Fuel 214 (2018) 528–537

Contents lists available at ScienceDirect

Fuel

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

Prediction of growth of jet fuel autoxidative deposits at inner surface of a replicated jet engine burner feed arm

Ehsan Alborzi*, Simon Blakey, Hassan Ghadbeigi, Christophe Pinna

Department of Mechanical Engineering, The University of Sheffield, Sheffield, England, United Kingdom

ARTICLE INFO

Keywords:
Aviation fuel
Thermal oxidative stability
Surface deposition

ABSTRACT

A low thermally stable jet A-1 fuel was heated up to 115 h under engine representative condition in a simulated burner feed arm with cylindrical shape using "Aviation Fuel Thermal Stability Test Unit (AFTSTU)". The local growth of surface carbonaceous deposits was measured by the use of three K-type thermocouples which were inserted in discrete locations along the inner surface of heated tube. Subsequently, the deposited tube was sectioned and prepared for "Scanning Electron Microscopy(SEM)" to visualise the circumferential profile of the carbonaceous deposit. This helped to identify the axial profile of deposit thickness by integration of the average deposit thickness at five cross sections along the tube. Using the temperature rise data, a one dimensional, analytical heat transfer model was used to calculate local deposit thickness as a function of time.

A transient fuel dependent, two stage chemical kinetic model was developed to simulate the growth of deposit as a function of time, temperature, and fuel chemical composition. In this model, the growth of deposit was assumed to be equal as a geometrical displacement in radial direction. Such a displacement is explicitly calculated using an initial rate of deposition(steady state at t = 0) and accelerating deposition rate(at $t = t + \Delta t$) to account for the non linear rate of deposition over the time period of thermal exposure. The concentration of insoluble species and initial rate of deposition as well as temperature at the adjacent layer to the heated surface were obtained through a steady state "computational fluid dynamics(CFD)" simulation using pseudo detailed mechanism of fuel autoxidation by Kuprowicz et al. (2007). The rate parameters of the accelerating deposition were optimised by the application of pattern search method with respect to the calculated deposit thickness from one dimensional heat transfer model. Eventually, the optimised model was used with a transient CFD simulation with dynamic mesh using Ansys Fluent commercial package to predict the growth of deposit in a reactive flow medium. The predicted results are in good agreement with the experimental data obtained from visualised deposit.

1. Introduction

Gas turbine fuels are exposed to thermal stress on route from the fuel tank through the engine to the combustion chamber. Due to the heat transfer from engine components to bulk fuel, the fuel temperature increases. In such a situation fuel begins to degrade which manifests itself by formation of a series of soluble and insoluble products. These products collectively participate to the formation of surface carbonaceous deposits in fuel system. Within jet fuel system, burner feed arms are at the highest risk of deposition.

A robust theoretical framework allows the prediction and control of deposit build up so that feed arms may be designed with an acceptable maintenance frequency and life span. Several studies conducted on jet fuel thermal degradation over the past few decades have attempted to provide quantitative information on the impact of operating variables on surface deposition. However, given a large number of interacting parameters, many tests are needed to isolate the individual effects and hence a comprehensive predictive model for practical application is still lacking.

As an alternative solution, application of empirical models is useful approach where complex small scale events occurring at fuel-surface interface are solved by small number of equations with physically reasonable forms. The robustness of such models is primarily dependent on the similitude of the experiment with realistic conditions met in aero engines as the model parameters need to be calibrated based on the experimental results. It is noteworthy that due to the fuel volume and test time required, a representative test at full scale is remarkably costly; therefore there are always compromises between the number of controlling parameters and test conditions based on the goal of the research and available resources. The AFTSTU[2–4] is a pilot scale test

* Corresponding author.
E-mail address: e.alborzi@sheffield.ac.uk (E. Alborzi).

https://doi.org/10.1016/j.fuel.2017.10.006
Received 22 January 2017; Received in revised form 26 June 2017; Accepted 4 October 2017
Available online 23 November 2017
0016-2361/

Nomenclature

Δy	distance to the nearest wall (m)
ϵ	emissivity (W/m^2)
$\frac{d\delta}{dt}$	initial rate of deposition (kg/m^2.s)
μ	dynamic viscosity (kg/m.s)
ρ	density of fluid (kg/m^3)
$\rho_{precursor}$	density of insoluble materials (kg/m^3)
τ_w	wall shear stress (kg/m.s^2)
$f_{precursor}$	precursor mass fraction in the first row of computational cell in heated wall adjacency
J_k	effective diffusivity of species k (m^2/s)
M_W	molecular weight of insoluble (kg/mol)
Q	heat flux (W/m^2)
Sd_k	chemical source term for consumption of species k
Sf_k	chemical source term for formation of species k
$\left[\frac{d\delta}{dt}\right]_{t+\Delta t}$	cumulative rate of deposition (kg/m^2.s)
$\Delta\delta$	deposit thickness (m)
δP	penetration depth (m)
μ_m	magnetic permeability of stainless steel (H/m)
ρ_D	density of deposit (kg/m^3)
ρ_R	resistivity of stainless steel (Ωm)
σ	Stefan–Boltzmann constant()
A_1	pre exponential factor for initial deposition stage (s^{-1})
A_2	pre exponential factor for transient deposition stage (s^{-1})
E_{a1}	activation energy for initial deposition stage (kcal/mol)
E_{a2}	Activation energy for transient deposition stage (kcal/mol)
f_i	frequency of induction (kHz)
h_{fuel}	natural convection heat transfer for fuel (W/m^2.K)
n	surface factor (dimensionless)
R	universal gas constant (J/mol K)
r	updated radial position (m)
r_0	initial radial position (m)
T	absolute temperature (K)
T_0	wall temperature at time zero (K)
T_a	air temperature (K)
T_t	wall temperature at time t (K)
T_w	wall temperature (K)
T_{bulk}	bulk fuel temperature (K)
y^+	distance from the inner wall to the nearest node (dimensionless)

rig capable of assessing interactions of a simulated aero engine fuel system with fuel thermal degradation. This rig replicates conditions in a range of current and future aero engines ensuring that the fuel arrives at the simulated burner feed arm in a fairly representative condition to that in service.

The work presented here describes a new transient fuel dependent, two stage kinetic, empirical model for jet fuel autoxidative surface deposition. This model was implemented into a two dimensional axis symmetric CFD case file created in Ansys Fluent with a moving boundary corresponding to the fuel wetted surface along the heated tube. It was assumed that the boundary displacement is the net result of transformation of all insoluble materials generated in heated surface adjacency into the deposit layer. This is according to the assumption made by Moses [5] that when the temperature at fuel wetted surface is at least 45 °C higher than core temperature, almost 90% of the insoluble materials will be formed within the laminar sublayer [6]. This assumption is based on the fact that approximately two thirds of temperature changes occur within the laminar sub layer and that the formation of deposit precursors follows an exponential relation to the bulk fuel temperature. The AFTSTU was used for the experimental study of autoxidative deposit build up in a simulated burner feed arm. Pattern search optimisation technique was used outside the CFD calculation loop to calibrate the model parameters with respect to the experimental data obtained from the AFTSTU. Contrary to the previous transient deposition models such as Krazinski et al. [7], Roquemore and Reddy [8] and Katta and Roquemore [9], the empirical model presented here employs more realistic autoxidation chemical kinetic mechanism for conventional petroluem derived jet fuel as presented in references [1,10–12].

2. Experimental work

2.1. Jet fuel thermal stressing test

The burner feed arm represents a cold drawn 316 stainless steel, cylindrical tube with 6 mm od and 2 mm id. This contains a series of 6 K-type sheathed thermocouples silver brazed into the tube wall. The thermocouples were arranged in two sets of three and inserted in the locations 2(Thermocouple A), 3(Thermocouple B) and 4(Thermocouple C) as shown in Fig. 1. The three outer thermocouples are 0.2 mm from the tube outer surface and the three inner are 0.4 mm from the inner tube surface respectively. A radio frequency induction coil with a total length of 120 mm was centered on the second axial thermocouple (point 3 in Fig. 1). The fundamental principle of the induction heating is based on the electromagnetic induction, where the current is induced in the conductive materials and as a result of the electrical resistance, heat is generated in the material. The electromagnetic field penetrates to a certain depth from the surface of the material, known as the skin effect [13]. The skin effect is explicitly described in the numerical section of this work. The simplified schematic of the AFTSTU is shown in Fig. 2.

The fuel sample was analysed externally using an in house method as developed by Intertek. This method determines sulfur containing compounds and group types in middle distillates using an Agilent 7890N “Gas Chromatograph(GC)” equipped with a Zoex thermal modulation and an Agilent 355 sulfur chemiluminescence detector. Quantification of sulfur classes was carried out by the normalisation to

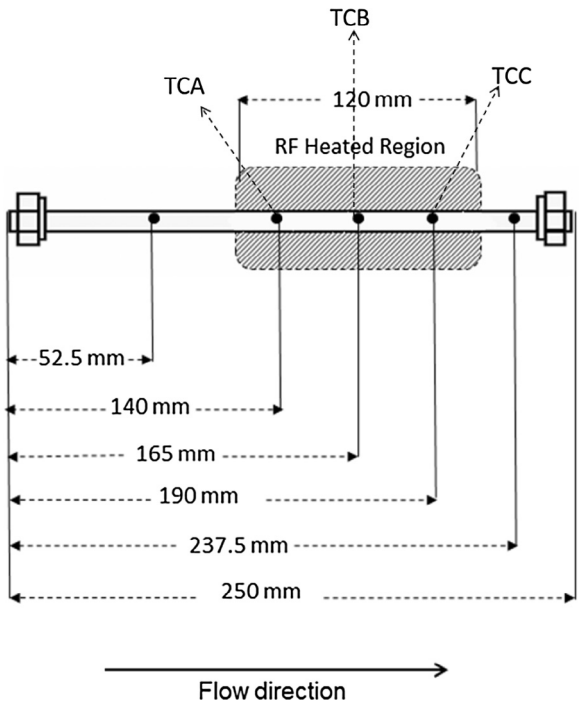

Fig. 1. Cutting cross sections along the heated tube(not to scale).