

# Secondary flow and oxidation coking deposition of aviation fuel



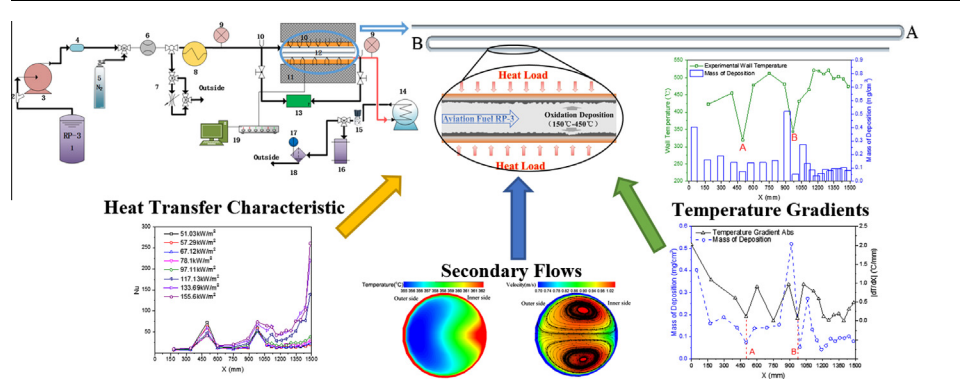
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## HIGHLIGHTS

- The effect of secondary flow on deposition depends on heat transfer and sublayer.
- The high temperature gradient results in the large deposits.
- The fuel temperature and oxygen amount affect the coke deposition.
- The heat-transfer correlation in the S-bend tube is modified and fitted.

## GRAPHICAL ABSTRACT



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## ABSTRACT

The effects of a complex flow and heat transfer of aviation fuel in an S-bend tube on oxidation coke deposition were both experimentally and numerically investigated. Deposition rates on the tube walls were measured by weighing for the regional analysis. Thermal oxidation deposits in the normal and high inlet temperatures were compared at a supercritical pressure of 3 MPa and the fuel outlet temperature up to 450 °C. The secondary flows at the bend have much influence on heat transfer characteristic, resulting in a sharp decline in wall temperature and deposition in the bend section. A large amount of deposits are corresponding to the high temperature gradients before and after the two bends. The high inlet fuel temperature significantly enhances the fuel temperature and oxygen consumption in the oxidation deposition reactions. The modified heat-transfer correlation in the S-bend tube was fitted at the supercritical pressure and different heat fluxes.

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## 1. Introduction

Recently, a promising technique that is to use aviation fuel to cool high-temperature air has been investigated for thermal management systems of next-generation aircraft [1]. The fuel absorbs heat as high heat-sink in an air–fuel exchanger and reacts with the dissolved oxygen to form coke deposits [2]. Any coke deposition on the surface of a heat exchanger from the reactions degrades

the cooling desired. Thus the thermal stability of fuel becomes a crucial aspect of justifying fuel quality.

In an actual fuel-cooling system, fuel undergoes complex flowing states from the fuel tank to the nozzle of combustor through cooling passageways. The structure of the heat-transfer passageways and the control of fluid parameters are of importance to avoid the coke deposition on the wall induced by high wall and fuel temperatures. The previous research mainly concentrated on the relationship between flow regimes and oxidation deposition in straight cylindrical tubes, including the investigations on flow pattern [3], Reynolds number [4], Prandtl number [5], buoyancy effect [6], stable and vibration environment [7], and cooling passage shapes

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[8,9]. However, the fact is that a heat-exchanger with high-efficiency contains complex flow passageways, such as a few bends in a compact space. It is obvious that secondary flows are induced in curved or bend tubes. Many previous studies [10–17] have already systematically investigated the phenomenon and enhancement effect of the secondary flows on heat transfer characteristics. Hawthorne [10] has found that secondary flows in bends were oscillatory and the direction of the circulation was changed periodically. Rowe [11] has studied the behaviors of the induced secondary flows in transition regions before the curved flow fully developed in various pipe bends experimentally and computationally. Dravid et al. [12] studied laminar flow heat transfer in helically coiled tubes both in the fully developed region and in the thermal entrance region to examine the effect of secondary flow. Hedlund and Ligrani [13] observed that in a channel with a straight portion followed by a portion with mild curvature, Nusselt number of fluid was enhanced due to a transition of laminar-to-turbulent flow and then drastically varied in the downstream curved portion. Stoesser et al. [14] and Aly [15] predicted the secondary flows and primary helical flow patterns. Kumar et al. [16] investigated hydrodynamic and thermal performance in the curved tube due to the variation of the thermo-physical properties of fluids. Naphon and Wongwises [17] studied the heat transfer and characteristics of single-phase and two-phase flow in curved tubes and summarized the correlations of heat transfer coefficients.

The fuel thermal stability and coke deposition were affected by many factors, including physical and chemical ones. Chin et al. [18] concluded that the temperature was the most important factor for deposition reactions. The flow conditions, determined by the system pressure [19], flow mass rates or velocity, and test duration [20,21], were varied to examine their influences on coke deposition. As for the chemical aspects, fuel compositions [22,23], additives [24,25] and catalysis and surface effect [26,27] were investigated systematically in a variety of fuel samples and reactors. Especially, Edwards and Zabarnick [28] pointed that the reaction of dissolved oxygen with hydrocarbons formed hydroperoxides which were intimately involved in deposit formation.

However, the influences of secondary flow on oxidation deposition of aviation fuels have not been studied previously. In this work, an S-shape tube with two 180° bends, operating at a supercritical pressure of 3 MPa, was chosen to simulate the heat-exchanger in the fuel-cooling system. The behaviors of the induced secondary flows were presented in detail. The effects of secondary flows on heat transfer characteristic and fuel oxidation deposition were analyzed. Thermal oxidation deposits in the normal and high inlet temperatures were compared experimentally.

## 2. Experimental setup

The setup of oxidation deposition flowing experimental is illustrated in Fig. 1. The apparatuses consist of four subsystems, including feeding, heating and reactor, data acquisition/controlling, and sampling/online analysis systems. An indirect electrically heated S-tube with stainless steel of SS-316 (inner diameter: 2 mm; outer diameter: 3 mm; length: 1500 mm) was utilized to simulate a heat-exchanger, in which the heat transfer and thermally oxidation deposition of fuel occurred. In view of the fact that the amount of oxidation deposition is strongly affected by the test duration, the heating lasted for 2.5 h to guarantee the formation of sufficient deposits for analysis. The amount of deposition was measured by weighing method. A high-precision balance (ESJ182-4, LongTeng Inc.) was implemented to weigh each segment with an accuracy of 0.01 mg. The detailed experimental parameters are given in Table 1. The pressure in the tube and the mass flow rate were controlled at 3 MPa and 1 g/s, respectively. The oxygen concentration

was monitored via an oxygen sensor (17, InPro 6850i, Mettler Toledo Inc.) dipped in the fuel sample system at the outlet of test section. Chinese No. 3 (RP-3) kerosene was chosen as the investigated aviation fuel for its widely application. The physical properties of RP-3 aviation kerosene are listed in Table 2 [29].

The outer wall temperatures of the reactor tube were measured by using 18 K-type thermocouples which were uniformly arranged along the S-tube. The inlet and outlet fuel temperatures were monitored by a tee that enabled the thermocouple inserted into the flow. The temperature measurement error was  $\pm 1.5$  °C. The model of the reaction section is showed in Fig. 2 and the locations of A and B are the first and the second bend location, respectively. The length of the reactor was 1500 mm, and the inner diameter was 2 mm with 0.5 mm wall thickness.

Heat transfer coefficient of the experiment can be calculated as:  $h = q/(T_w - T_b)$ , where  $q$  is the heat flux which depends on the heating power and excludes the heat loss. The Nusselt number ( $Nu$ ) is defined as:  $(h * d)/\kappa$ , where  $h$  is the convective heat transfer coefficient,  $d$  is the inner diameter of the tube and  $\kappa$  is the thermal conductivity of the fuel. The system heat loss to the environment can be minimized through insulation and obtained through calibration without a fuel flow.

## 3. Numerical model

A commercially software, Ansys Fluent [30], was applied to solve the steady and three-dimensional flow as well as heat transfer in the S-bend tube model. Due to the fact that there was the transition from laminar to turbulent flow, the turbulent model of standard  $k-\epsilon$  was used. The governing equations in finite volume form were solved iteratively by using a second-order upwind scheme. In addition, the SIMPLEC pressure-velocity coupling scheme was employed in the solution of the momentum equations. When the normalized error residuals for all of the calculated variables reduced to six orders of magnitude below their maxima, the solution was deemed to be converged. The inlet condition was set as a constant mass flow rate of 1 g/s. The exit plane velocity and temperature profiles were obtained by extrapolation from interior cell values. The mesh of the second bend and the cross section that is the o-grid of the S-tube are showed in Fig. 3. On account of the fact that the autoxidation reaction is not violent comparing to the thermal-cracking reaction, the processes of the oxidization deposition and the chemical reactions were neglected in the simulations. The near-wall mesh was fine enough to be able to resolve the viscous sublayer, typically with the first near-wall node placed at  $y^+ \approx 1$  for the simulation. The total number of mesh nodes was 182,520.

The 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-components surrogate model [31]. When the flow state is close to the critical point, small changes in pressure or temperature significantly influence the thermal properties. The fuel becomes a supercritical fluid with gas-like diffusivity, density and viscosity. The experimental heat sink, that represents the heat-absorbing ability of fuel are compared to the calculated data in Fig. 4 to verify the simulation model. Based on the energy balance principle, the overall heat sink capacity of the fuel was measured directly [32]. The experiments and simulations in the study were just focused on the autoxidation reactions ranged from 150 °C to 450 °C. In Fig. 4, the heat sink of fuel is influenced by the oxidation deposition only slightly, therefore, the numerical results are in good agreement with the experimental ones in the range of autoxidation. Beyond the 450 °C, the thermal-cracking reaction begins to dominate in the flow, resulting in that the experimental heat sink

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