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Fully transient modeling of the heavy fuel oil droplets evaporation

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ABSTRACT

In this paper, evaporation of heavy fuel oil (HFO) droplet under atmospheric pressure is studied through a fully transient approach. The HFO is considered as a multi-component liquid with temperature-dependent properties. The performance of this fully transient approach is evaluated for different fuels and results are compared with available experimental data for gasoline and diesel fuel. The comparison shows excellent agreements, and also reveals the flexibility of this approach for interpretation and justification of the evaporation process details by using of internal distribution of temperature and composition. Based on distillation curve, several multi-component compositions are presented for the HFO. The composition is broken down into several pseudo-components and the effects of number of components and their method of selecting are studied comparatively. It shows that despite the wide range of compositions of heavy fuels, a compound consists of a few numbers of pseudo-components can be a suitable representative for them. Also pseudo-components should be chosen with equal interval temperature and narrow boiling temperature range. The effects of environment temperature on the evaporation of droplets are investigated in a parametric study. The results show that internal temperature distribution is not very sensitive to the ambient temperature due to the high boiling temperature of heavy components of the fuel. Also wide span of temperature in the heavy fuel droplet makes it possible to predict the initial condition of pyrolysis and thermal cracking of heavier components.

1. Introduction

Heavy Fuel oils (HFOs) which are formed by adding cutter stock to refinery residue [1], have extensive applications in power plants, marine engines, industrial furnaces and other combustion systems. Also, decreasing the quality of crude oils and new non-conventional petroleum reservoirs, leads to higher production of lower quality HFO [2], therefore, its abundance and lower price make it an interesting option as fuel. However, HFO combustion results in sulfur oxides emissions and particulate matters such as smoke, cenospheres and ash [3], therefore, their application in gasification process to obtain syngas became interesting. Produced syngas can be used for power generation in integrated gasification combined cycle (IGCC) or for using as feedstock for chemical production [4,5]. In most of the applications, HFO is introduced to reactors and combustors as spray. When fuel droplets are exposed to hot ambient, first, significant portion of them undergoes evaporation. Vapor produced from the vaporization and remaining residue of droplet participate in chemical reactions. Therefore, evaporation of HFO droplets is an important stage in its combustion and gasification, and study of evaporation of HFO droplet enhances our understanding of its behavior in chemical processes.

One of the challenges in the modeling of processes on HFO, rises from its complex composition which strongly depends on its origin and refinery process. Therefore, it is not readily possible to assign a known composition to the HFO. For characterization of undefined hydrocarbon mixtures, like HFO, several methods have been developed which can be categorized into two groups: continuous approach, discrete components approach. In continuous thermodynamics continuous distributions for components properties in terms of some parameter like molecular weight, boiling point or carbon number are used [6]. As a result, only mean and variance of the distribution function are sufficient for describing the fuel mixture. For better describing a complex mixture with wide range boiling point, multi-distribution functions are used [7,8]. In discrete components approach, finite number of components are defined to describe the fuel properties. These components can be real or pseudo components (PCs). For HFO, due to its large number of compounds, pseudo component approach is more suitable. Pseudo components of a fuel are in fact petroleum cuts which are defined based on its distillation curve and each one is treated like a compound. These pseudo components are characterized by an average boiling point and specific gravity. Miquel et al. calculated the specific gravity of each PC by dividing the distillation curve into a number of fractions based on equally temperature steps and solving the conservation equations of volume, mass, and mole [9]. Several correlations are proposed to

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determine the critical constants and thermophysical and transport properties of PCs. Lee-Kesler correlations are among the most common used ones [10]. A comprehensive collection of the different correlations are presented by Riazi [11]. The pseudo component approach were used by several researchers to characterize heavy oil and HFO. Kariznovi et al. investigated the solubility of different gases in Bitumen by defining the PCs and extraction the thermodynamic parameters and presented its overall PC composition [12]. In order to modeling of heavy fuel phase equilibrium, Díaz et al. divided the distillation curve into three light, middle, and heavy regions and defined a number of PCs for each region. They compared the existing correlations for determining the critical properties and molecular weight and extracted the phase equilibrium parameters for a cubic equation of state [13]. Also, He and Ghoniem modeled the phase equilibrium between fuel oil and solvent by defining of PCs [10]. They estimated the occurrence of functional molecular groups in order to determine the binary interaction parameters for each PC.

As it was mentioned, HFO consists of large number of components. Hence, its droplet evaporation should be studies based on multicomponent droplet evaporation models. Evaporation of multicomponent droplet is different from single component one in both liquid and gas phases. The more volatile species, evaporates earlier and in most cases preferential evaporation is dominant. The different volatile components evaporate at different rates and this causes a concentration gradient inside the droplet. Different vapors are presented around the droplet. Each component penetrates in the environment with its own velocity. Therefore an extremely variable ambient is created. This causes temporal variation of heat transfer from ambient to the droplet as a controlling factor. At the surface, a portion of heat is consumed for providing evaporation latent heat and the remaining leads to droplet heating up. Variation of droplet composition with time causes variable heating rate of droplet. Therefore, it is needed to account for time variations of different processes. Matalon and Law reported that unsteadiness in the gas phase changes droplet evaporation rate in order of square root of gas to liquid densities ratio [14] and hence as fuel becomes heavier the effect of unsteadiness in the evaporation is magnified. It should not be expected that the HFO evaporates completely, since it contains resins and asphaltenes. Temperature gain is not enough for evaporation of fuel's very heavy components. It has been showed that some heavy components instead of vaporization are break down through pyrolysis at relatively low temperature [15]. In other words, some part of fuel, which does not evaporate, converts into gas phase and solid phase which mostly consists of carbon. Therefore, this part is burned in a heterogeneous combustion of solid and gas phases [16].

The evaporation of multicomponent droplets, due to their diverse applications, have been studied with different models. These models can be categorized into three groups: multicomponent discrete models, multicomponent continues models, and hybrid models. In discrete models, each component is considered individually and the species transport equation for all the component is solved [17]. In continuous models, as it was described earlier, the composition of fuel is denoted as a continuous distribution function in terms of a parameter, and the transport equations are solved for distribution function parameters [18]. Finally, hybrid models divide fuel into discrete components and consider a distribution function for each discrete component [19].

Discrete models have been widely used for multicomponent droplets studies. However, there are a few studies for heavy fuel based on these models. Shyu et al. presented an analytical model for combustion and evaporation of heavy fuel droplet by using simplifying assumptions and reported that the results are improved with considering variations of thermo-physical properties with temperature [20]. Stamoudis et al. presented a model for combustion and evaporation of a heavy fuel droplet in marine engine, and assumed that the fuel consists of a light and a heavy component [21]. One of the conventional assumption in the discrete modeling of the multicomponent droplet is gas phase quasi steadiness. Aggarwal and Mawid studied effect of fuel vapor accumulation around the droplet, which leads to unsteadiness behavior at the gas phase, in combustion and evaporation of multicomponent droplet and reported that vapor accumulation according to gas phase Lewis number can lead to oscillatory vaporization [22]. Wong et al. showed that considering gas phase unsteadiness has great importance in the accurate prediction of ignition delay [23]. For this reason, some studies are done for droplet evaporation modeling by considering gas phase unsteadiness. Zhu et al. investigated single component heptane droplet evaporation by solving unsteady equations at liquid and gas phases and reported that gas phase unsteadiness has significant importance in the initial stage of evaporation and high pressures [24].

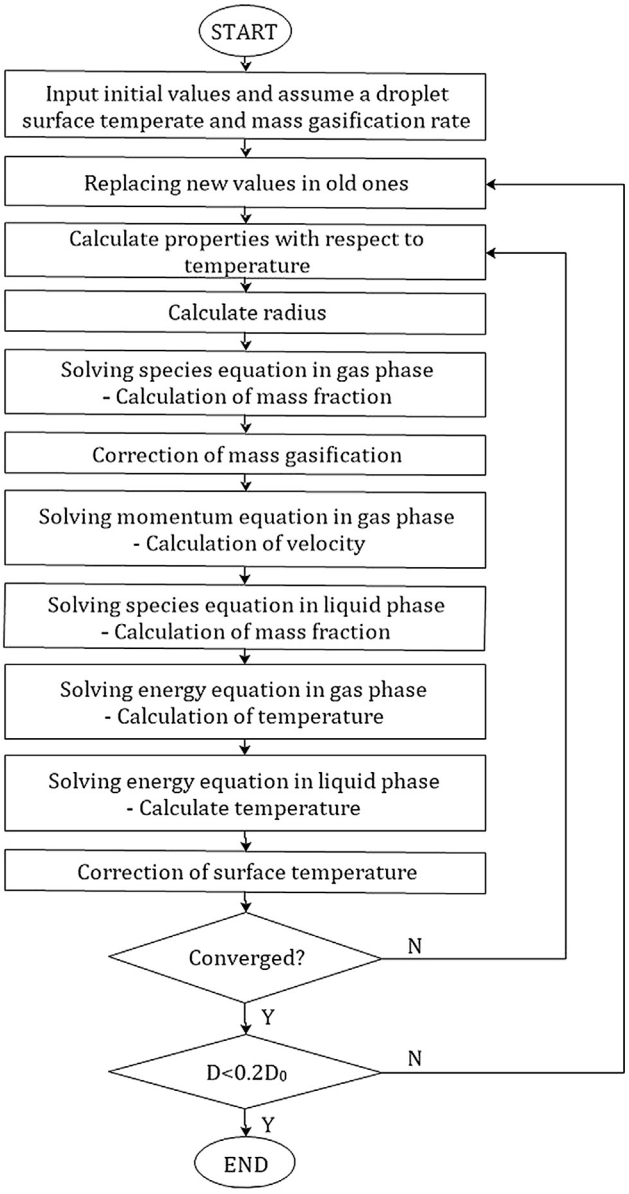

Fig. 1. Flowchart of the solution algorithm for droplet evaporation model.

According to the mentioned studies, it seems that there are limited studies on heavy fuel droplet evaporation. Following our previous researches on fully transient modeling of single component [25], and multicomponent [26] droplet evaporation, it is concluded that gas phase unsteadiness on evaporation of these sorts of droplets has greater importance than light fuel. Therefore this study aims to investigate the heavy fuel oil droplet evaporation using fully transient approach.

The main contribution of this work are marked as follows: