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Research article

Effect of dissolved oxygen concentration on coke deposition of kerosene

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ABSTRACT

Coke deposition is an obstacle to the application of fuel cooling. The effect of dissolved oxygen concentration at the supercritical pressure on the thermal oxidative coking deposition of Chinese RP-3 kerosene was investigated using thermal fluid experiments. Tests were conducted in a small-diameter, indirectly electrically heated, single-pass straight tube covering the temperature range of the thermal oxidation reaction. The amount of coke deposition was measured by weighting. The results of the experiments for high-dissolved-oxygen, air-saturated, and deoxygenated fuels were compared at the supercritical pressure of 3 MPa and a fuel outlet temperature of 410 °C. In comparison with the air-saturated fuel, the high-dissolved-oxygen fuel experienced a sharp rise in deposits, while the deoxygenated fuel had the lowest deposition quantity. The consumption fraction of the dissolved oxygen increased notably above 200 °C and fitted a pseudo-first-order reaction. The entrance effect, inducing high depositions, was interpreted by the temperature gradient and the boundary layer. Finally the relationship between thermal oxidative deposition and heat transfer was examined.

1. Introduction

Recent advances in jet aircraft technology have induced an ever-increasing heat load on aircraft air cooling systems. Cooled cooling air with hydrocarbon aviation fuels is a potential technique for the thermal management systems of next-generation aircraft [1]. As the jet fuel exposed to air, oxygen in the air is dissolved in the fuel. Accordingly, autoxidation reactions occur in the fuel temperature range of 150–400 °C [2]. The jet fuel reacts with dissolved oxygen to produce oxidized products, and deposits form on the inner-wall surface. These deposits would block fuel lines, valves, nozzles, and various other aircraft components, potentially resulting in engine function failure [3].

Various experiments have been performed on the thermal oxidation stability. Many physical and chemical factors [4,5] influence the thermal oxidation stability, listed as temperature [6], system pressure [7,8], flow mass rates or velocity, test duration [9,10], fuel compositions [2,11], additives [12,13], catalysis and surface effect [14,15], especially, the dissolved oxygen concentration [16,17] which is one of the most important factors for oxidation deposition. It is well cognized that the reaction of dissolved oxygen with hydrocarbons forms hydroperoxides, which are intimately involved in deposit formation [18]. The effect of dissolved oxygen has been studied using many different devices, classified as static [19] and dynamic ones [20]. In static experiments, the jet fuel thermal oxidative stability in quartz–crystal microbalances has been examined using crystal electrodes with various metal materials, namely gold, platinum, aluminum, and silver [19,21,22]. In dynamic experiments, a near-isothermal flow test rig was applied to investigate the role of dissolved oxygen by reducing the oxygen concentration in various fuels subjected to a thermal environment, with the carbon burn-off analysis of surface deposits [2,16,23]. It has been indicated that control of dissolved oxygen at sub parts-per-million (ppm) levels greatly improved the thermal stability and decreased heat exchanger fouling. In addition to the oxygen concentration, fluid dynamics and heat transfer also affected fuel oxidation deposition [24,25]. The removal of oxygen has been proposed as a promising method for improving the thermal stability of fuel [16,17]. Most studies have focused on the mechanisms and reactions of thermal oxidation and decomposition coking for various fuels [26–28], and few studies have considered the effect of oxygen consumption on deposition and heat transfer.

The above researches prove that it is important to understand the main factors affecting the deposit formation for a given jet fuel. The objective of this work is to examine the effect of dissolved oxygen concentration on coke deposition of jet fuel at supercritical pressure and temperatures. In the experiments, the oxygen in the fuel was partly consumed, and was monitored at the inlet and exit of the reactor during the tests. The influence on deposition of the entrance effect, which is characterized by the boundary layer and the temperature gradient, was interpreted. The relationship between heat transfer and the oxidation stability of RP-3 was investigated based on the Nusselt number (Nu) and deposition rate.

2. Experimental

Chinese No.3 (RP-3) kerosene was chosen as the fuel. The physical properties of RP-3 aviation kerosene are listed in Table 1 [29]. The

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Table 1
Characteristics of RP-3 aviation kerosene.

Critical pressure (MPa)	Critical temperature (°C)	Density (g/cm^3) (20 °C)	Flash point (°C)	Distillation range (°C)	Relative molecular weight (g/mol)	Averaged molecular formula
2.39	372.5	0.7913	50	163–212	148.33	$C_{10.5}H_{22}$

thermal physical properties of the aviation kerosene are temperature-dependent. The bulk temperature of fuel along the reactor tube could be predicted in the simulation results. The thermal physical properties were determined by using a three-component surrogate model [30].

An indirectly electrically heated tube was employed to simulate a heat-exchanger in which heat transfer and thermal oxidation deposition of fuel occur. As shown in Fig. 1, the experimental apparatus consisted of four subsystems, i.e., feeding, heating and reactor, data acquisition/controlling system, and sampling/online analysis systems. A vacuum pump (6, N86 KT.18, KNF Inc.) and a magnetic stirrer (3) were applied to deoxidize the fuel. The oxygen concentration was monitored via two observation windows fixed on the opposite walls of the fuel tank (4) and an oxygen sensor (5, InPro 6850i, Mettler Toledo Inc.) dipped in the fuel. The oxygen sensor was designed for continuous measurement of dissolved oxygen over a 0–100% full range, i.e., up to 70 ppm. The transmitter, which was coupled to the sensor, was a Mettler Toledo dissolved oxygen microprocessor transmitter (Model 3000). A mass flow controller (2; CS2000, Seven-star Inc.) was used to control the amount of oxygen bubbled into the deoxidized fuel to the desired dissolved oxygen concentration. The fuel with a specific dissolved oxygen concentration was introduced into the reactor through a filter (7) to remove any impurities. The inlet mass flow rate was set at 1 g/s, and was monitored using a plunger metering pump (8) and coriolis mass flow meter (11; DMF-1-1-ADMF-DX, Sincerity Inc.). The fuel pressure stability was maintained using a pressure damper. Nitrogen was used to blow down the residual fuel in all pipes before heating. The reactor straight tube was made of the 316 stainless steel with a length of 450 mm, an inner diameter of 2 mm and a wall thickness of 0.5 mm. The test section was fixed horizontally and the heating flux was simulated by an electrical heating stove. After heating, the fuel was cooled using a counter-flow water-fuel exchanger (18). The fuel pressure was adjusted to 3 MPa using a back-pressure regulator (19; SS-9833F-1P-B, Xiongchuan Value Inc.) installed after the heat-exchanger to guarantee the jet fuel in a supercritical phase. The oxygen concentrations after the thermal experiments were measured continuously, but the oxygen sensor could not be placed immediately downstream of the heated test section exit because of the high exit temperature and pressure. A sampling and online analysis system (21) was therefore installed behind the cooling exchanger for consistent measurements. To ensure a constant oxygen concentration along the whole tube, the seal design was tested at pressure of 3 MPa by checking the inlet and exit oxygen concentrations to verify the absence of oxygen leakage from, or addition to, the system. The residuals were collected in a container (20). A pressure difference transducer (22; 300S1AAD1M5, Rosemount Inc.) was used to monitor the pressure drop between the inlet and outlet of the reactor during heating. The outer-wall temperature of the reactor tube was measured using 18 K-type thermocouples spot-welded at 2.5 cm intervals along the tube. The fuel inlet and outlet temperatures were measured using K-type thermocouples inserted into the center of the tube. The amount of oxidized deposition was strongly affected by the test time, therefore heating was performed for 105 min to guarantee the formation of sufficient deposit for analysis.

As the amount of deposit formed by oxidation is smaller than that formed by thermal cracking, a segmentation method was used to weigh the mass of oxidized deposition [31]. The formation of oxidation deposits depends on a two-step mechanism: firstly, the chemical formation of deposit precursors by fuel reacting with the dissolved oxygen; and secondly, the mass transport of deposit precursors to the wall. As the fuel heated in the reactor, the coke was gradually deposited on the inner surface of the tube with increase in the temperature and the heating duration. After each experiment, the tube was divided into 11 sections with each length of 4 cm. Each segment surface was polished out and cleaned with ethanol. This operation was to eliminate errors introduced by the insoluble impurities on the surface. And then the segments were dried above 100 °C for at least 1 h to remove residual water and ethanol. A high-precision balance (ESJ182–4, Long-Teng Inc.) was used to weigh each segment. The segments were then washed for at least 2 h in an ultrasonic vibrator filled with potassium

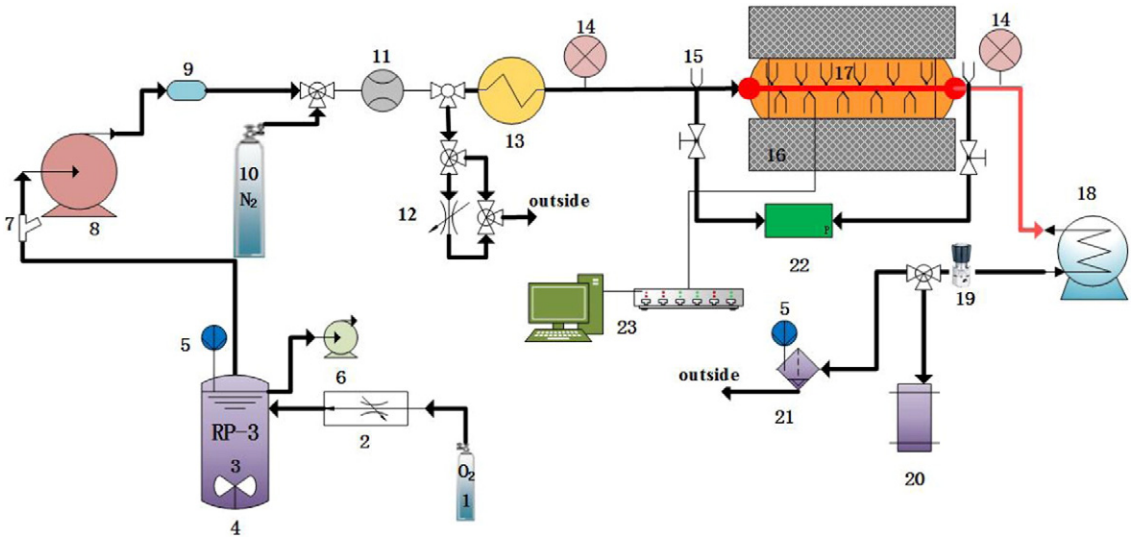

Fig. 1. Experimental setup for the coke deposition. 1: Oxygen cylinder; 2:Gas mass flow controller; 3: Magnetic stirrer; 4: Fuel tank; 5: Online oxygen sensor; 6: Vacuum pump; 7: Filter; 8: Plunger metering pump; 9: Pressure damper; 10: Nitrogen cylinder; 11: Mass flow meter; 12: Relief valve; 13: Preheater; 14: Pressure gauge; 15: Thermocouple; 16: Electrical heating stove; 17: Reactor tube; 18: Water-cooled exchanger; 19: Backpressure regulator; 20: Collection container; 21: Sampling and online analysis system; 22: Pressure difference transducer; 23: Data acquisition/controlling system.