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# INFLUENCE OF RECIRCULATION RATE ON CO AND NO EMISSION IN HTAC COMBUSTION TECHNOLOGY WITH NATURAL GAS

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## WPŁYW STOPNIA RECYRKULACJI NA EMISJĘ CO I NO PODCZAS SPALANIA GAZU W TECHNOLOGII HTAC

Technologia HTAC (High Temperature Air Combustion) jest jednym z najważniejszych osiągnięć w technice spalania w ostatnich latach. Jej ideą jest taka organizacja procesu spalania, aby reakcja zachodziła w całej objętości komory spalania przy wyrównanych profilach temperatury i koncentracji. Może to być zrealizowane poprzez podgrzanie powietrza powyżej temperatury zapłonu paliwa, oddzielenie dysz powietrza i paliwa i wysoką recyrkulację spalin wewnątrz komory spalania. Wyrównana i umiarkowana temperatura we wnętrzu komory pozwala na osiągnięcie niskiej emisji NO a z drugiej strony dostatecznie długi czas pobytu owocuje niską emisją CO. W niniejszej pracy autorzy przedstawiają model matematyczny pozwalający ilościowo ująć wpływ temperatury powietrza oraz stopnia recyrkulacji na końcowa emisję NO i CO.

## Summary

HTAC (High Temperature Air Combustion) technology is one of the most important achievements in combustion engineering of recent years. The main idea of the technology is to organize combustion in such a way that reaction takes place in almost whole volume of combustion chamber with very uniform gas and temperature field. It can be done by preheating air above the ignition temperature of fuel, separation of air and fuel nozzles and by high recirculation inside the combustion chamber. Uniform and moderated temperatures result in very low thermal NO emission, and on the other hand, long enough residence time in the chamber results in low CO and incomplete products emission. In this paper authors present simple mathematical model which allows for estimation of influence of air temperature and flue gas recirculation rate on final emission on NO and CO.

## INTRODUCTION

Combustion has been the main source of primary energy from the beginning of our civilization. It is forecasted that this will not change in the nearest future. On the other hand, combustion is the main source of environmental pollution. For these reasons it is very important to develop combustion technologies which provide high energy efficiency and low toxic compounds emission [1].

Fuels are used for fueling industrial furnaces in ceramic, glass and metallurgy industry. In industrial furnace energy of combustion gases is transferred, by radiation, to a load having temperature of hundreds Celsius's. In order to achieve high enough radiation fluxes gas temperature has to be significantly higher than temperature of load. As an effect flue gases, at the exit of chamber, have temperature about thousand of Celsius and as a consequence energy efficiency is lower than 50%.

HTAC (High Temperature Air Combustion) technology is a new technology discovered in recent years. The main idea of it is to organize combustion in such a way that reaction takes place in whole volume of combustion chamber with very uniform temperature and concentration fields. This can be achieved in an installation presented in Fig. 1. Flue gas (2) and high temperature are used for heating combustion air (3) to the temperature exceeding self ignition. Fuel and air are supplied separately which allows to mix air with recirculating gases before mixing it with fuel. Combustion takes place in diluted air which results in flat temperature profiles, with maximum temperature not exceeding 1400°C which prevents NO formation [10].

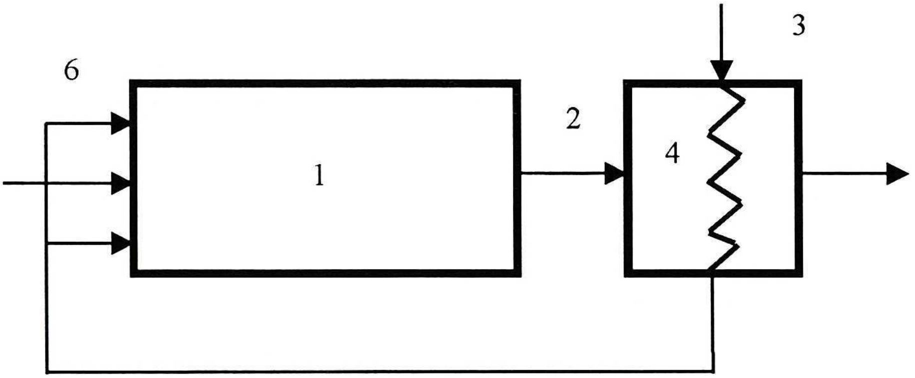

Fig. 1. Scheme of the HTAC technology
1 – combustion chamber, 2 – flue gas, 3 – fresh combustion air, 4 – heat exchanger, 5 – flue gases exhaust, 6 – fuel and air supply

HTAC technology gives very low both NO and CO emissions. Low NO emission is achieved as a result of moderated temperature, while CO emission is decreased by long residence time in the reaction zone. Moreover, large volume of radiating gas results in high radiative heat fluxes [7].

## MATHEMATICAL MODEL

Combustion is a very complicated phenomenon in which simultaneously heat and mass transfer, diffusion, chemical reaction and other processes take place. For this reason usually simplifying assumptions are made in order to create mathematical and numerical description of the process [4–6, 10]. Moreover, some of the base processes are not well understood, as for example interaction of chemical reaction and turbulence.

Mathematical modeling of HTAC is in its early stage of development since the technology itself is very new. Therefore, almost all of achieved progress was done by experimental investigations [2, 3, 6].

Authors of the present paper created a simple, zero-dimensional model which is illustrated in Fig. 2. Fuel (1) and air (2) are supplied to combustion chamber where reaction takes place. In the model single cell of gas (5) is analyzed while it flows along combustion chamber. Initially in the cell there is pure air. Air in this cell mixes with recirculating flue gases (4) and fuel (1) and simultaneously heat from the cell is transferred to chamber's walls. Equations of the model describe changes of temperature and composition of gas in the cell as functions of time. It is assumed that flue gases ($\dot{m}_s$[kg/s]) and fuel ($\dot{m}_p$[kg/s]) flow rates are known functions of time and those gases can be treated as semi-ideal. Described cell is analyzed in known period of time $\tau_c$, which is the time needed for this cell to flow through whole length of combustion chamber.

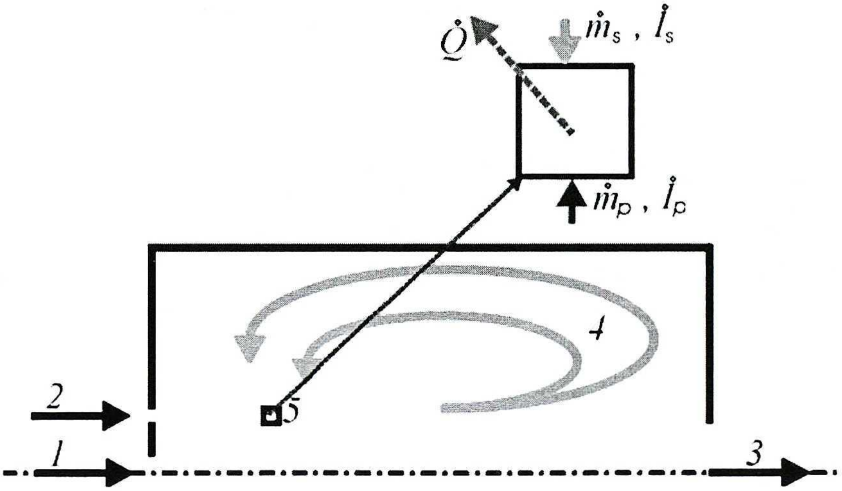

Fig. 2. Scheme of the analyzed system
1 – fuel supply, 2 – air supply, 3 – flue gases outlet, 5 – analyzed cell of air

Total amount of flue gases $m_s$ delivered to the analyzed cell can be expressed as:

$$m_s = \int_0^{\tau_c} \dot{m}_s \, d\tau \tag{1}$$

where: $m_s$ – total amount of flue gases [kg],
$\dot{m}_s$ – flue gases flow rate [kg/s],
$\tau_c$ – total time of the combustion [s].

Total amount of fuel delivered to the cell $m_p$ [kg/s] can be calculated as:

$$m_p = \int_0^{\tau_c} \dot{m}_p \, d\tau \tag{2}$$

where: $m_p$ – total amount of delivered fuel [kg],
$\dot{m}_p$ – fuel flow rate [kg/s].

Denoting initial mass of air in the cell as $m_a$ recirculation rate $r_s$ can be defined as:

$$r_s = \frac{m_s}{m_a} \tag{3}$$

Final air excess ratio $\lambda$ can be calculated as:

$$\lambda = \frac{m_a}{m_p \; m_{a\,\min}} \tag{4}$$

where $m_{amin}$ denotes stoichiometric air ratio [$kg_{air}/kg_{fuel}$]

Total mass of the analyzed cell $m$ increases as flue gas and fuel is supplied, which can be expressed by following equation:

$$\frac{dm}{d\tau} = \dot{m}_s + \dot{m}_p \tag{5}$$

In combustion processes mass balances should be written not only for total mass but also for each compound separately. Mass of i-th compound (which can be expressed as $mg_i$, where $g_i$ denotes mass fraction of this compound) varies due to the flue gas and fuel delivered to the cell and due to the chemical reactions taking place in the cell. Denoting flue gas and fuel composition as $g_s$ and $g_p$ mass balance of i-th compound can be written as follow:

$$\frac{d(mg_i)}{d\tau} = \dot{m}_s g_{i,s} + \dot{m}_p g_{i,p} + \dot{\omega}_i V M_i \tag{6}$$

where: $V$ – volume of the cell [$m^3$],
$M_i$ – molecular weight of i-th compound [kg/kmol],
$g_{si}$ – mass fraction of i-th compound in recirculating gases,
$g_{pi}$ – mass fraction of i-th compound in fuel,
$\dot{\omega}_i$ – reaction rate [kmol/($m^3$s)] calculated on the base of chemical reaction scheme.

Equation (6) can be transformed to the following form:

$$m\frac{dg_i}{d\tau}+g_i\frac{dm}{d\tau}=\dot{m}_s g_{i,s}+\dot{m}_p g_{i,p}+\dot{\omega}_i VM_i \tag{7}$$

Introducing (5) to (7) gives following equation:

$$m\frac{dg_i}{d\tau}+g_i(\dot{m}_s+\dot{m}_p)=\dot{m}_s\, g_{i,s}+\dot{m}_p\, g_{i,p}+\dot{\omega}_i VM_i \tag{8}$$

Simple algebraic transformation of (8) leads to final form:

$$\frac{dg_i}{d\tau}=\frac{\dot{m}_s}{m}(g_{i,s}-g_i)+\frac{\dot{m}_p}{m}(g_{i,p}-g_i)+\frac{\dot{\omega}_i VM_i}{m} \tag{9}$$

Equation (9) can be written for each compound taking place in chemical reactions. It describes changes of mass fractions of compounds in time.

Next equation describing analyzed cell is energy balance which can be written as follows:

$$\frac{dI}{d\tau}=\dot{I}_s+\dot{I}_p-\dot{Q} \tag{10}$$

where: $I$ – enthalpy of analyzed cell [J],
$\dot{I}_s$ – enthalpy of flue gases [J/s],
$\dot{I}_p$ – enthalpy of fuel (total) [J/s],
$\dot{Q}$ – heat flux transferred from the cell [W].

Taking into account that for ideal mixtures $I=\sum g_i i_i$ equation (10) can be written as:

$$\frac{d(m\sum g_i i_i)}{d\tau}=\dot{m}_s\sum g_{i,s}i_{i,s}+\dot{m}_p\sum g_{i,p}i_{i,p}-\dot{Q} \tag{11}$$

which can be transformed to the form:

$$m\frac{d(\sum i_i g_i)}{d\tau}+\sum i_i g_i\frac{dm}{d\tau}=\dot{m}_s\sum g_{i,s}i_{i,s}+\dot{m}_p\sum g_{i,p}i_{i,p}-\dot{Q} \tag{12}$$

After introducing (5) to (12) and performing algebraic transformations energy balance can be finally written as:

$$\frac{dT}{d\tau}\sum g_i c_{p,i}=\frac{\dot{m}_s}{m}(\sum g_{i,s}i_{i,s}-\sum g_i i_i)+\frac{\dot{m}_p}{m}(\sum g_{i,p}i_{i,p}-\sum g_i i_i)-\frac{\dot{Q}}{m}-\sum i_i\frac{dg_i}{d\tau} \tag{13}$$

This equation can be used for calculating changes of temperature in analyzed cell as a function of time.

It was assumed that heat transfer is done by means of radiation and in such case heat losses can $\dot{Q}$ be written as

$$\dot{Q} = A(T^4 - T_w^4) \tag{14}$$

where $T_w$ denotes temperature of walls to which radiation flux is transferred.

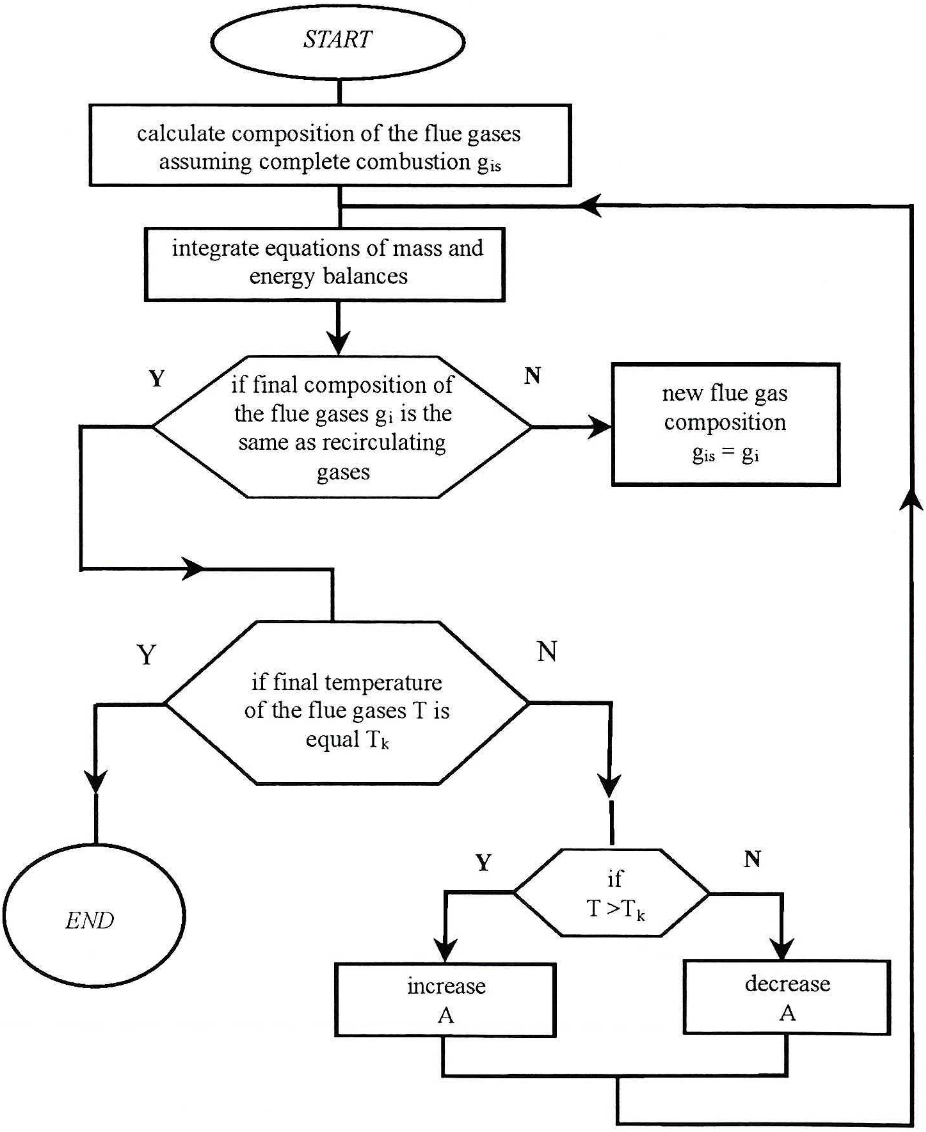

Fig. 3. Computer program flowchart

Unknown coefficient A can be iteratively calculated basing on the assumption that exit temperature of flue gases is known. In real industrial furnaces this coefficient, describing heat transfer inside the chamber, depends on geometry and temperatures of furnace, but gas temperature of flue gases is usually assumed while designing of furnace [9].

The program has to perform two nested, iterative loops. One for iterative calculation of the coefficient A from equation (14) and second for determining composition of flue gases. This is presented in Fig. 3.

## EXAMPLE RESULTS OF CALCULATIONS

It was assumed that flue gases and fuel mass fluxes are given functions of time. These functions are presented in Fig. 4. Such shape of recirculation and fuel delivery are based on the observation of real system [10].

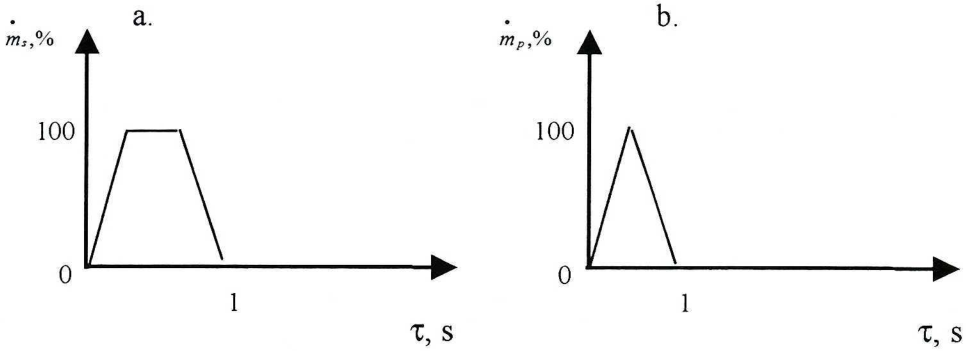

Fig. 4. Assumed, relative mass fluxes of recirculation gases (Fig. a) and fuel (Fig. b) as functions of time

It was assumed that system is fueled with methane. Chemical kinetic scheme of methane was taken from [9].

In Figs 5–8 there are shown final concentrations of CO and NO as functions of recirculation rate for various temperatures of combustion air. It can be observed that independently of temperature, CO and NO rise with decreasing recirculation rate, but the dependence of NO on recirculation rate is far more evident. Below $r = 5$ both NO and CO remain at almost constant level.

Figs 9 and 10 present final NO and CO concentrations as functions of temperature for various recirculation ratios. It can be observed that an increase of temperature results in higher CO concentrations, while recirculation rate has almost no influence on it. This can be explained by dissociation process of $CO_2$ caused by temperature. Thus CO concentration is affected mainly by the final temperature of flue gases.

While gas combustion NO is mainly formed via thermal mechanism and therefore Fig. 10 should be analyzed from the point of view of maximal in-flame temperature. It can be observed that increase of temperature leads to growth of NO concentration since the higher air temperature the higher flame temperature. It can be also observed that in the case of high recirculation rate ($r = 5$) the dependence is rather weak which means that if recirculation is high enough air temperature can be increased without increasing of final NO concentration.

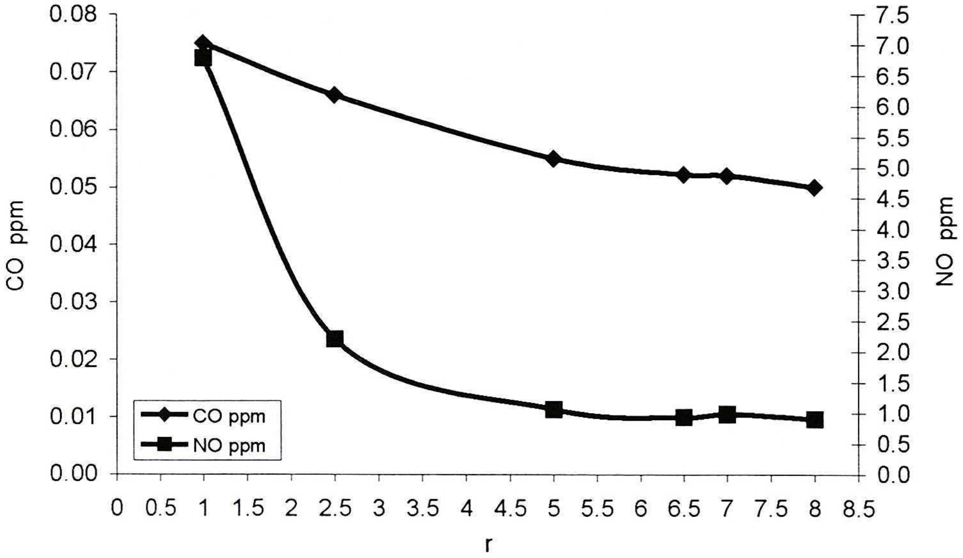

Fig. 5. Calculated final CO and NO concentrations as functions of recirculation rate *r* for air temperature 1050K

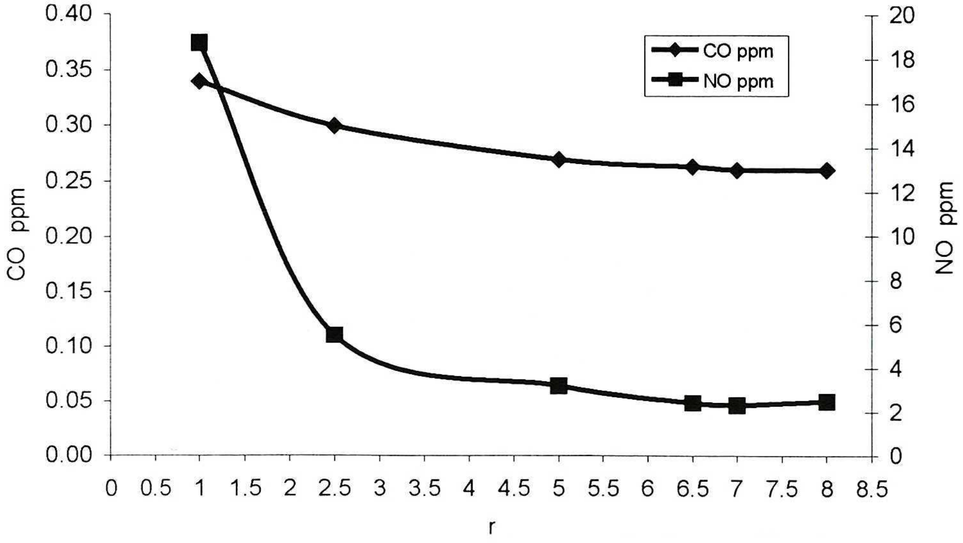

Fig. 6. Calculated final CO and NO concentrations as functions of recirculation rate *r* for air temperature 1150K

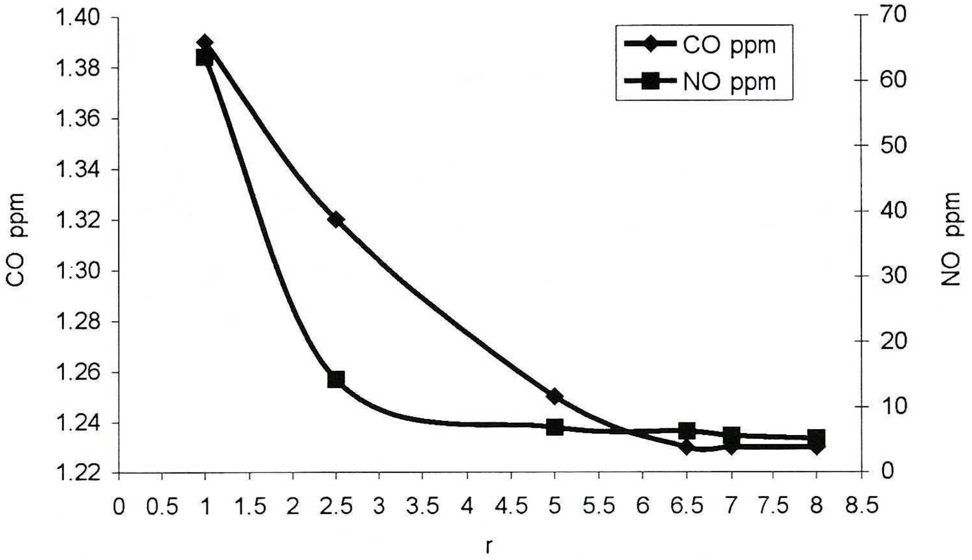

Fig. 7. Calculated final CO and NO concentrations as functions of recirculation rate *r* for air temperature 1250K

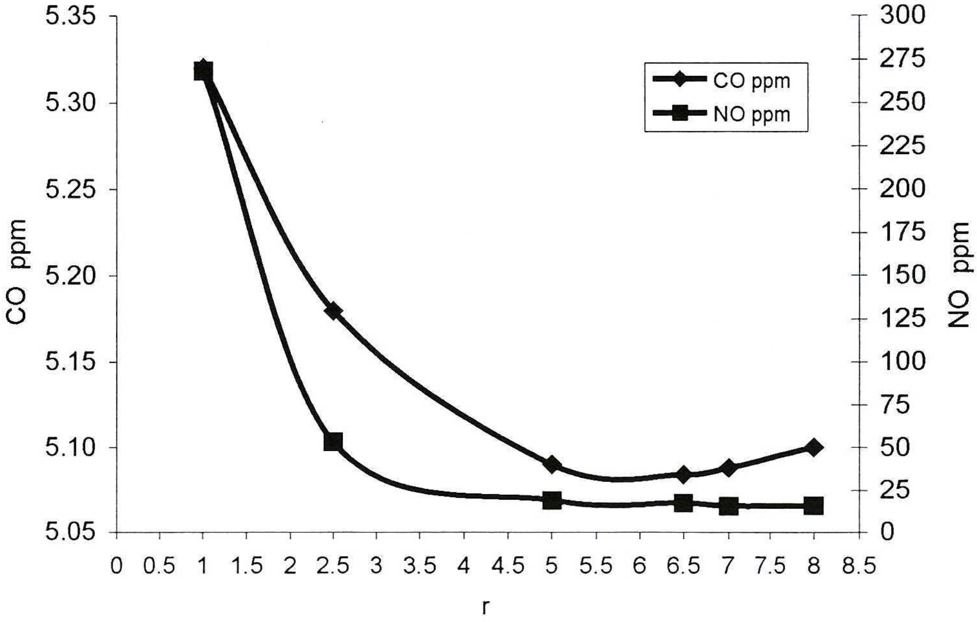

Fig. 8. Calculated final CO and NO concentrations as functions of recirculation rate *r* for air temperature 1350K

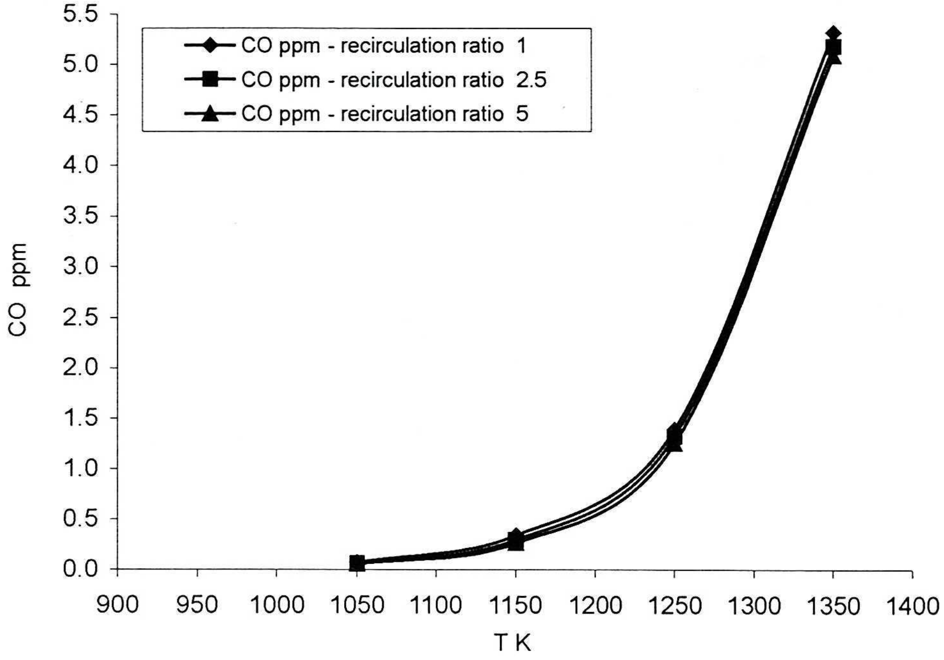

Fig. 9. Final CO concentration as a function of air temperature

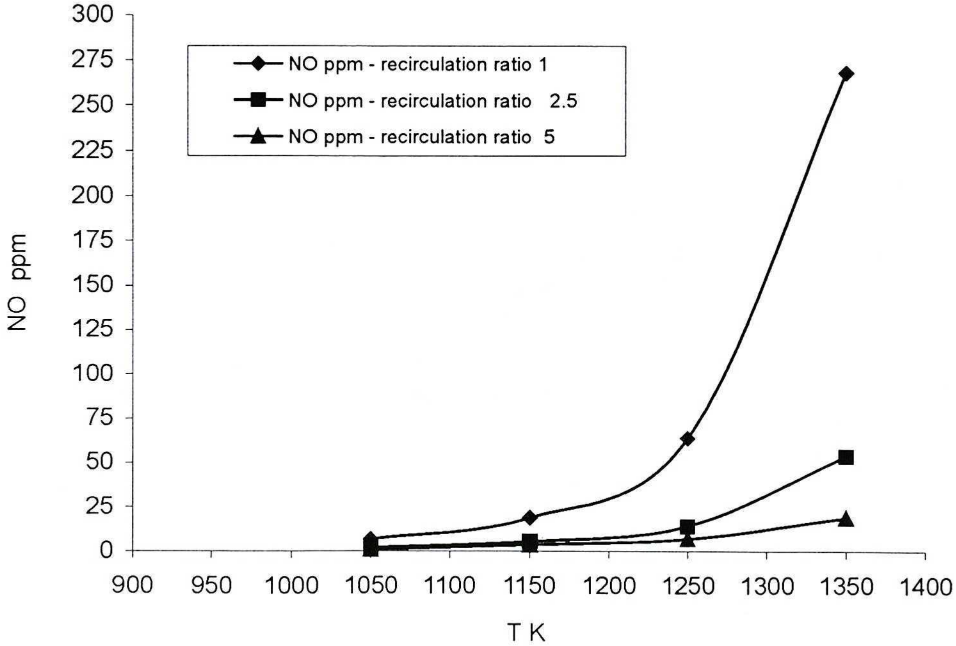

Fig. 10. Final NO concentration as a function of air temperature

This is the same result as observed in measurements of FLOX burner which were presented in [8, 11].

## CONCLUSIONS

The presented calculations indicate that recirculation ration of flue gases in HTAC technology affects significantly final NO and CO concentrations. What is very important is the fact that in the case of high enough recirculation air temperature can be increased without increasing of final NO emission. This conclusion has very important practical meaning because it proves that it is possible to increase energy efficiency of industrial furnaces without increasing NO emission.

In the case of CO the influence of recirculation rate is rather weak and temperature is the main parameter which affects its concentration. This is because in gas combustion temperatures are high enough to ensure complete combustion and final concentration is a function of dissociation.

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