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Investigation of deposition in aviation gas turbine fuel nozzles by coupling of experimental data and heat transfer calculations

Spiridon Siouris *, Simon Blakey, Christopher W. Wilson

Department of Mechanical Engineering, The University of Sheffield, Mappin Street, Sheffield S1 3JD, England, UK

HIGHLIGHTS

- ▶ Fuel deposits were generated experimentally and modelled by heat transfer model.
- ▶ Results showed that deposition is largely dependent on fuel inlet temperature.
- ▶ Heated tube initial wall temperature had a lesser effect on deposit formation.
- ▶ Uncertainty analysis demonstrated the reliability of the heat transfer calculations.
- ▶ The heat transfer model was found sensitive to thermocouple measurement accuracy.

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ABSTRACT

Fuel deposition in gas turbine nozzles is a problem that needs to be avoided, and for this reason many studies concerned with either experimental or Computational Fluid Dynamics methodologies for the investigation of deposition are being carried out. In this work, a Radio Frequency heated tube design is employed with the Aviation Fuel Thermal Stability Test Unit facility in which three sets of thermocouples are installed at different depths along a straight tube. Using thermocouple measurements and heat transfer calculations based on the locations of these thermocouples allowed for the generation of data such as radial heat transfer, deposition thickness, deposition thickness growth rate, and total deposit volume for each instant of the logged measurements. Deposition experiments were carried out with varying initial wall temperature and fuel inlet temperature, and it was observed that the most important parameter for deposition growth is the initial wall temperature rather than the fuel inlet. Furthermore, it was shown that as deposition forms, the total heat transfer from the tube wall to the fuel remained the same. In addition to this, a shift of heat transfer from the tube outlet towards the tube inlet was observed where the deposition was less.

1. Introduction

The operating temperatures in gas turbine engines create an environment where fuel is thermally stressed to the point where deposition becomes an important consideration. Fuel deposition can affect the amount of flow through a pipe because when deposits form, the cross-sectional area through which fuel flows is reduced, leading to a decreased flow rate. This in turn may result to uneven flow between the fuel injectors, affecting spray patternation and creating areas of elevated temperatures, which in turn can thermally stress the fuel even more. The effects of spalting of deposits from areas that are upstream to the ejector nozzles may also contribute to flow restriction the nozzles. In addition to the reduction in cross-sectional area, another effect that deposition has is the insulation against heat transfer between the pipe and the fuel flowing through it. Since an additional aim of the fuel is to transfer heat away from the hot components, the deposition layer will reduce this function due to the added thermal resistance from the deposits. This can therefore render the fuel ineffective at cooling, resulting in higher-than-normal temperatures of the metal components at the deposition site.

Fig. 1 displays a schematic representation of a cross section of a tube, and a deposit layer on the inner surface that has caused a reduction in cross sectional area where fuel flows. Furthermore, it can be seen from this figure, that the deposits lie between the metal and fuel, effectively forming an additional layer for the heat transferred from the metal to the fuel.

Deposition can either be investigated by experimental methods, or by numerical simulations. Numerical simulations are based on solving a combination of flow equations with either particle trajectory models [1], or chemistry models with a sticking probability

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* Corresponding author.
E-mail address: s.siouris@sheffield.ac.uk (S. Siouris).

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Nomenclature

A_r	infinitesimal tube cross-sectional area at radial location r (m^2)
k_d	deposit thermal conductivity (W/m K)
k_{ss}	tube thermal conductivity (W/m K)
l	tube axial length (m)
q_r	radial heat transfer (W)
r_d	deposit wetted surface radius (m)
r_i	tube inner radius (m)
r_o	tube outer radius (m)
r_{in}	radial location of inner thermocouple (m)
r_{out}	radial location of outer thermocouple (m)
t_d	deposit thickness (m)
T_{in}	temperature at inner thermocouple (°C)
T_{out}	temperature at outer thermocouple (°C)
V_d	deposit volume (m^3)

mechanism [2]. Other examples of such numerical methods have also been reported elsewhere. Fluid flow simulations on a cylindrical co-ordinate system representing pipe flow were carried out in [3]. In this study, a chemical kinetics model was used to account for the production of deposits, subsequently affecting the inner diameter of the tube and therefore the extent of the computational domain. Very good agreements between experimental and computational results were presented, highlighting the effects of fouling on heat transfer and blockage of the fluid flow. However, the effects of changes in deposit density were not accounted for. This was addressed in [4] where Direct Numerical Simulation (DNS) allowed an insight on how density changes throughout the deposition layers. In addition to density, particle size plays an important role in the deposition process. The study in [5] showed that for large particles, gravity plays an important role in deposition, whereas for smaller particles the hydrodynamic interactions tend to randomize the particle location on the deposition surface.

The other method for deposition investigation is by means of experimental methods, and the most fundamental implementation is in a simple pipe flow configuration such as in [6]. In that study, an apparatus was developed in which the dissolved oxygen in the fuel could be varied prior to entering stainless steel pipes inside heated block sections. The determination of deposits was made by slicing these pipes at the end of the experiments and results showed that there can be cases where fuel de-oxygenation may increase the tendency for deposition. Furthermore, this study demonstrated that the chemical kinetics of reactions leading to deposition with fuels of low oxygen concentration, are different to those with air-saturated fuels.

Such method of slicing the tube for carbon deposition measurements was also employed in [7]. From inspection of the carbon deposits on the tubes, it was found that for higher heat fluxes, the structure of the deposits was more ordered, compared to the amorphous structure from lower heat fluxes. Another experimental study that used a similar method can be seen in [8] for the parameters that affect deposition. The apparatus consisted of a parallel configuration of tubes that were heated by the same block, and supplied by a single source of fuel. The conclusion was that the most important parameter for deposit formation is fuel temperature. For the case of low and moderate Reynolds numbers, species transport and diffusion are the next more important factors, while residence time is less important at high temperatures at low to moderate Reynolds numbers.

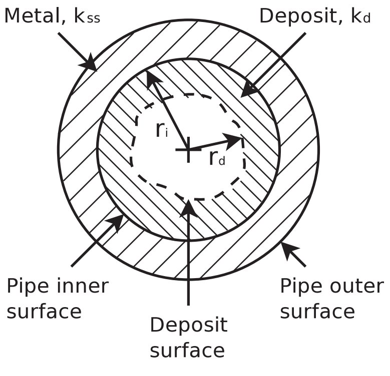

Fig. 1. Cross sectional area of a tube of inner radius r_i, thermal conductivity k_{ss}, and a deposit with a thermal conductivity of k_d, where its inner surface is at a mean distance r_d from the centre of the tube.

An improved representation of gas turbine fuel system was presented in [9] using the *Aviation Fuel Thermal Stability Test Unit* (AFTSTU) experimental facility, which is the same facility used for the investigations in current article. This study focused on the effects of additive packages in terms of fuel thermal stability and deposition. It was found that additive effectiveness depends on the stability of the base fuel, and also that deposit formation was decreased with the introduction of additives in the JP-8 + 100 fuel. Furthermore, a reduction of deposit build-up was observed in the high-pressure system filter units in the JP-8 + 100 fuel.

From the above methods, the main drawback for the determination of deposition is that such information can only be derived for the final stage of an experiment. In order to derive deposition thickness and growth rate versus time, several experiments need to be carried out. The work in the current article aims to overcome this problem by using experimental methods in combination with a heat transfer model that uses as input, the measurements from thermocouples placed at specific locations along tube and at different depths. This work is based on [9], but with the main focus being the effects of fuel inlet and initial wall temperatures on the deposition characteristics. Using such methodology enables deposition calculations that allow the investigation of deposition as the experiment is carried out.

2. Experimental apparatus

The work in this article used the AFTSTU [9] to promote fuel deposits in a straight tube. This test rig offers accelerated engine operating conditions at a fraction of the costs involved in gas turbine engine endurance testing. The AFTSTU is of a modular construction, as shown by the block diagram in Fig. 2. This configuration is representative of aviation gas turbine heat loads which cause the formation of chemical pre-cursors to carbon deposition.

Fuel flows in a single pass through the rig from the Fuel Supply Tank, through the Low Pressure (LP) system which contains a representative LP filter. The operating conditions at this region are nominally 50 °C at 3.5 bar. The fuel then passes though an intermediate temperature, high pressure (HP) region (nominally 180 °C at 35 bar) which contains a hydraulic stiction valve, a HP filter, and finally the Radio Frequency (RF)-heated tube which represents the burner feed arm. As the fuel is not combusted, the fuel then passes through filtration, cooling and further filtration before passing to a dump tank. This allows further information about soluble and insoluble deposits to be collected.