Applied Thermal Engineering 128 (2018) 1186–1195

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Thermal oxidation coking of aviation kerosene RP-3 at supercritical pressure in helical tubes

Yanchen Fu, Guoqiang Xu, Jie Wen *, Haoran Huang

National Key Laboratory of Science and Technology on Aero-Engine Aero-thermodynamics, Collaborative Innovation Center for Advanced Aero-Engine, School of Energy and Power Engineering, Beihang University, Beijing 100191, China

HIGHLIGHTS

- Thermal oxidation coking amount distribution is more uniform in helical tubes.
- Smaller helical diameter makes the coking peak closer to the flow downstream.
- The total coking amount sharply decreased with the increase of helical coil numbers.
- Three coking morphologies and various elements distributions are detected.

ARTICLE INFO

Article history:
Received 12 June 2017
Revised 3 September 2017
Accepted 20 September 2017
Available online 21 September 2017

Keywords:
Thermal oxidation coking
Supercritical RP-3
Helical tubes
SEM
Coking elements

ABSTRACT

The mechanism of thermal oxidation coking of aviation kerosene RP-3 at a supercritical pressure of 5 MPa in helical tubes was analyzed. The bulk temperature of the fuel was varied from 400 K to 723 K, and the mass flux was varied from 393 kg/m^2 s to 1178 kg/m^2 s. Four types of helical tubes with different helical diameters were bent and tested for a maximum duration of 5 h. The total coking amount and distribution were analyzed using weighing method, and the standard error was less than 0.07 mg. The results indicate that coking distribution is more uniform than in the case of a straight tube, and that there is no prominent coking peak because of the effect of centrifugal force. The maximum total coking amount among all the experiments decreased by approximately 69.5% compared with that in a straight tube. Through measurements performed using a scanning electron microscope, three main types of coking morphologies were observed: thin coking layer, dense clumps, and crystalline particles. Moreover, various types of coking elements were detected under different working conditions.

1. Introduction

In the cooled cooling air (CCA) technology [1], aviation kerosene can be used as the cooling medium that flows inside the heat exchanger tubes to provide a high heat capacity. As the pumping system for the hydrocarbon fuel is approximately 3.45–6.89 MPa in typical aero-engines [2], the hydrocarbon fuel will be under supercritical pressure during the heating process. According to previous researches [3–5], thermal coking deposition occurs when the bulk temperature is higher than 163 °C. The hydrocarbon molecules in the fuel react with dissolved oxygen to cause thermal oxidation coking in the temperature range of 163–450 °C. However, thermal pyrolysis deposition becomes the dominant reaction when the temperature is higher than 450 °C. The coke depositing on the inner surface of the tube will decrease the heat transfer between the aviation kerosene and cooling air. Furthermore, a certain mass of coke can block the combustion nozzle or heat exchanger tube and trigger an aero-engine accident.

Thermal coking of hydrocarbon fuel at supercritical pressures involves complicated physical and chemical reactions [6]. Many factors influence the coking process, such as bulk temperature, experimental time, dissolved oxygen concentration, and tube material. Marteney [7] and Hazllet [8] considered that bulk temperature is the most important factor that affects thermal oxidation coking, and that temperature directly determines the intensity of the coking process. The results show that coking deposition and colloid are not formed when the fuel temperature is lower than 150 °C. The coking rate increases with temperature, and reaches the peak level at a temperature of approximately 316 °C. This peak appears because of the coupling effect between temperature and dissolved oxygen [9], as the variations in these two factors produce opposite effects. The hydrocarbon fuel coking shows

---

* Corresponding author.
E-mail address: wenjie@buaa.edu.cn (J. Wen).

https://doi.org/10.1016/j.applthermaleng.2017.09.101
1359-4311/

different characteristics depending on the conditions of the coking experiments. Jones et al. [10,11] studied supercritical Jet-A thermal oxidation coking under different experimental durations, and found that the coking rate is mainly affected by the rate of consumption of dissolved oxygen in an experiment with 6 h duration. However, it was found that the coking rate decreases continuously as the metal surface is covered by coking in the experiment with 70 h duration. Hazlett [12,13] suggested that the porous medium formed during the coking process can enhance the contact surface area between the inner wall and the fuel. Furthermore, the porous structure on the coking surface can retain the fuel on the high temperature wall and increase the reaction time [14], which can enhance the adhesion ability of the surface coking. Later, Eser et al. [15] applied various types of metal coatings on AISI 304 and studied their effects on the inhibition of carbon deposition during thermal oxidative degradation of jet fuel. It was reported that coking inhibition effect is related to the acidity level of the oxygenated intermediates during thermal stressing with the coating surfaces.

Many researchers have studied thermal coking of Chinese aviation kerosene RP-3, the most popular jet fuel in China, with critical pressure and temperature of 2.319 MPa and 372.2 °C, respectively. Xu et al. [16,17] experimentally investigated the influence of various physical and chemical factors on thermal oxidation in vertical tubes, and evaluated different methods for coking inhibition. Besides, an additive named BHTD-E50D was developed to suppress thermal oxidation coking; by using this additive, the amount of coking deposition on the inner wall surface decreased by 73.5%. In recent research, Zhu et al. [18] studied the thermal oxidation coking in tubes having different surface treatments and concluded that electrolytically passivated treatments could reduce the total coking deposition by approximately 58.3% and 35.8% compared with untreated tubes. To simulate the actual working conditions, Tao et al. [19,20] experimentally studied the effect of vibration on thermal oxidation coking of hydrocarbon fuel at supercritical pressures. The results showed that vibration could make the coking distribution more uniform and extend the tube-blocking time.

Most of the research work to date focused on the thermal oxidation coking in straight stainless steel tubes [21–23]. However, compact heat exchangers consist of a series of curved tubes in actual applications of the CCA technology. In previous research, the investigations conducted on fluid characteristics in curved tubes were mainly concerned with the effects of tube geometry on heat transfer [24–26] and resistance to flow [27,28]. In several

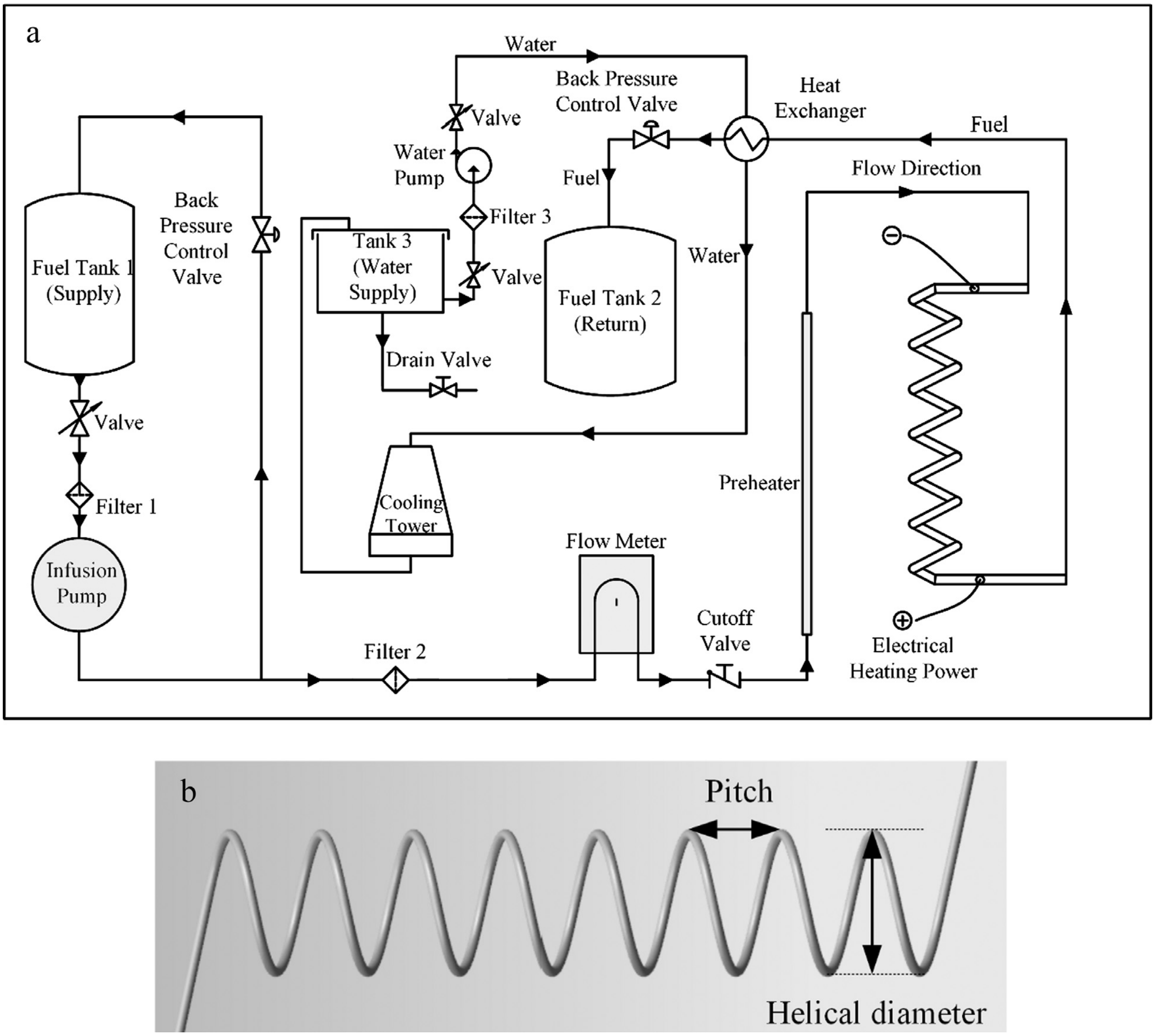

Fig. 1. Schematics of supercritical hydrocarbon fuel coking system (a) and helical tube (b).