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Characteristics analysis of water film in transpiring wall reactor

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ABSTRACT

Transpiring wall reactor can significantly overcome reactor material corrosion and salt deposition problems by forming a protective water film on its inner porous wall. In this work, a simplified physical model of transpiring wall reactor was built to analyze the process of heat and mass transfer between the water film and bulk fluid. Furthermore, two quantitative correlations between the thickness of water film and main operating parameters were proposed for the first time using theoretical analysis and mathematical deduction method. For a given transpiring wall reactor, appropriately increasing the flow rate and inlet temperature of transpiration water is conducive to maintain the growth of the water film thickness. A positive linear relation exists between the mass flow rate of transpiration water and the thickness of water film under constant feedstock parameters conditions. These quantitative correlations together with some meaningful conclusions help to guide the optimization of operating parameters as well as the design of transpiring wall reactor.

1. Introduction

Water above its critical point ($T = 374$ °C, $P = 22.1$ MPa) exhibits certain unique properties, such as non-polar character, high diffusivity, excellent dissolution and transportation features [1]. Supercritical water oxidation (SCWO) utilizes these excellent properties to achieve rapid and complete degradation of organic waste in the presence of excess oxygen. SCWO possesses some prominent advantages such as very short reaction time, easier salts separation, achieving heat self-sufficiency and absence of secondary pollutants [2]. It is feasible for the harmless treatment of high toxicity, high concentration and refractory organic waste. However, its core equipment (i.e., reactor), easily suffers with serious corrosion due to the harsh working conditions and plugging problems caused by salt deposition [3]. Innovative reactor design is an effective means to solve these two problems, wherein transpiring wall reactor (TWR) attaches much attention. The reactor consists of outer pressure-bearing wall and inner porous non-load-bearing transpiring wall. A protective water film, covering the inner surface of the porous wall, can effectively isolates corrosion substances and inorganic salts, so reducing the material corrosion rate and the risk of salt deposition. Numerous experiments regarding organic matter removal, material corrosion and salt deposition have been conducted in transpiring wall reactor SCWO plants [2,4–7]. The experimental results indicate that transpiring wall reactor plays an effective role in resistance to corrosion and salt deposition [8–11].

However, there are no in-depth studies concerning the impacts of operating parameters on the water film characteristics (such as the thickness, uniformity and continuity), resulting in some inconsistent, even contradictory conclusions on the performance of TWR. For instance, Rice et al. [8], Crooker et al. [9] and Xu et al. [10] reported that no obvious corrosion and salt deposition phenomena were observed in SCWO of actual wastewater or simulated salt-containing wastewater. Nevertheless, Fauvel et al. [12,13] and Gong et al. [6,14] discovered that porous transpiring wall was seriously corroded and plugged by inorganic salts after a certain period of time. Water film characteristics seem to be a key factor to exert the advantages of transpiring wall reactor, while operating parameters have decisive impacts on it. It has been proven that the higher transpiration intensity helps to form a better water film, but excess cool transpiration water easily results in the fluctuation of temperature and the reduction of organics removal efficiency near the water film [1]. Therefore, it is necessary to seek appropriate correlations between the water film characteristics and operating parameters to guide reactor design and optimization of operating parameters.

Till now, some researchers have investigated heat transfer and dynamics of supercritical fluid in the porous medium. Reda et al. [15] studied the mixed convection phenomenon in vertical porous medium following Darcy law. Fauvel et al. [13] discussed the pres-

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Nomenclature

A	surface area of porous wall, m^2
c_p	specific heat of transpiration water, J/(kg K)
D	generalized diffusion coefficient, m^3/s
d	porous wall diameter, m
F_c	mass flow rate of transpiration water, kg/ s
g	gravity acceleration, m/s^2
Ga	Galileo number
l	porous wall length, m
p	pressure, Pa
Pr	Prandtl number
q_m	mass flow rate through one transpiration water section, kg/s
$\delta Q(z)$	heat transferred across the differential surface area, w
$t_c(z)$	average temperature of the water film, K
$t_i(z)$	outer surface temperature of the water film, K
$t_w(z)$	porous wall temperature, K
$t_0(z)$	inlet temperature of transpiration water, K
T_0	inlet temperature of bulk fluid, K
u_z	transpiration water velocity at the z-direction, m/s
u_r	transpiration water velocity at the r-direction, m/s
u_Θ	transpiration water velocity at the θ-direction, m/s
U	bulk fluid velocity, m/s
r, θ, z	coordinates, m

Greek symbols

δ	water film thickness, m
λ	thermal conductivity, w/(m K)
μ	dynamic viscosity, Pa s
ρ	fluid density, kg/m^3

Subscripts

0	cool transpiration water inlet
c	cool transpiration water
bulk	bulk fluid
i	interface between water film and bulk fluid
m	mass flow rate
w	porous wall
l	mass loss

sure drop of supercritical fluid in the porous wall governed by Darcy law as well. Jiang et al. [16] obtained the correlations of describing pressure drop and convective heat transfer coefficient, considering multiple factors such as non-Darcy effect, inertia term, thermal dispersion, variable porosity, variable properties, buoyancy and particle diameter. These factors strongly influence heat transfer and flow characteristics of the fluid in porous medium. Chen et al. [1] experimentally observed that the fluid displayed anisotropy across a porous wall by a visual glass apparatus imitating SCWO conditions. Bermejo et al. [17] investigated the effects of the porous type, pore size and reaction temperature on the protective water film in a transpiring wall reactor at constant operating conditions. On the whole, existing literature concerning the porous medium or transpiring wall mainly concentrates on the temperature profiles, pressure drop and heat transfer coefficient. The studies did not consider the process of heat mass between the water film and bulk fluid, which was helpful to guide reactor design and the optimization of operating parameters.

In respect to transpiring wall reactor, the influence of operating conditions (i.e., transpiration intensity and the temperature of transpiration water) on the reactor performance including the temperature profiles, salt deposition, product distributions and organic matter conversion rate have been studied extensively [4–6,17–20]. For instance, Wellig et al. [18] experimentally studied the effects of operating characteristics of transpiring wall SCWO reactor on the temperature profiles near the transpiring and pressure-bearing wall. They pointed out that the natural convection effects were not negligible in the reactor, but no in-depth studies were carried out to investigate the convection effect and more operating conditions (i.e., the temperature and flow rate of bulk fluid in the reactor) on the formation of water film. Furthermore, some process parameters were optimized based on the temperature profiles and gas–liquid products in a transpiring wall reactor SCWO pilot plant by Zhang et al. [20]. Some calculated models of TWRs are also proposed to simulate and improve the performance of the reactor [1,12,21–24]. Bermejo et al. [22] established a simplified model of a TWR and studied the effects of transpiring water temperature, flow rate and composition of the oxidant on the reactor performance such as the temperature and composition contours, flow path lines and effluent compositions using the commercial software Fluent 6.3. Zhang et al. [24] also presented a numerical model of TWR for SCWO and discussed the effect of the transpiration intensity and the transpiring water temperature on the temperature profile and TOC removal rate in the reactor. Moreover, the temperature of water film was optimized by controlling the inner surface temperature of the porous tube less than 374 °C. However, these studies did not consider the effects of other operating conditions such as the feedstock parameters (i.e., the temperature and concentration of organics) on the formation of the water film, lacking the optimization means of TWR for a better water film in resistance to corrosion and salt deposition. The flow and heat transfer characteristics between its protective water film and bulk fluid need to be deeply explored due to their crucial roles in the formation of the water film. To the best of our knowledge, there are no related investigations concerning the characteristics of the water film in a TWR presently. No concrete and quantitative theory is applicable to the optimization of water film characteristics such as the thickness. Nonetheless, these characteristics are decisive for the ultimate realization of reactor's functions minimizing corrosion and salt deposition. A novel TWR and its SCWO system had been developed in previous reports [10,25]. In this paper, a simplified model of TWR was built to theoretically analyze the heat and mass transfer processes between its water film and bulk flow, based on mass, momentum and energy governing equations. Two quantitative relations are firstly proposed to describe the relationship between the water film characteristics and operating parameters in TWR, which were available to guide the reactor design and optimize operating parameters. As an extension of our previous research, this is firstly documented in the literature.

2. Physical model and theoretical analysis

As shown in Fig. 1, transpiration water is pumped into the annular space between the pressure-bearing wall and the non-load-bearing porous transpiring wall, and gradually pervades the inner side of the porous wall with the driving effect of differential pressure. Bulk fluid (reaction fluid) is introduced from the reactor top, and restricted in the central zone where oxidation reactions take place and form a supercritical region there [5]. The mixture of reaction products and cool transpiration water flows downward