

Modeling of combustion of gas oil and natural gas in a furnace: Comparison of combustion characteristics



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ABSTRACT

This paper deals with a furnace which its fuel (gas oil) is replaced by natural gas in such a way that the flue gas temperature and the rate of heat removal from the furnace are remained unchanged. The question now is: what are the benefits due to replacement of the fuel of the furnace? The objective of this work is to answer this question. Modeling the furnace similar to a continuous flow stirred-tank reactor, the computational results show that the production of NO for equivalent natural gas is considerably less than that for gas oil. It is also obtained that the production rates of CO₂ for both gas oil and natural gas are approximately close together. Considerable cost reduction is obtained by using natural gas in gas oil furnaces.

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1. Introduction

Energy forecasting is an important task of immense value for predicting the future development and implementation of energy technologies [1]; see for example [2–7]. This paper deals with the simulation of a furnace which its fuel (gas oil) is replaced by natural gas in such a way that the flue gas (furnace exit gas) temperature and the rate of heat removal from the furnace are remained unchanged. The question now is: what are the benefits due to replacement of the fuel of the furnace? The main aim of this study is to answer this question.

When we speak of “benefits”, we mean lowering the energy cost of the furnace (economic evaluation) and reducing production of CO₂ and NO_x (environmental evaluation) [8,9]. The primary greenhouse gas emitted through fuel is CO₂, which is a stable molecule with less than 10 years average residence time, i.e. 3 years in the troposphere, though its residence time is over 100 years in the atmosphere, and its present concentration in the atmosphere is increasing at an astonishing rate of 0.4% per year [10]. On the other hand, NO_x (as a generic term for NO and NO₂) causes a wide variety of health and environmental impacts (e.g. acid rain).

Indeed, modeling the furnace, we want to compare the amounts of CO₂ and NO_x produced by gas oil and equivalent natural gas, also the energy costs due to both fuels will be compared. It has been conventional to predict the combustion phenomena via CFD (Computational Fluid Dynamics) where the governing mass, momentum and energy equations have been solved at the microscopic level, see for example [11–20], in which what is happening to the fluid mixture in a small region within the equipment has been examined [21]. This approach has become an important design tool to help the engineers to optimize the operating conditions and reduce pollution emission, however, CFD models tend to be really complicated to build, require significant computing facilities and are time consuming [22]. In the present study, we consider the furnace similar to the continuous flow stirred-tank reactor (CSTR) where the output concentration and temperature are identical to the concentration and temperature of the material inside the furnace [23]. As we shall see in the next section, transport phenomena are studied here at the macroscopic level leading to the problem with less computational effort. At the macroscopic level we write down a set of equations called the “macroscopic balance”, which describe how the mass, momentum and energy in the system change because of the introduction and removal of these entities via the entering and leaving streams and no attempt is made to understand all the details of the system, which leads to a global assessment of the problem [21]. In other words, at the microscopic level we deal

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with conservation laws as differential equations which must be solved simultaneously while at the macroscopic level the conservation laws often lead to a set of simultaneous algebraic equations (for steady state systems) that can be solved with considerable saving in computing and storage.

This paper is structured as follows. Modeling assumptions and solution method to obtain equivalent natural gas are first detailed in section 2. Simulation results are presented and discussed in Section 3. Finally, a summary of main conclusions are given in Section 4.

2. Method

Two inlet streams including gas oil and air enter the furnace, as shown in Fig. 1, with the same temperature (298 K). The combustion process carried out at constant pressure (1 atm) is similar to the continuous flow stirred-tank reactor (CSTR) in which the furnace is run at steady state with continuous flow of feed streams and flue gas. The chemical formula of gas oil is considered as $C_{12.9}H_{23.9}$ [24]. Also, input air is assumed as a mixture containing 79 mole % N_2 and 21 mole % O_2 . Various compositions for natural gas may be considered, here, we assume a mixture of 92 mole % CH_4 , 3 mole % C_2H_6 , 1 mole % CO_2 and 4 mole % N_2 .

2.1. Assumptions of flue gas (furnace outlet)

1) ideal gas behavior 2) includes 10 species (CO_2 , CO , O_2 , H_2O , H_2 , OH , H , O , N_2 , NO) 3) the species of flue gas are in thermodynamic equilibrium with one another and six equilibrium equations are considered for them as follows [25,26]:

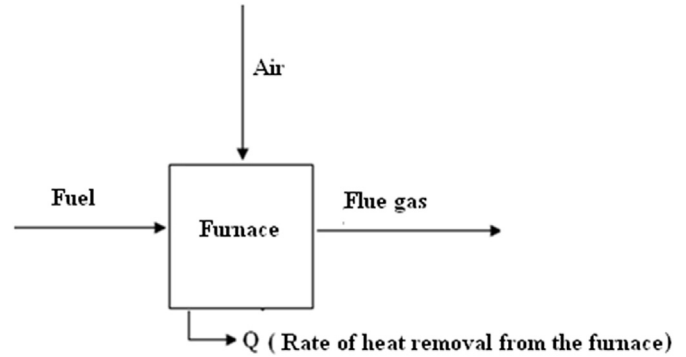
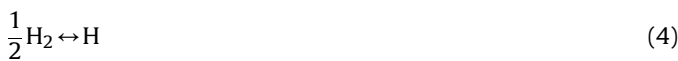


Fig. 1. A schematic illustration of the furnace.

2.2. Solution algorithm

The alternative flow rate of natural gas must be determined so that the operating conditions of the furnace, i.e. the flue gas temperature (T_{exit}) and the rate of heat removal from the furnace (Q), do not change. The flow rate of gas oil and the flue gas temperature are considered to be known, therefore, the first step in the solution algorithm is to obtain the rate of heat removal Q from the furnace.

To study this problem, as mentioned before, we adopt the macroscopic description of conservation laws where we focus on the entering and leaving streams (as shown in Fig. 1) instead of a small region within the system (microscopic level), so Q can be obtained by the macroscopic energy balance as

$$\sum H_{input} = \sum H_{output} + Q, \quad (7.a)$$

$$\sum H_{input} = \dot{n}_1 H_{Fuel} + \dot{n}_2 H_{Air}, \quad (7.b)$$

$$\begin{aligned} \sum H_{output} = & \dot{n}_3 H_{CO} + \dot{n}_4 H_{CO_2} + \dot{n}_5 H_{O_2} + \dot{n}_6 H_{H_2} + \dot{n}_7 H_{H_2O} + \dot{n}_8 H_{H_2O} \\ & + \dot{n}_9 H_{N_2} + \dot{n}_{10} H_{H_2O} + \dot{n}_{11} H_{OH} + \dot{n}_{12} H_{NO}, \end{aligned} \quad (7.c)$$

where \dot{n} denotes the molar rate and H is the enthalpy per mole. Indeed, Q is the difference between enthalpies of the entering and leaving streams. It can be seen from the above equations that only molar rates are required for obtaining Q since the temperature is known in the entering and leaving streams. Considering the stoichiometric reaction, the molar rate of air can be obtained as

molar rate of flow of fuel = \dot{n}_1 = known

$$\begin{aligned} & [\dot{n}_1(C_{12.9}H_{23.9}) + \left[\dot{n}_1 \left(12.9 + \frac{23.9}{4} \right) \right] (O_2 + 3.76N_2) \rightarrow \\ & [12.9\dot{n}_1](CO_2) + \left[\frac{23.9}{2} \dot{n}_1 \right] (H_2O) + \left[3.76\dot{n}_1 \left(12.9 + \frac{23.9}{4} \right) \right] (N_2), \end{aligned} \quad (8)$$

$$\text{molar rate of flow of air} = \dot{n}_2 = \left(1 + \underbrace{\% \text{excess air}}_{\text{e.g. 0.15}} \right) \left(\dot{n}_1 \left(12.9 + \frac{23.9}{4} \right) \right).$$

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