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Distribution optimization for plate-fin catalytic combustion heat exchanger

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Abstract

The characteristics of a plate-fin catalytic combustion heat exchanger (PFCCHE) which integrates catalytic combustion and heat exchange into one device have been investigated by experiment and numerical simulation. One combustion chamber was integrated with two evaporation chambers to constitute a single unit of PFCCHE. The Pt/Al_2O_3 catalyst pellets were packed into the combustion chamber. The uniform concentration and temperature distribution contributes to the higher thermal efficiency of PFCCHE. A porous media model was supplied to three-dimensional computational fluid dynamics (CFD) simulations of flow field in the PFCCHE. And cold test was performed to validate the numerical model. Results indicated that the numerical prediction of the porous media model was in agreement with experimental data. Fluid maldistribution was observed for the first generation distributor. Thus a second distributor was designed and validated by the cold- and hot-state experiments. Scale-up for 5 kW fuel processing system was performed successfully.

Keywords: Packed bed; Porous media; Distributor; CFD

1. Introduction

Compared with ordinary flame combustion, catalytic combustion has been widely applied due to its unique features. Lower combustion temperature can avoid the thermal NO*x* production, and lower lean limit of flammability can achieve the stable combustion of lean fuels such as fuel cell anode off-gases [1]. These features provide the basis for the development of more efficient, cleaner and safer equipment or process.

The catalytic combustion heat exchanger (CCHE) integrates catalytic combustion and heat exchange into a single device, thus capable of replacing the conventional boiler and heat exchanger. Some improvements were done to intensify heat transfer from the following aspects: the catalyst-loading mode, cross-section structure of CCHE as well as hydraulic diameter of channel when phase change happens. The wall coating catalyst represents a superior geometry due to the lower pressure drop as well as improved heat transfer [2]. Further studies demonstrated that channel dimensions play a critical role in determining heat transfer mechanisms and have a strong effect on the heat transfer coefficient [3]. Compared with finned tube heat exchanger, plate-fin heat exchanger (PFHE) is easier to scale up and can provide larger heat transfer area as well as multi-stream configuration. Due to its large heat transfer area (around 2500 $m^2\ m^{-3}$), compact structure (fins and flat plates with a thickness of 0.2 mm) and high heat transfer coefficient (up to 9697 $W\ m^{-2}\ s$), many applications of PFHE have been achieved in such fields such as air separation and petrochemical industries. In this paper, PFCCHE was derived from PFHE.

The nonuniformity of flow field is detrimental to longitudinal wall conduction and the distribution of the interior temperature, which is the main reason that causes the deterioration of heat exchanger efficiency, especially for the compact heat exchanger [4,5]. It has been well recognized that the flow nonuniformity through the exchanger is generally associated with improper exchanger entrance configuration. Therefore, most of previous studies mainly investigated the effects of different header configurations on the fluid flow distribution in PFHEs and tried to minimize the effect of flow maldistribution by optimizing the design of header configuration for PFHEs [4–8], with more attention paid to the optimization of industry-scale exchangers. Their large dimension of optimized distribution methods is not suitable for PFCCHE. So it is impossible to apply the previous improvements on the header configuration of PFHE to the

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Nomenclature

C, D	the prescribed matrices
C_p	molar capacity ($J\,K^{-1}\,mol^{-1}$)
C_s	species mass fraction
C_2	inert resistant factor (m^{-1})
D_p	mean diameter of catalyst pellets (m)
f_{ave}	the mean molar fraction
f_n	the specie mole fraction in nth sampling location
L	height of packed bed (along the flow direction) (m)
N	the number of concentration collector
Δp	pressure drop in the packed bed (Pa)
S_D	standard deviation
S_i	source items in the ith dimension
v_i	velocity in ith (x, y, z) dimension ($m\,s^{-1}$)
v_j	the velocity components in the x, y, and z directions for differential units ($m\,s^{-1}$)
v_∞	the velocity of a 100% open area ($m\,s^{-1}$)
Greek letters	
α	permeability (m^2)
ε	porosity of the packed bed
μ	viscosity ($kg\,m\,s^{-1}$)
ρ	density of fluid ($kg\,m^{-3}$)

optimization of PFCCHE. In PFCCHE, temperature distribution is strongly dependent on concentration distribution. When the fuel with high calorific value is used such as CH_4, CH_3OH and H_2, non-uniformity of concentration distribution will lead to the occurrence of local hot spot, resulting in the deterioration of the thermal efficiency of PFCCHE, which would be a security hazard for operation. So it is necessary to study the concentration distribution in PFCCHE. The realization of uniform distribution will contribute to the enhancement of the heat transfer and thermal efficiency of PFCCHE.

The objective of the present study is to identify the uniformity of the concentration distribution in PFCCHE under different operating conditions and improve its flow flied distribution. First of all, experimental and theoretical researches were performed on cold test concentration distribution in PFCCHE. Then a numerical model predicting the performance of the conventional distributor was proposed and its validity was discussed by comparing experimental and numerical results. Finally, a novel distributor was designed. Its performance was evaluated by cold- and hot-state experimental researches. The distribution behavior of its scale-up was also studied.

2. Experimental

2.1. Plate-fin catalytic combustion heat exchanger

A pilot PFCCHE was designed and installed. The PFCCHE is composed of three chambers. Catalytic combustion reaction occurs in the middle chamber. Evaporation process arises in two symmetrical side ones. Cross flow arrangement was adopted. Some 30–40 mesh combustion catalyst pellets (Pt/Al_2O_3) were packed into the combustion chamber. The catalyst, which was developed independently in our laboratory, has been widely applied in the removal of VOC as a commercial catalyst and exhibited durable stability in long-term stability testing lasting for thousands of hours. During experiment, H_2/air was ignited at ambient temperature over the catalyst. The detailed drawing and photograph of PFCCHE are presented in Fig. 1. According to practical needs, PFCCHE can be expediently scaled up.

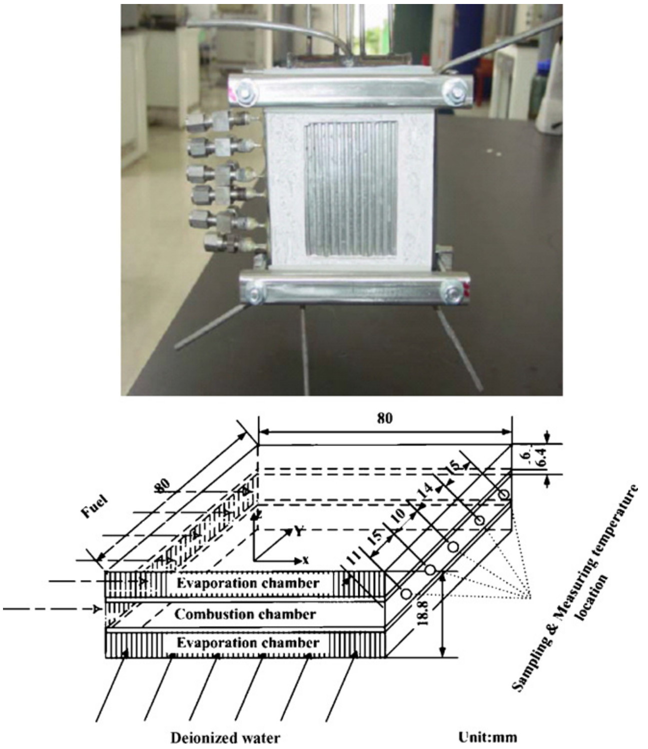

Fig. 1. Photograph and schematic drawing of the catalytic combustion heat exchanger.

2.2. Experimental procedure

Gaseous reactants entered the system at room temperature, and their individual flow rates were regulated by mass flow controller. Different evaporated liquids were supplied into the evaporation chamber by flow pump. A schematic drawing of the experimental system is shown in Fig. 2. Fuel and oxidant passed through their distributors and then entered the combustion chamber of PFCCHE. During experiments, hydrogen and air were used as working medias, and deionized water as evaporated fluid. Methane or other combustible gases were also used as fuels. For the generating hydrogen system fed by liquid fuels such as methanol, ethanol or gasoline, partial anode off-gases from fuel cell returned PFCCHE and supplied heat directly to the endothermic process in evaporation chamber. Then superheated steams were supplied to the reformer. The PFCCHE was made of stainless steel 304, which has a good heat-transfer capability. The center parts of two side plates were caved to embed into two symmetric glass windows. Thus protuberant part of the quartz