

# Thermal modeling of radiation and convection sections of primary reformer of ammonia plant

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## Abstract

The primary reformer is basically a furnace containing burners and tubes packed with supported nickel catalyst. Due to the strongly endothermic nature of the process, a large amount of heat is supplied by fuel burning (commonly natural gas) in the furnace chamber. Accordingly, selection of primary reformer operating parameters has an important influence on reduction of operating costs and increasing the reactor performance (conversion efficiency).

In this paper, the radiation and convection sections of primary reformer are investigated. The effects of key parameters on reformer performance are studied and the related developed software program is presented. The stirred-reactor furnace model which was used to simulate the radiation section of primary reformer was found to make substantially correct predictions of the overall heat transfer process in the furnace.

Comparison of the numerical data obtained from the simulation program with the measured data collected from primary reformer of Razi petrochemical plant showed a mean difference of 0.23% in estimating produced hydrogen mole fraction, as well as 1.7% and 7.25% in computing the outlet temperature of process fluids and induced draft fan (ID) speed, respectively.

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## 1. Introduction

Hydrocarbon reforming in primary reformer furnace (PRF) to produce hydrogen or gases used in the chemical processes (such as producing ammonia, methanol, oxo-alcohol, dimethyl ether) is important from technical and economical aspects.

Several primary reformer designs are available today, basically they differ in the arrangement of the tubes and the location of the burners in the furnace chamber. These basic designs are classified as top-fired, bottom-fired and side fired (radiant wall) types [1,2].

The steam reforming process converts hydrocarbons into hydrogen, carbon monoxide and carbon dioxide, the

so-called synthesis gas. The process is carried out on supported Ni catalysts in multitubular reactors operated at temperatures varying from 500 °C (inlet) to 800 °C (outlet), pressures ranging from 20 to 40 bar and molar steam-to-carbon ratios in the feed between 2 and 4. A typical reformer may contain between 40 and 400 tubes. The inside diameter is in the range of 70–160 mm with a tube thickness 10–20 mm [3].

Thermal energy of combustion products is transferred to the outer surface of tubes by radiation and convection, and then to the inner surface of tubes by thermal conduction. The mixture of steam and feed gas absorb energy through diffusion and convection processes and the decomposed gas products in catalyst filled tubes enter the secondary reformer through several risers.

The primary reformer furnace considered in this paper was top fired type. The developed software program

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## Nomenclature

$A$	surface area, m <sup>2</sup>	$T$	temperature, K
$A_T$	total area of furnace chamber, m <sup>2</sup>	$T_{af}$	adiabatic flame temperature, K
$B$	tube pitch ratio	$T_{g,s}$	arithmetic mean of $T_g$ and $T_s$ , K
$c$	ratio of tube outside surface area to furnace chamber area, $\frac{A_s}{A_T}$	$T_{ref}$	reference temperature, 298 K
$c_p$	specific heat, J/kg K	$\Delta T$	temperature difference, K
$d$	tube diameter, m	$u$	velocity, m/s
$D'$	reduced firing density	$U$	overall heat transfer coefficient, W/m <sup>2</sup> K
$g_{rad}$	radiation heat transfer coefficient from gas to tube walls and refractory	$V$	volume of furnace chamber, m <sup>3</sup>
$g_{rad,c}$	corrected radiation heat transfer coefficient	<i>Greek letters</i>	
$h$	convection heat transfer coefficient, W/m <sup>2</sup> K	$\alpha$	radiative absorptivity coefficient
$h_{g,i}$	specific enthalpy of inlet gases, W/m <sup>2</sup> K	$\varepsilon$	radiative emissivity coefficient
$h_{g,o}$	specific enthalpy of outlet gases, W/m <sup>2</sup> K	$\rho$	density, kg/m <sup>3</sup>
$\Delta \bar{h}$	sensible enthalpy difference from the reference temperature (298 K) enthalpy J/kg	$\mu$	viscosity, Pa s
$h_f$	formation enthalpy, J/kmol	$\sigma$	Stephan–Boltzmann constant
$k$	thermal conductivity, W/m K	<i>Subscripts</i>	
$L'_{loss}$	refractory loss factor	amb	ambient
$\dot{m}$	mass flow rate, kg/s	c	convective
$n$	number of moles of $i$ th element	eff	effective
$Nu$	Nusselt number	g	combustion products
$Pr$	Prandtl number	i	inside
$Q'$	reduced furnace efficiency	m	feed gas and steam mixture
$\dot{Q}$	heat transfer rate, W	o	outside
$R$	thermal resistance, m <sup>2</sup> K/W	rad	radiative
$Re$	Reynolds number	r	refractory wall
		s	reformer tube

permits using any number of tunnel and auxiliary burners. The combustion products exiting the radiation section were sucked into the convection section by a variable speed induced fan (located at the end of the convection section) in order to preheat the process fluids used in primary reformer and other sections of the plant (Fig. 1).

## 2. The radiation section of the primary reformer furnace

The temperature of combustion products in the furnace chamber varies with the furnace configuration and dimensions, reformer tube arrangements, and the position and number of top burners. Heat generated by top and tunnel burners was computed using parameters such as the fuel type, hydrocarbon mole fractions in the fuel composition, fuel heating value, fuel supply temperature, and mass flow rate, ambient conditions (air temperature, pressure and relative humidity), and excess air.

### 2.1. Heat transfer from combustion products

Heat transfer from combustion products to the tube walls by convection and radiation is:

$$\dot{Q}_s = g_{rad} \sigma (T_g^4 - T_s^4) + h_c A_s (T_g - T_s) \quad (1)$$

where  $g_{rad}$  is radiation heat transfer coefficient:

$$g_{rad} = \frac{A_T}{\left(\frac{1}{\varepsilon_{eff}}\right) + \frac{1}{\varepsilon_g} - 1} \quad (2)$$

where  $A_T (\equiv A_r + A_s)$ , is the total area of the furnace chamber,  $c (\equiv \frac{A_s}{A_T})$  is the fraction of furnace chamber area covered by the reformer tubes which varies in range of 0.4–0.6. The effective emissivity coefficient of the reformer tubes,  $\varepsilon_{eff}$ , is computed using tube pitch ratio,  $B$  (the ratio of center to center distance of two adjacent tubes to the tube outside diameter) [4].

Also the average emissivity of combustion products,  $\varepsilon_g$ , was evaluated at a beam length equal to the mean beam length for the entire furnace chamber ( $\cong 3.5 \frac{V}{A_T}$ , where  $V$  is the furnace chamber volume [4,5]), partial pressure of water vapor and CO<sub>2</sub>, as well as the temperature of combustion products [5].

For estimating  $h_c$ , the convection heat transfer coefficient, Geankoplis correlation was used [6]:

$$h_c = \frac{0.163 k_g}{d_o} \left(\frac{d_o}{u} \rho_g \mu_g\right)^{0.632} \left(\frac{\mu_g c_{p,g}}{k_g}\right)^{0.33} \quad (3)$$

The convective heat transfer term in Eq. (1) can be approximated by linearization in  $T_g^4$ , then the overall heat transfer

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