Applied Thermal Engineering 143 (2018) 988–1002

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

A computational fluid dynamics model of a rotary regenerative heat exchanger in a flue gas desulfurization system

Koray Özdemir[a,*], Mustafa Fazıl Serincan[b]

[a] Tubitak Marmara Research Center Energy Institute, Gebze, Kocaeli, Turkey
[b] Gebze Technical University, Mechanical Engineering Department, Gebze, Kocaeli, Turkey

H I G H L I G H T S

- A CFD model is presented for thermal-fluids analysis of a rotary heat exchanger.
- Sophisticated geometric details of matrix are reduced to porous media parameters.
- Operating conditions and their effects are addressed by means of virtual tests.

A R T I C L E I N F O

Keywords:
Rotary regenerative heat exchanger
Flue gas desulfurization
FGD
Computational fluid dynamics
CFD

A B S T R A C T

Rotary regenerative heat exchangers (RHEX) are commonly used in flue gas desulfurization (FGD) systems to improve the dispersion of pollutants, reduce the visible plume, avoid liquid droplet rainout from the stack and avoid corrosion problems on the system materials. In this study, transient behaviors of heating and cooling cycles of a rotary regenerative heat exchanger in an FGD system were investigated via a 3-D computational fluid dynamics (CFD) model. For this purpose, the rotary regenerative heat exchanger was modelled using porous media approach for the heat transfer surfaces (i.e. matrix) inside the heat exchanger. A standalone channel model as used to obtain porous media parameters and heat transfer coefficient. Numerical results confirmed by published literature. Effects of different operating conditions on the performance of the heat exchanger have been investigated. In conclusion treated gas outlet temperature increases with increasing angular velocity and treated gas inlet temperature while it decreases with decreasing load. Consequently, untreated gas outlet temperature decreases with increasing angular velocity and decreases with the decreasing treated gas inlet temperature and load. By means of overall system performance it is observed that overall system performance increases with decreasing angular velocity and treated gas inlet temperature while it increases with decreasing load.

1. Introduction

Rotary regenerative heat exchangers (RHEX) or simply regenerators are widely used in many applications such as gas turbines, thermal power plants, flue gas desulfurization systems and air conditioning systems. RHEXs are commonly used in flue gas desulfurization (FGD) systems to improve the dispersion of pollutants, reduce the visible plume, avoid liquid droplet rainout from the stack and avoid corrosion of system materials. Energy of the flue gas is used to raise the temperature of the treated flue gas leaving the absorber before it is discharged from the stack in the heating cycle. Temperature of the untreated flue gas entering the absorber is decreased in the cooling cycles.

Thermal design of the regenerators have been studied analytically [1–13], semi-analytically [14] and numerically [15–38]. However heat transfer and flow modeling of regenerators via computational fluid dynamics has not been studied widely. Pascoli [39] has developed a mathematical model describing the heat and fluid flow in a rotary regenerator using porous media approach. He assumes the regenerator operating at constant mass flow rates, rotation speed and inlet temperatures, no thermal energy sources or sinks within the regenerator walls, and single phase operation. The heat transfer coefficient at the wall/fluid interface is assumed to be independent of the temperature and time. His results agree well with Kays and London's analytical approach and experimental data. This model is preferred since the details of single channel are not required thanks to the porous medium definition of the entire wheel.

* Corresponding author.
E-mail address: koray.ozdemir@tubitak.gov.tr (K. Özdemir).

https://doi.org/10.1016/j.applthermaleng.2018.08.011
Received 9 January 2018; Received in revised form 2 June 2018; Accepted 4 August 2018
Available online 07 August 2018

Nomenclature

c	specific heat capacity (J/kg K)
E	energy source
h_{gs}	heat transfer coefficient ($W/m^2 K$)
k	thermal conductivity
m	mass flow rate
T	temperature
w	angular velocity
μ	dynamic viscosity
γ	porosity
ρ	density
β	packing density (m^2/m^3)

Subscripts

c	treated gas
fg	flue gas
g	gas
h	untreated gas
i	Inlet
o	outlet
s	matrix solid material

Kaydan and Hajidavalloo [40] investigated the thermal behaviour of a full-scale rotary air-preheater using three-dimensional approach as treating the preheater matrix as a porous media. Mass, momentum and energy equations inside the matrix have been solved using moving reference frame to represent the effect of the rotational speed. They have obtained the porous media inputs experimentally. CFD results agreed with the experimental data with a 7.5% error margin. According to the analysis isotherms within the matrix are shown to be almost linear except those close to the center of the matrix. They also show that angular velocity of the matrix has significant effect on the efficiency up to a certain limit. Analyzing the different types of matrix materials, it has been concluded that material with low thermal diffusivity has better thermal efficiency.

Corsini et al. [41] have described a methodology to account for the effects of the Ljungström, the first efficient air preheater invented in Sweden by Frederick Ljungström, they have implemented a CFD model based on the work of Molinari and Cantiano. In order to reduce the computational cost for modelling of the rotating matrix, which is filled with hundreds of narrow channels, a synthetic description of the Ljungström is applied. In this method a series of source terms have been implemented in momentum and energy equations to account for the detailed channel geometry. Also a porous medium approach is used to simulate the flow inside the matrix. Standard high Reynolds k-ε Reynolds-averaged Navier–Stokes equations (RANS) method was used to solve the incompressible momentum equations. CFD results are compared with available measurements in a real power plant where pressure drops and temperature at the outlets are underestimated around 3%. Owing to fast calculation times authors suggest the approach to study different ducting configurations Ljungstrom inlet to maximize the effectiveness of the heat exchanger.

Sözen & Çiftçi [42] use a simplified model of a regenerator with sinusoidal shaped ducts. They have only simulated the first shell modeled from 0° to 360° using a commercial CFD software. Their model consists of both fluid regions and the matrix geometry. Defining interfaces between the fluid regions and the matrix walls, they use sliding mesh method to represent the rotation of the matrix. Alhusseny & Turan [43] have carried numerical analysis of the fluid flow and heat transport phenomena through a rotary thermal regenerator using a porous media approach. They have obtained the pressure drop and heat transfer coefficient data to define the porous media parameters based on the empirical equations for circular, square and triangular ducts. They have presented the results by means of overall regenerator effectiveness, pressure drop, and the overall system performance (OSP) and investigated the impact of different design parameters such as the core geometrical features, and operating conditions. They have revealed that OSP increases with increasing wall thickness, rotor length, rotor frontal area and characteristic temperature difference; and decreases with increasing rotor hydraulic diameter.

In none of the above studies a complete 3D geometry of a rotary heat exchanger in a FGD system has been modeled. Also transient temperature variations inside the regenerator for different operating conditions have not been studied rigorously.

2. Methodology

In this study, a rotary regenerative heat exchanger with corrugated sinusoidal ducts have been pre-designed and modeled. In the design corrugated sinusoidal ducts are selected as they the most common in rotary regenerative wheels due to the simplicity of construction and having large heat transfer surface area (Fig. 1).

RHEX operates with the flue gas composition of 13.91% CO_2, 3.02% O_2, 14.46 H_2O % and 68.61% N_2. SO_2 is not included in the flue gas composition due to its negligible small content in this particular system. Flue gas thermo-physical properties are obtained from a thermodynamics software specially developed for flue gas calculations. The thermo-physical property values obtained between 40 °C and 130 °C are then expressed as a function of temperature as shown in Table 1. 0.5% Carbon steel is defined as the material for the matrix with thermo-physical properties given in Table 2. Geometric properties and operating conditions of the modeled RHEX are shown in Table 3. Treated gas mass flow rate is lower than the untreated gas mass flow rate since desulfurization occurs before treated gas enters the RHEX.

Channel geometry has been simplified by using the porous media approach as described by Pascoli [39], and Kayden and Hajidavalloo

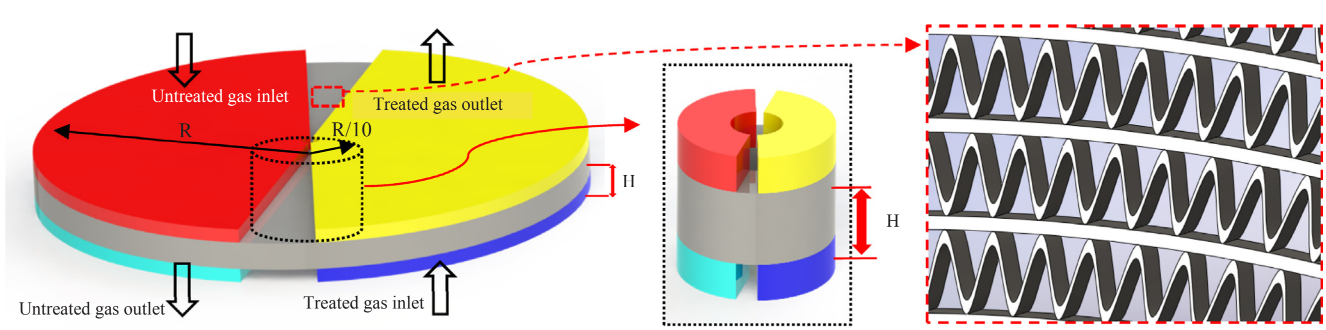

Fig. 1. Corrugated sinusoidal ducts.