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# ACTIVE CONTROL OF PERFORMANCE AND $NO_X$ EMISSIONS OF STAGED GASEOUS FUEL BURNER

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## ABSTRACT

Closed loop feedback control is implemented in gaseous fuel staged burner to maintain low $NO_x$ emission. The experimental set-up is a swirl-stabilized, diffusion flame, staged combustion gaseous fuel burner. The emissions of $NO_x$ and carbon dioxide are monitored in real time and controlled as a function of burner load. The control input to the system is the primary and secondary air flow rate. The $NO_x$ emissions and $CO_2$ concentrations are measured through two analyzers near the burner exit plane. This information is conveyed to a computer control system which invokes an optimization algorithm to maintain the low $NO_x$ emissions in addition to high $CO_2$ concentrations which, for fixed overall air/fuel ratio, entails achievement of high combustion efficiency. The success of the control methodology encourages its application on practical systems.

## KEY WORDS

Combustion, pollution, control.

## NOMENCLATURE

$G(s)$ the transfer function
$k$ the gain of the process
$t_0$ the dead time
$\tau$ the time constant

## 1-INTRODUCTION

Nitrogen oxides ($NO_x$) are major pollutants from all fossil-fuel combustion systems. In the combustion of gaseous fuel there are two sources of $NO_x$ emission [1,2]. The first is concerned with the relatively slow Zeldovich mechanism, in which nitrogen is oxidized directly by oxygen to give NO;

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The second is related to the faster Fenimore or 'prompt' mechanism, wherein hydrocarbon radicals such as CH react with nitrogen to give HCN, which in turn is oxidized to NO in a series of steps.

Because of the introduction of legislation aimed at reduction of $NO_x$ emissions [3], methods of minimizing those emissions have received a great deal of attention world-wide in recent years. This has led to the development and commercialization of a number of $NO_x$-reduction methods for industrial combustor [2,3], such as:

I-Injection of ammonia, isocyanic acid or other related compounds into the flue gases, whereby nitrogen oxides are reduced to harmless nitrogen;

II-Catalytic filters, such as those used in car exhausts, where nitrogen oxides are removed by reaction on the surface of a catalytically active pad;

III-Staged addition of fuel and/or air, in which fuel and air are added stagewise in order to control the temperature fields within the combustion chamber, which in turn affects the production of $NO_x$;

IV-Flue gas recirculation, in which a proportion of the combustion products are fed back to the combustion chamber in order to lower the flame temperature and hence the rate of formation of $NO_x$.

All four of these methods work extremely well on industrial-size combustion equipment. However, the first two methods entail high cost and the second two methods reduce combustion efficiency, the continued lowering of combustion zone temperatures and the use of high aeration burners can result in poor combustion performance and consequently increased emissions of CH4 and CO [4-6]. In order to meet ever-increasing regulations, designers must strive to reduce pollutant emissions without reducing combustor performance. Active control techniques have been applied in recent years to reduce pollutant emissions while maintaining high combustion performance over a wide range of operating conditions [7-8]. The present paper reports on a step towards development and application of such methodology. While active techniques are being developed and demonstrated for gas turbine model combustors and traditional research burners, the present paper addresses the practical application of active control to a staged gaseous fuel burner. The current control methodology uses a simple controller mode to achieve the purpose. The performance and emission variables selected for control are $CO_2$ and $NO_x$ respectively.

The objective of the present study is to delineate a strategy for the application of active control technology to staged gaseous fuel burner in order to reduce the $NO_x$ emission while maintaining high level of overall efficiency by reducing the excess air level which causes increased flue gas losses. The present paper is organized as follows. In section 2, the description of experimental burner with fuel and air system has been presented. In section 3, the description of the control scheme, components with controlled and manipulated variables are reported. The parameters of the dynamic response (gain, time constant, and dead time) are presented in section 4. The closed loop response of the controlled variables has been shown in section 5. Conclusion is given in section 6.

## 2-DESCRIPTION OF EXPERIMENTAL BURNER

The combustion device used in this study is a swirl stabilized, diffusion flame, and staged combustion gaseous fuel burner. The experimental burner is shown schematically in Fig. 1. The fuel-rich/fuel lean flame zones are produced by physically separated regions of the combustion chamber (external staging). The fuel gas is introduced through a central jet and the primary air is injected tangential through three pips to an annulus surrounding the fuel pipe, so that double concentric jet is formed. The inner tube has 7.5 cm diameter and 20 cm length and uniform distribution of air pipes around the surface of the outer pipe. The fuel and air are mixed and burned in the first stage, which consists of 10 cm tube diameter and 60 cm length, to produce a rich-fuel diffusion flame. The products of fuel-rich pyrolysis zone are then burned with the rest of the air in the second combustion chamber (second stage). The second combustion chamber consists of a 13 cm diameter tube and 8 cm length. The flow continues through 21 cm diameter by 260 cm cylindrical furnace section. Similar to the primary air induction mentioned above, the secondary air is introduced through other three pipes, uniformly distributed around the outer surface of the combustor. The primary and secondary air is given a 0.33 swirl number to enhance the jet and flame mixing characteristics. The secondary air swirl leads to a pronounced improvement in the stability of flame and leads to a reduction in the flame length.

The air is supplied to the burner (first and second stage ) from two blowers. The output of each blower terminates with a distributor plate containing three ports, which are connected with corresponding three ports on each stage of the burner. The air flow rate in each blower is measured by an orifice plate with differential pressure manometer. In order to control the air flow rate in each stage, two butterfly valves are mounted on the entrance of blower tubes.

## 3-CONTROL SCHEME

The approach for control scheme consists of the following steps:. 1)use suitable sensors to measure $NO_x$ and $CO_2$ concentrations, 2)select a convenient burner input parameters that have important influence on burner performance and are amenable to control, 3)establish a simple closed-loop control strategy that would transform measurements of sensors into action by the burner input parameters, 4)implement the control strategy in real time.

The $CO_2$ infra-red analyzer and Beckman $NO_x$ analyzer are used to measure the $CO_2$ and $NO_x$ emissions. For controlling the performance of the burner and the $NO_x$ emissions, a number of options are available. The primary and secondary air are selected as a control input to the burner. The air flow rates are amenable to direct control, and the performance of the burner and $NO_x$ emission have been found to be highly dependent on these parameters, according to several simulation studies [2].

The implementation of the control strategy consists of mounting the sampling probe on certain port near the burner exit plane, igniting the burner at the given load, and transmitting the measured information from the sensors to the control computer. The computer in turn invoked an optimization routine to determine the air flow rates which minimize $NO_x$ and maximize $CO_2$ emissions. The sensors continually monitor the performance of the burner, and the air flow rates are adjusted as necessary to achieve and maintain the desired operating conditions. The control system consists of: 1) sensors, 2)actuators, and 3)computer with data acquisition system. The schematic diagram of the control scheme is shown in Fig. 2. In this figure, the burner is the object under control (plant). The controller is a feedback mechanism consisting of the emissions sampling equipment (sensors), the actuators, a data acquisition system. All of which are integrated into an 80386-based personal computer.

*Sensors*

The $NO_x$ concentration is measured with $NO_x$ analyzer, and the $CO_2$ concentration with infra-red analyzer. The sampling of gases for the measurement of $CO_2$ and $NO_x$ is achieved by means of a water-cooled stainless-steel probe. The collected gases are analyzed in real-time processing.

*Actuator*

The actuator is the device, which can adjust the control input burner parameters according to the computer orders. There are two actuators; one for each blower entrance. The actuator consists of: 1) a butterfly valve to change the air flow rate according to requirement. The driven shaft of the butterfly is coupled to a DC motor. A potentiometer is installed in the driven shaft to measure the open angle of the butterfly valve, 2)DC motor to move the butterfly valve, and 3)electronic circuit to drive the DC motor. The developed circuit passes the computer commands to the DC motor to adjust the butterfly valve in the required direction, which consequently provides the suitable air flow rate.

## 4-CHARACTERIZATION OF THE DYNAMIC RESPONSE OF THE PROCESS FROM OPEN LOOP STEP TEST

The purpose of the open loop test is to determine the transfer function of the process (the relation between the process output variables and its input variables). The process output variables are the $NO_x$ and $CO_2$, and the process input variables are the primary and secondary air which have strong effect on the output variables.

Open-loop tests have been carried out by causing a step change in the process input, primary and secondary air, and recording the resulting response of the transmitters signal, $NO_x$ and $CO_2$. The parameters that can be estimated from the results of a step test are the process gain, the time constant and the dead time. Most controller methods require these three parameters [9].

The steady state gain or, simply, gain is one of the most important parameters that characterize a process. It is a measure of the sensitivity of the process output to changes in its input:
$K$= change in output / change in input

a

## 4.1-Estimation Of Dead Time And Time Constant

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Time constant and dead time are measures of the process dynamic response. The two point method has been used to estimate these parameters because it does not require the drawing of the tangent line. In this method it is necessary to determine the point at which the step response reaches 63.2% of its total steady-state change, and the point at which the step response reaches 28.3% of its total steady-state change. The two points chosen by Smith result in the following simple estimation formulae for the time constant $\tau$ and dead time $t_o$ [9]:

$$\tau=1.5(t_1-t_2) \qquad (1)$$

$$t_o=t_1-\tau \qquad (2)$$

The time response of the process, which is obtained due to a step change in the inputs, has been shown in Figs. 3 and 4. Fig. 3 shows a step change in butterfly valve of the "angle$_2$" secondary air, the $NO_x$ emissions and $CO_2$ increase as the open angle of the butterfly valve$_2$ (degree of staging) decreases. The step change in the angle$_1$ (primary air) is shown in Fig. 4, the variation of $CO_2$ is larger than $NO_x$, hence $CO_2$ is more affected by primary air than $NO_x$. The small oscillations of the input angles does not appear on the output response. The values of dead time $t_o$, time constant $\tau$, gain $k$ are tabulated in table 1, together with the corresponding numbers of the figures from which these values are deduced.

Table 1. Parameters of the process.

| Fig. No. | Transmitter | $\tau$ | $t_o$ | $k$ |
|---|---|---|---|---|
| 3 | $CO_2$ | 7.5 | 15.5 | 1.1 |
| | $NO_x$ | 6.4 | 19.2 | 1.74 |
| 4 | $CO_2$ | 10 | 18.9 | 1.8 |
| | $NO_x$ | 8 | 18.7 | 1.2 |

The process constants vary from step test to another due to the nonlinearity in the process. The relatively long dead time is due to the length of the suction pipes of the sampling probe and connections and the long time required for the transmitters ($CO_2$, $NO_x$ analyzer) to analyze the sample. Notice that the gain of the process is negative.

## 4.2-Transfer Function

The transfer function of the open loop (process, actuators and transmitters) has the following form:

$$G(s)=\frac{ke^{-t_0 s}}{1+\tau s} \qquad (3)$$

where $k$ is the gain of the process

$t_0$ the dead time

$\tau$ the time constant

The varying nature of these parameters, as shown in table 1, assures the process nonlinearity.

## 5-CLOSED LOOP SYSTEM

Proportional controller is initially proposed to each controlled variable. Extensive closed-loop study has been performed to show how the disturbance affects the performance. The $CO_2$ variation as the process is exposed to a disturbance from fuel is shown in Fig. 5. The set point of $CO_2$ is 3.8, after the disturbance the $CO_2$ adjustment is achieved by trimming the primary air ratio. The butterfly valve$_1$ will be opened wider or closed tighter to bring down or to raise the $CO_2$ to its desired set point. Fig. 6 shows the $CO_2$ variation for a set point 4.2 and disturbance from secondary air. Steady-state error needs to be minimized.

Controlling the $NO_x$ emissions is achieved by turning the butterfly valve$_2$ (secondary air). When the measured value of $NO_x$ is higher than the set point the butterfly valve$_2$ will be opened wider to bring down the $NO_x$ emissions to its desired value. Otherwise the butterfly valve$_2$ will be closed tighter to raise the $NO_x$ emissions. The $NO_x$ emissions as exposed to disturbance from fuel with set point 50 ppm is shown in fig. 7, and for disturbance from primary air with set point 45 ppm is shown in fig. 8.

## 6-CONCLUSION

An active control strategy for minimizing $NO_x$ emissions as a source of pollution and maximizing $CO_2$ as a measure of excess air decreasing in gaseous fuel staged burner has been delineated. This strategy utilizes the primary and secondary air as control inputs and provides feedback to the control loop by measuring the $CO_2$ and $NO_x$ near the burner exit plane. The results show that the active control provides the potential to achieve and maintain the desired operating conditions of the burner by trimming the excess air and reducing the $NO_x$ emissions. Nonlinear process behaviour hinders controller tuning. Nonlinear control strategy would enhance closed-loop performance.

The paper focuses on the preparation of the experimental setup and provides it with acceptable measurement system. The closed-loop control strategy is implemented initially by proportional controller to test the overall system performance. The control system will be developed to advanced type in the following stage.

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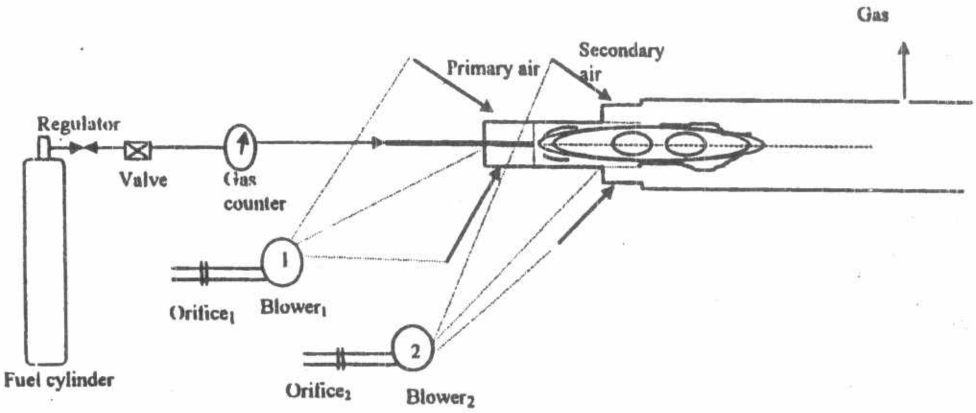
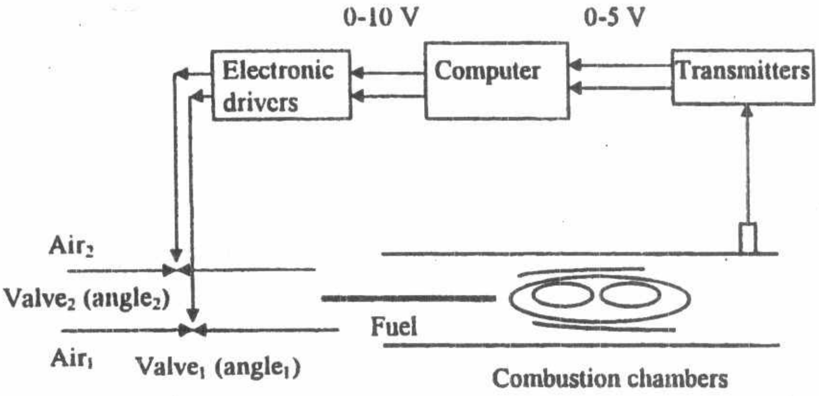


Figure (1). Schematic diagram of the test rig.



Figure( 2). Schematic diagram of the active control scheme

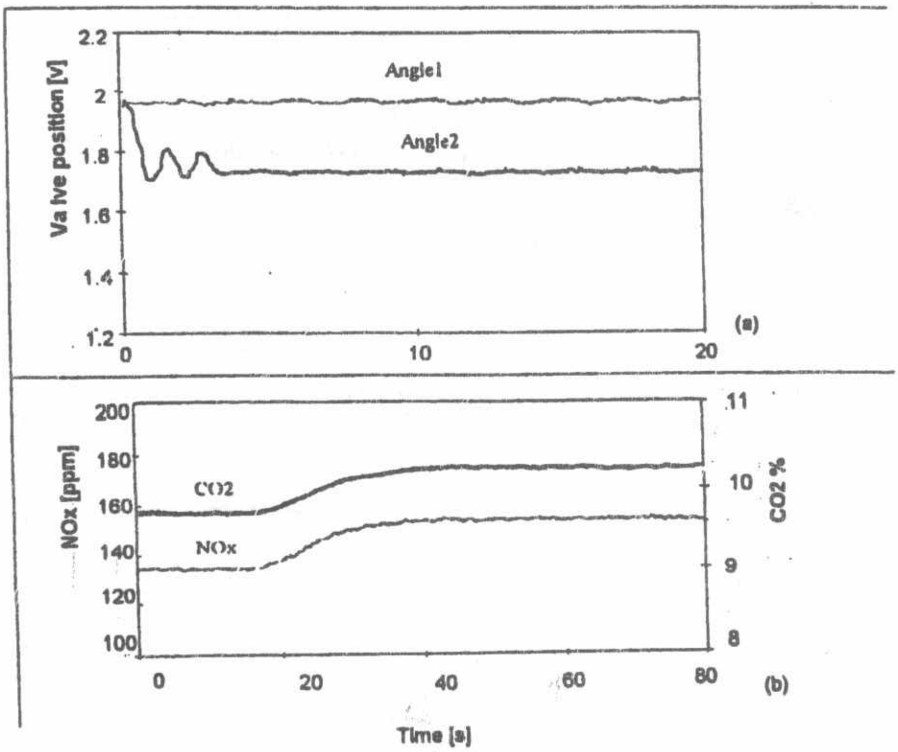


Fig.3. a-Negative step change in the valve$_2$ position with 2 kg/h fuel, b-Time response of $NO_x$ and $CO_2$ as exposed to negative step change which decreases the secondary air.

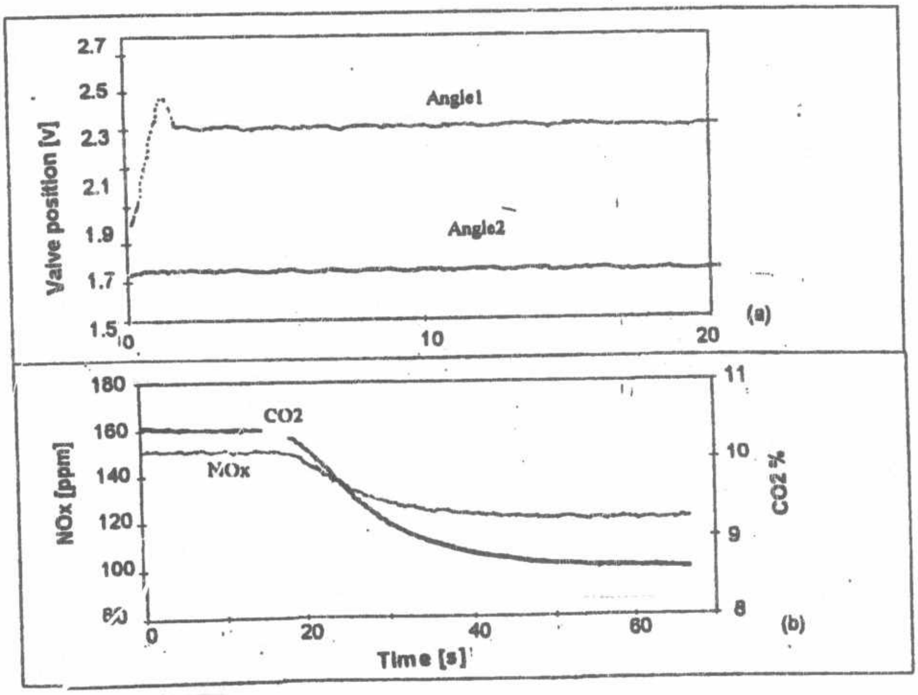


Fig. 4. a-Positive step change in the valve$_1$ position with 2 kg/h fuel, b- Time response of $NO_x$ and $CO_2$ as exposed to positive step change which increases the primary air.

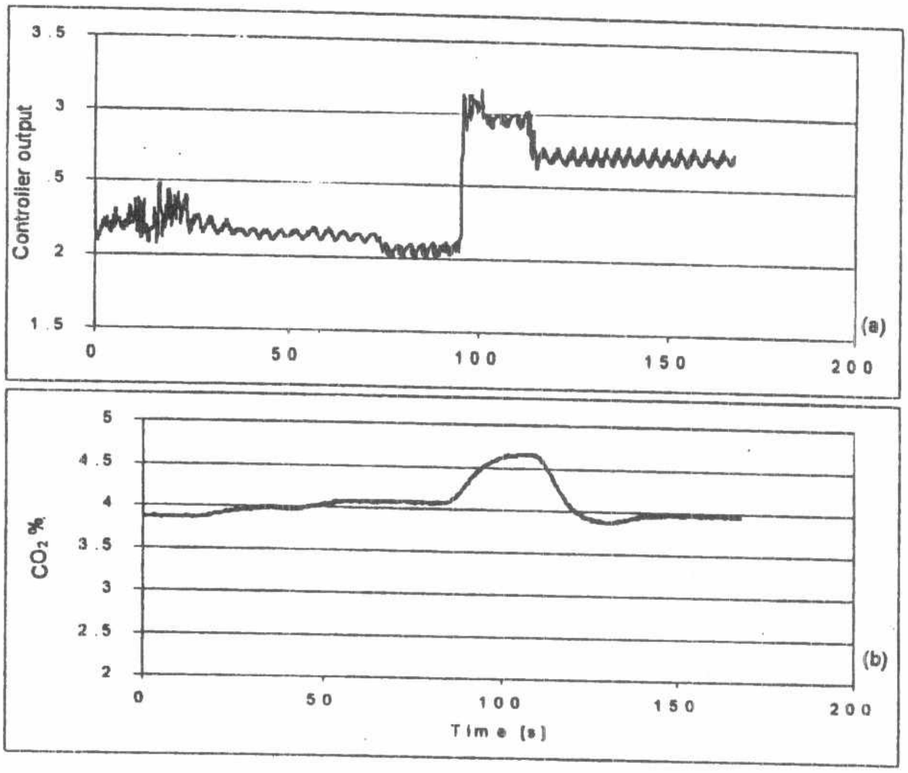


Fig.5. Closed-loop rejection of fuel disturbance, a-Controller output; b- $CO_2$ response (set point=3.8)

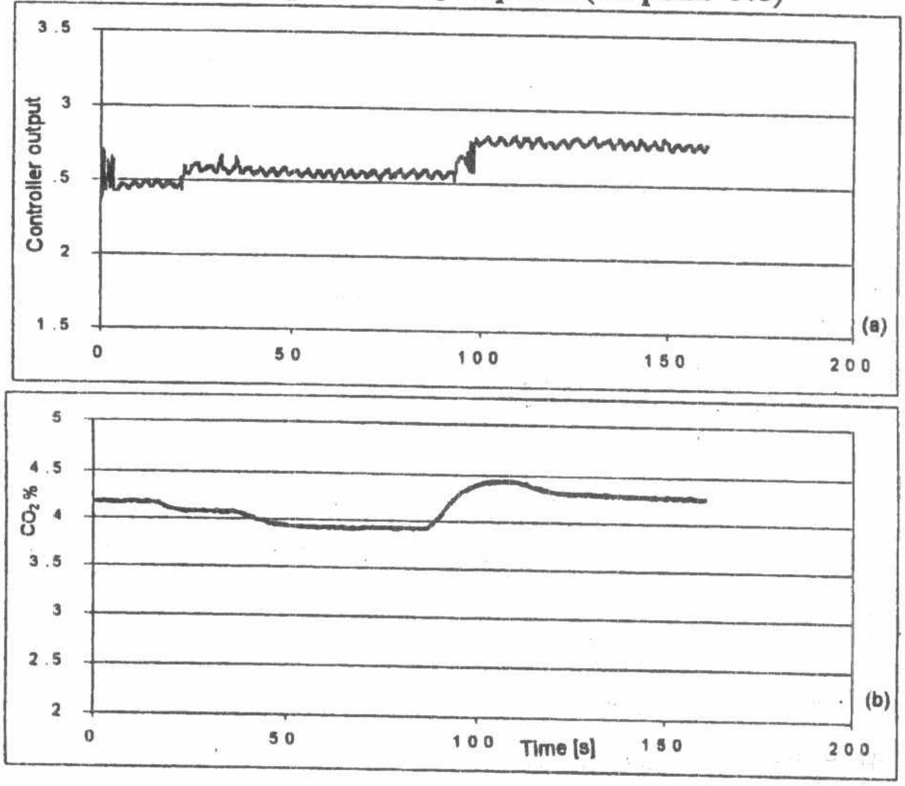


Fig. 6. Closed-loop rejection of secondary air disturbance, a-Controller output; b- $CO_2$ response (set point=4.2)

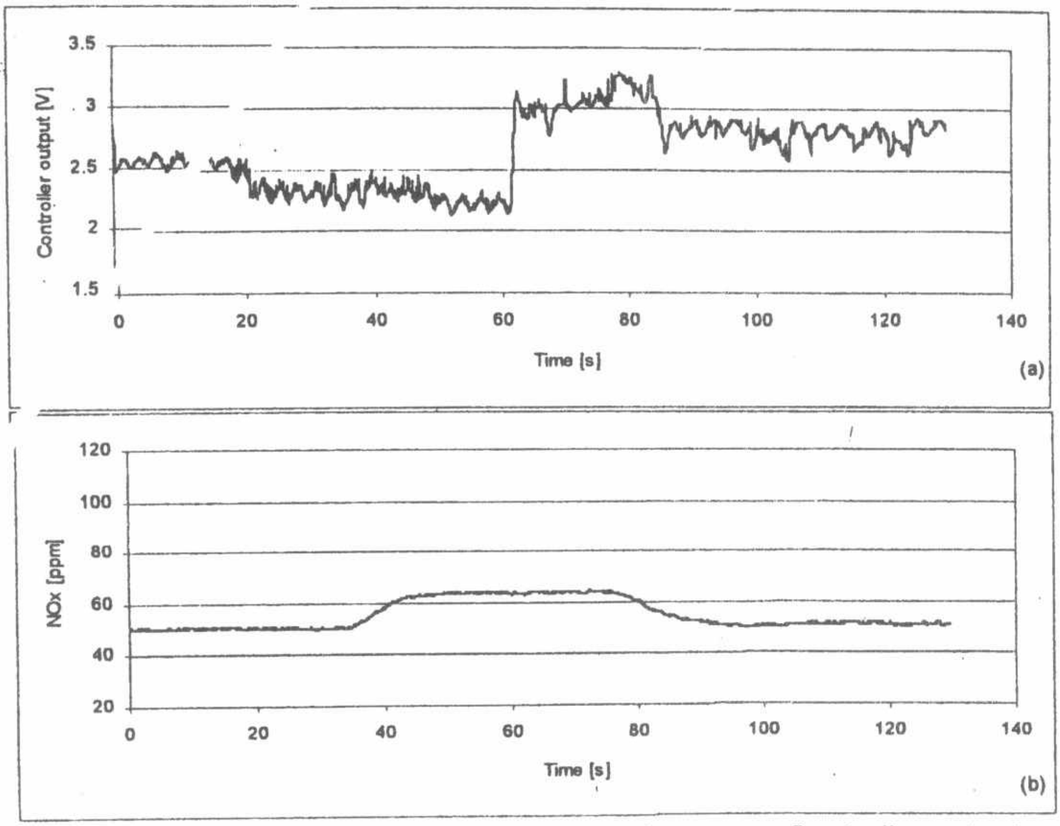


Fig. 7. Closed-loop rejection of fuel disturbance, a-Controller output; b-$NO_x$ response (set point=50 ppm)

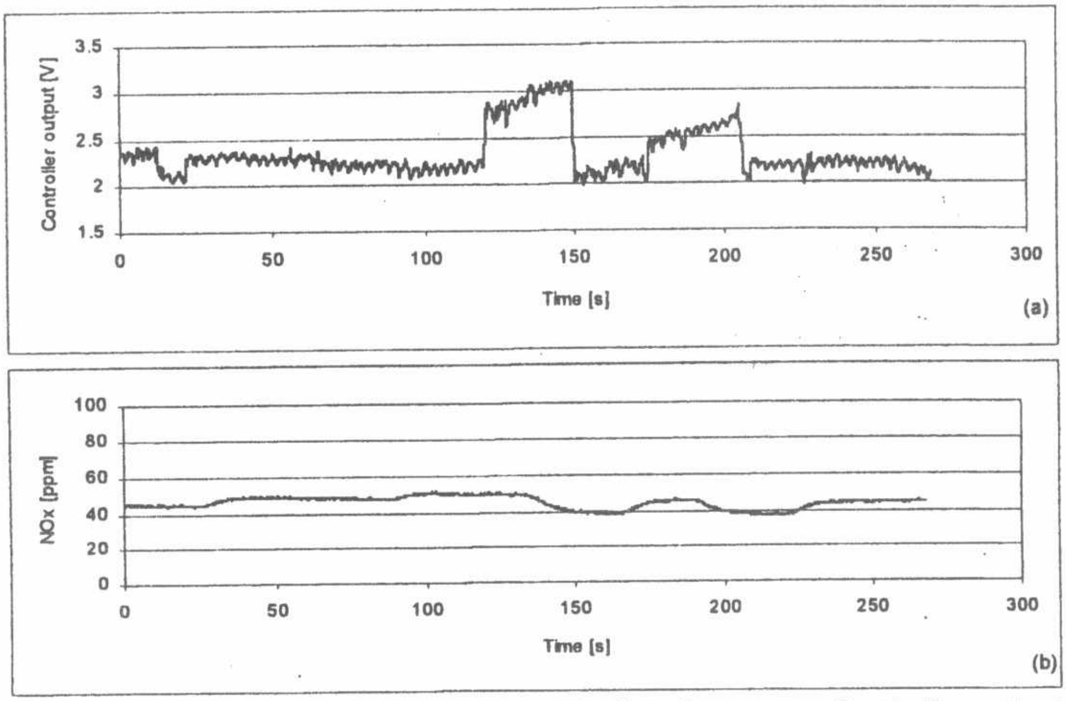


Fig. 8. Closed-loop rejection of primary air disturbance, a-Controller output; b-$NO_x$ response (set point=45 ppm)