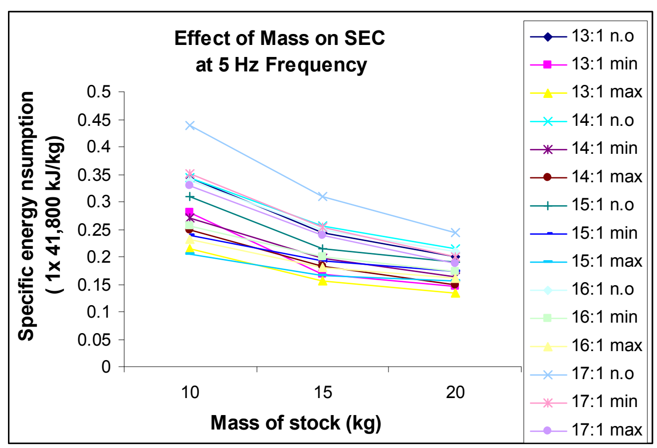
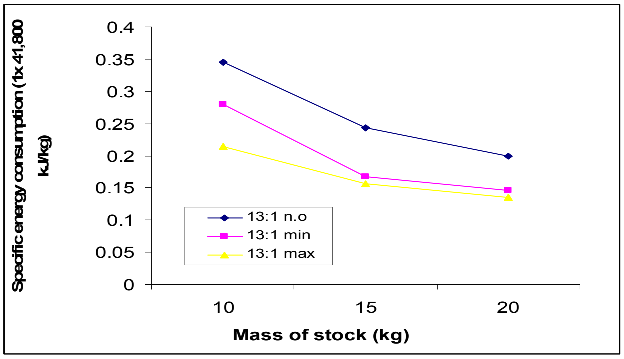


Figure 8. Effect of mass on specific energy consumption



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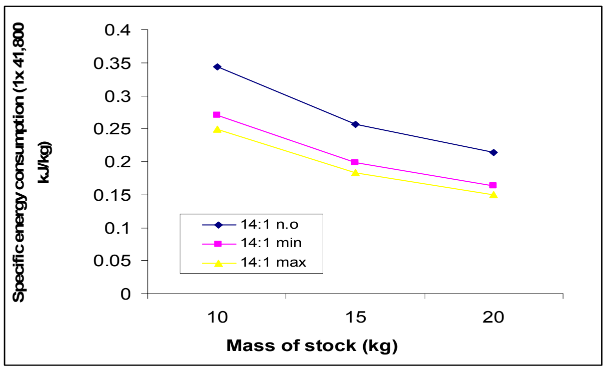

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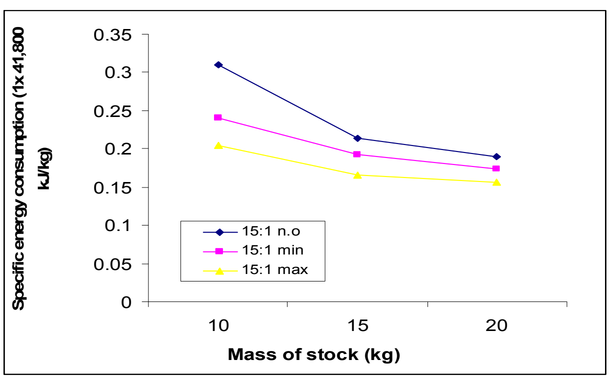

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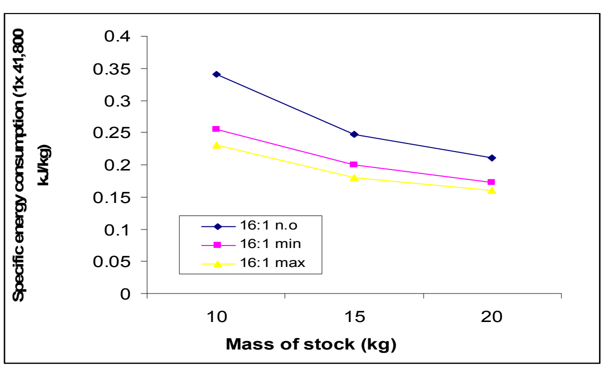

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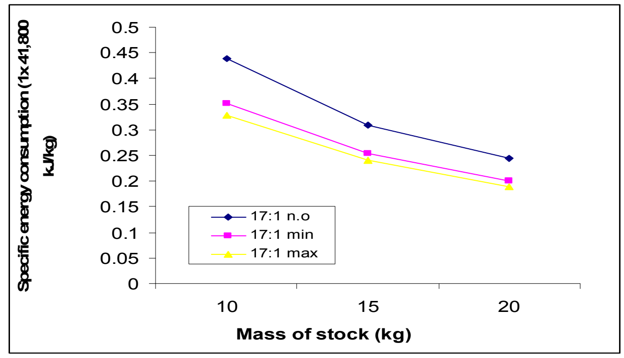

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Figure 9. Effect of mass on melting time at each a/f ratio

Specific energy consumption (SEC) is the ratio of quantity of fuel or energy consumed to the quantity of metal processed. Furnace utilization and standby losses plays important role in achieving the low specific energy consumption. 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.

The SEC is found to be more for all air- fuel ratios and different mass at non-oscillating combustion. However, the same SEC for a given air-fuel ratio and load tend to decrease sharply during oscillating combustion as shown in Figure 8 and Table 3. From the figure 9 it can be noticed that, there is a significant decrease in SEC at 15:1 air-fuel ratio, 20kg load. For the non-oscillating mode the SEC was observed as 0.400(1*41800)kJ/kg and for oscillating mode was 0.210(1*41800)kJ/kg. The lowest SEC at lower frequency (5Hz) and higher amplitude (20^0) is the result of maximum absorption of heat release by the load due to oscillating combustion and greater utilization of heat energy from available energy. This phenomenon can be attributed to the breakup of thermal boundary layer in the oscillating combustion mode. Again, it can be seen from the figures, low specific energy consumption was noticed at the maximum amplitude for all air-fuel ratios.

4.4. Effect of air-fuel ratio on thermal efficiency

Table 4. Air-fuel ratio and efficiency at 5 Hz frequency

Air-fuel ratio	Condition	Frequency (Hz)	Amplitude (Degree)	Efficiency at different loads (%)		
				10 kg	15 kg	20 kg
13:1	Without Oscillation	--	--	8.02	11.40	13.90
	With Oscillation	05	10	8.80	12.40	15.82
			20	12.90	17.75	20.44
14:1	Without Oscillation	--	--	8.07	10.82	12.90
	With Oscillation	05	10	9.23	12.82	14.61
			20	11.12	15.10	17.87
15:1	Without Oscillation	--	--	8.93	11.52	13.85
	With Oscillation	05	10	10.25	13.40	15.30
			20	13.51	16.62	17.75
16:1	Without Oscillation	--	---	8.14	11.16	13.19
	With Oscillation	05	10	9.71	13.02	15.43
			20	12.00	15.38	17.31
17:1	Without Oscillation	--	--	6.32	8.91	11.28
	With Oscillation	05	10	7.19	10.10	12.73
			20	8.41	11.50	14.61

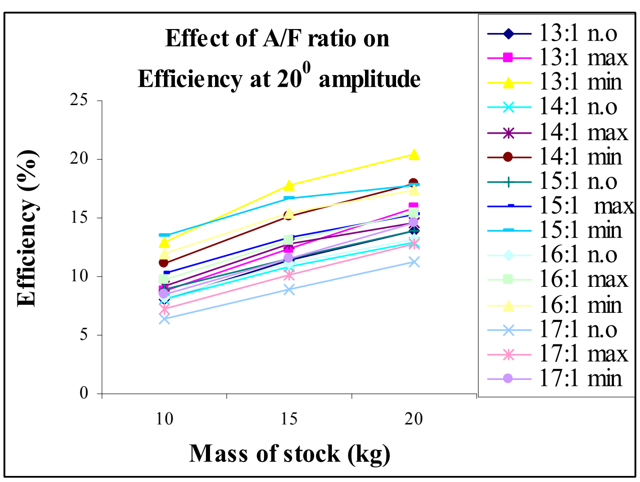
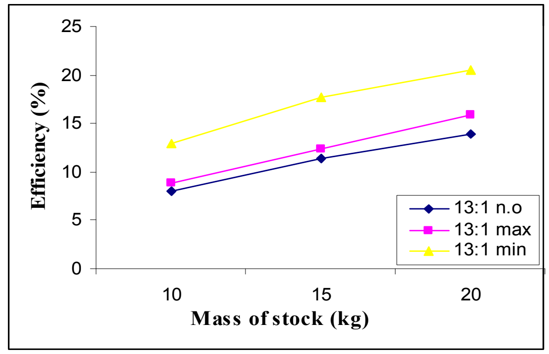
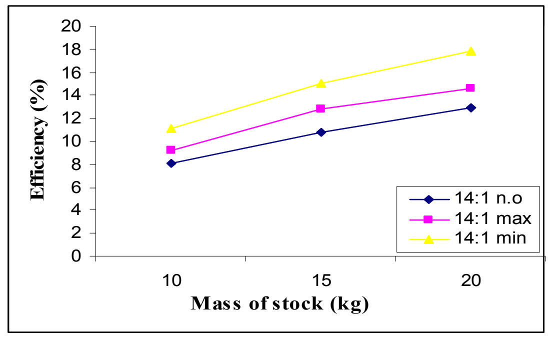


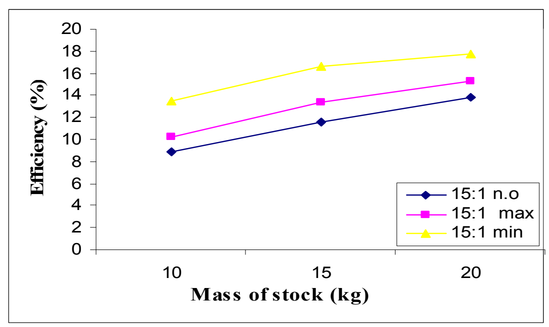
Figure 10. Effect of a/f ratio on efficiency



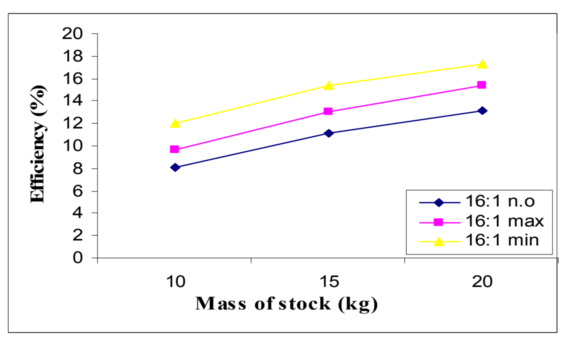
a



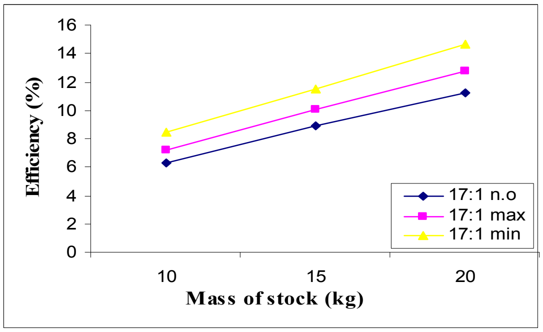
b



c



d



e

Figure 11. Effect of mass on melting time at each a/f ratio

Various losses occur in the fuel-fired furnace which directly affects the thermal efficiency or furnace efficiency of the furnace. The efficiency of the furnace can be calculated without considering those losses. The total heat input is provided in the form of fuel or power and the desired output is the heat supplied for heating the material or process. It is imperative to breakup the thermal boundary layer in the steady state mode for the optimum energy efficiency. The comparison of the efficiency is shown in Figure10 and Table 4, for oscillating and non-oscillating combustion mode. From the figure 11 it can be observed that maximum efficiency was clearly found for the oscillating combustion mode and is higher at 13:1 air-fuel ratio for a 20kg load. Maximum efficiency is clearly found for the oscillating combustion mode and is higher at 13:1 air-fuel ratio for a 20kg load. Here, one factor is to be noted that the efficiency was found for a 20kg load was 12.90 % at 14:1 air-fuel ratio during the non-oscillating mode and 17.87% for the oscillating mode. The maximum efficiency was observed with oscillations for 20kg load at 13:1 air-fuel ratio was 20.44%. At lean air-fuel ratio the heat release from the mixture per unit time becomes less hence decrease in efficiency. The results are quite appealing and demonstrate that the increase in efficiency was due to the breakup of the thermal boundary layer by using the oscillating combustion mode. The oscillating valve oscillates the mixture at 13:1 air-fuel ratio above and below the stoichiometric ratio causing alternate fuel-rich and fuel-lean zones in the flame thus increasing the heat transfer to the load

4.5 Visual observations

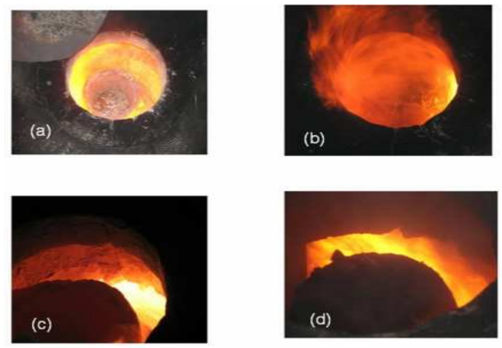


Figure 12. Types of Non-oscillating combustion flames.

(a) Non-luminous flame. (b) Red colored flame.
(c) Low swirling flame. (d) Low radiant flame.

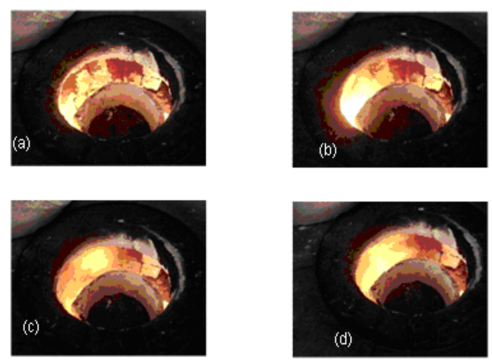


Figure 13. Types of oscillating combustion flames.

(a) & (b) Fuel-rich zones, (c) & (d) Fuel-lean zones.

Figure 12 and 13 depicts the pictures of different flames as recorded by camcorder for flames without and with oscillations. The non-oscillating flame was found to be a red flame with low swirl and did not exhibit significant influence on the velocity flow field of the flame compared to oscillating flame. The images obtained are for an air-fuel ratio of 13:1 and at a flow rate of 1.4g/s for steady state combustion and oscillating combustion mode The red flame during non-oscillating mode around the load in the furnace is an indication of burning rich-mixture. In fact the side walls of the furnace became glowing red or radiant heat after test duration of 20 minutes. However the oscillating flame which produces the high turbulence level and found to be bright, high luminous and longer flame than non-oscillating flame. These oscillations create successive fuel- rich and fuel-lean zones which can be observed from the figures as shown. The load heats up faster since heat transfer rate from flame to load increases due to more luminous fuel-rich zones. The increased turbulence and high luminous flames created by the flow oscillations breakup the thermal boundary layer.

4.6. Emissions

The stack gasses of the furnace were observed during the experiments conducted for different air-fuel ratios, loads, frequencies and amplitudes of the oscillating combustion valve. It was observed with visibly apparent reduced flue-gas volumes and reduced pollution emissions. The exhaust gas volumes were found to be clean and no soot or black smoke was observed.

Conclusions

The results obtained from the experiments that were conducted, it can be said that the thermal efficiency was found to be increasing for the values near the stoichiometric ratio and up to 16:1. The efficiency was also found to be higher for higher loads. However, lowest efficiency was observed at 17:1 air-fuel ratio. This can be explained as the mixture tends to lean, energy supplied by the combustion per unit time was very low, thereby the time taken to complete the melting will be more which resulted in excess fuel consumption and low efficiency.

The cumulative heat transfer from hot gases to the load directly or indirectly is a function of time. Thermal boundary layer can be offset if the heat transfer could be accomplished within a given flow path with higher velocity which shortens the heat up time to the load. Installed on the fuel line an oscillating combustion valve developed by the author and experimented keeping the conditions same for with and without oscillation combustion experiments. It is found out experimentally that fuel–rich zones produced by oscillating combustion has longer and more luminous flames can breakup the thermal boundary layer around the load and increase the rate of heat transfer. Visual observations of the flames showed fluctuations in the flame’s size were more in the radial than axial direction during the oscillating combustion. This was significant because it is important that the flame’s momentum remain mostly more radial as well axial, which would put it closer to the load in the furnace. The momentum comes from the combustion air and the oscillated fuel flow.

The main conclusions that were drawn based on the experimental results are:

- Low fuel consumption was noticed in oscillating combustion mode.
- Crown temperature of the furnace was reduced thereby reduced temperature stack gases.
- Significantly low melting time for the oscillating mode combustion.
- Increased heat transfer rate to the load thereby less processing time.
- Specific energy consumption was observed to be very low during the oscillating combustion mode.
- It’s a retrofit valve needs no much modifications to employ.
- Visibly apparent clean and reduced flue gas volumes were observed.

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Biographical notes

GVS. Rao graduated in Science and Engineering from Andhra University in 1996 and 1969 respectively. He received his Master's degree (M.E) with Thermal Science as specialization from Regional Engineering College, Warangal in 1972 under Osmania University. He pursued his Doctoral Work and received Ph.D from Indian Institute of Technology, Madras in 1978. He served in Research and Development of Bharat Heavy Electricals Limited (BHEL) and designed, developed combustion system for M.H.D Power generation of a pilot plant, and National Project with participation of BHEL and BARC of DAE. For 23 years in BHEL served in different Engineering areas and R&D. His main areas of interest are combustion, gasification and new energy developments. He has published many articles in various International Journals and Conferences.

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