Numerical investigation of the new regenerator–recuperator scheme of VOC oxidizer

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Abstract

The new regenerator–recuperator scheme of filtration combustion VOC oxidizing reactor is under research. Its main characteristics, such as maximum temperature of reactor, temperature of exhaust gases, NO emission and others are calculated and compared with the same characteristics of other types of reactors (co-flow filtration combustion wave reactor, counter-flow heat exchange recuperative reactor, reverse flow regenerative reactor). It is shown that the regenerator–recuperator scheme provides important advantages (wide range of flow rate, and equivalence ratio of the combustible, low temperature of the exhaust gases) compared to conventional schemes.
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Keywords: Filtration combustion (FC); Heat recuperation; Heat regeneration; Porous media; Volatile organic components (VOC); Oxidizer

1. Introduction

Recreation of polluted flue gases remains an actual problem for a variety of mechanical, chemical and biochemical technologies [1,2]. There are numerous industrial methods to recreate flue gases: sorption, condensation, combustion (conventional or catalytic), membrane separation, chemical/biochemical transformation of pollutants to neutral components [1,2]. The sorption process of gas purification consumes sorbents which have limited lifetime and demand recreation or replacement. Condensation to liquid phase is appropriate only to components characterized by relatively high temperature of condensation and in the case of high concentration of pollutants [1]. Direct combustion of the polluted air in open flames is not effective economically if the process is not combined with an industrial boiler, furnace or power generator. Membrane separation, catalytic oxidizing, chemical or biochemical transformation of the pollutants are rather selective and, in addition, expensive. Therefore they may be efficient only for specific cases [1,2].

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Nomenclature

$C_{p,i}$	heat capacity of ith gas component, J/K/mol	$\mathbf{u}$	gas filtration velocity vector, m/s
$\overline{C}_p$	average molar heat capacity of gas, J/K/mol	U_G	superficial gas velocity, m/s
$\mathbf{D}$	gas diffusivity tensor	X_i	molar fraction
$\mathbf{D}_d$	dispersion diffusivity tensor	x	transverse coordinate, m
D_p	longitudinal component of dispersion diffusivity	Y_i	mass fraction of the ith gas chemical component
D_t	transverse component of dispersion diffusivity	z	longitudinal coordinate, m
D	diffusivity coefficient, cm^2/s	z_f	front position
d_0	bedding particle diameter, m	z_r	front position for flow reverse (switch), m
d_1	diameter of the internal tube, m		
d_2	diameter of the external tube, m	*Greek symbols*	
G	gas flow rate, m^3/h	α_{vol}	heat exchange coefficient, W/K/m^3
H_i	molar enthalpy of ith component, J/mol	ε	emissivity of the bedding particles
h_i	mass enthalpy of ith component, J/kg	φ	equivalence ratio
$\mathbf{I}$	unit matrix	η_c	dimensionless temperature, have sense of effectiveness
k_0, k_1	filtration permeabilities	$\mathbf{\Lambda}$	heat conductivity tensor $\mathbf{\Lambda} = c_p\rho_g\mathbf{D}$
L	burner length, m	λ	conductivity, W/m/K
M	average molecular weight of gas, kg/mol	μ	gas viscosity, Pa s
m	porosity	ρ	density, kg/m^3
Pr	Prandtl number	$\dot{\rho}_i$	mass generation of ith component due chemical reactions
p	pressure, Pa		
p_0	outlet pressure, Pa	σ	Stefan–Boltzmann constant
R	absolute gas constant	τ_z, τ_r	axial and radial components of the velocity vector projection
$\mathbf{s}_i$	diffusion flux of ith chemical component, $\mathbf{s}_i = \rho_g\mathbf{D}\nabla Y_i$		
$\mathbf{q}$	heat flux in gas phase, $\mathbf{q} = \mathbf{\Lambda}\nabla T_g$	*Subscripts*	
T	temperature, K	1	relates to internal tube or fuel
T_0	initial temperature of the system, K	2	relates to external tube or oxidant
T_{ad}	adiabatic temperature of combustion, K, $\Delta T_{ad} = T_{ad} - T_0$	g	gas
		s	solid

The widely spread air pollutants—volatile organic components (VOC)—phenol, formaldehyde, acetone, benzole and others—have considerable heat content and may be eliminated by oxidation in inert porous media or filtration combustion [3–6]. Filtration combustion provides effective heat recirculation and consequently low energy costs of the process. Even in the case of low concentration of VOC ($\sim$1 mass%) the combustion process may be self-sustained due to the heat content of the pollutants. Takeno and Sato [9] researched sustained combustion of methane–air mixture in steady-state recuperative reactor with equivalence ratio as low as $\Phi = 0.026$.

Physical aspects of the filtration combustion (FC) in inert porous media are discussed in [4,7,8] and other papers. One of the principal features of FC is internal heat recirculation in the combustion wave, due to heat exchange between gas and solid in the preheat zone of the combustion wave. Practical systems designed for combustion of low calorific fuels utilize external heat recirculation in addition to internal. These heat recuperation is realized by means of counter-flow heat exchange between incoming and exhaust gases and heat regeneration due to periodical reverse of flow direction (Fig. 1). The first mentioned scheme works in steady state regime, the second works in non-steady periodical regime. Both schemes are examined in laboratory installations [3,4,9–11] and utilized in industrial VOC oxidizers produced by Thermatrix [12], ReEco-Stroem [13] and other companies.

The main technical difficulties of the regenerative scheme of reactor are connected with the need to sustain reliable operation of the mechanical switcher valves, particularly in conditions of increased temperature of the gas [3–5,10]. The disadvantage of the steady recuperative scheme of the reactor is the relatively narrow range of the gas mixture flow rate when heat recuperation efficiency is high.