International Journal of Heat and Mass Transfer 128 (2019) 115–124

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Drop evaporation of hydrocarbon fluids with deposit formation

Philipp Hänichen *, Achim Bender, Bernhard Voß, Tatiana Gambaryan-Roisman, Peter Stephan

Institute for Technical Thermodynamics, Technische Universität Darmstadt, Alarich-Weiss-Straße 10, 64287 Darmstadt, Germany

ARTICLE INFO

Article history:
Received 15 November 2017
Received in revised form 22 August 2018
Accepted 23 August 2018

Keywords:
Deposit formation
Phase change
Heat transfer
Drop evaporation
Contact angle measurements

ABSTRACT

The evaporation and deposit formation process of a hydrocarbon drop on a heated aluminium surface is experimentally investigated and compared to a physico-mathematical model. To analyze the effect of wall temperature on deposit formation, the experiments are conducted for three substrate temperatures below, one temperature close to and one temperature above the saturation point for atmospheric pressure. In each experimental run 500 single drops with constant volume are deposited and evaporated successively. The shape evolution of the drops is recorded with a monochrome camera sidewards. The deposited mass is evaluated as well as the contact angle evolution and drop lifetime. The experiments show a strong dependency of the contact angle on the deposit formation and on the wall temperature. With higher wall temperatures and an ongoing deposit formation, the initial contact angles increase and drop lifetime is reduced. The appearing deposits vary from light yellow and highly viscous films to dark brown solid layers and black particles, depending on the applied substrate temperatures. The model based calculations show a possibility to describe the evaporation process with effective diffusive transport.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

Evaporating fuel compounds on hot internal walls of automotive combustion engines tend to form deposits leading to increased NO_x and particulate emissions, misfire and reduced engine torque. The liquid hydrocarbons undergo various oxidative reactions and polymerization. This complex deposit formation process interacts strongly with the hydrodynamics and heat transport. Porous deposit layers are preferentially wetted and the liquid phase can be trapped inside cavities. During evaporation, low boiling fractions evaporate whereas the compounds with higher saturation temperatures remain on the walls. The local deposit layers lead to an uneven heat transfer through the wall. Depending on deposit morphology, roughness and porosity, the heat transfer and, thus, evaporation rate and deposit growth are influenced. A basic insight in the local evaporation phenomena is required to understand the mechanisms of the deposit formation.

In literature numerous engine dynamometer experiments are reported, in which the global impacts of fuel derived deposits on engine performance or the effect of operating conditions and different fuels on deposit growth are investigated. Arters et al. [1] found injector fouling to be correlated with fuel consumption, hydrocarbon and carbon monoxide emissions, as well as particulate emissions.

Generally, the deposit formation is stronger in direct injection gasoline engines than in port fuel injection engines [2]. Güralp et al. [3] conducted engine dynamometer tests with a homogeneous charge compression ignition test engine and concluded that the effect of combustion chamber deposits on bulk burning near the wall is greater than the global reduction of heat loss. As shown by Kinoshita et al. [4], injector nozzle temperatures above the fuel's T90 temperature lead to increased deposit formation as deposit precursors remain on the nozzle surface after a dryout. With an Electron Probe Micro Analysis of the deposits, the authors proved aromatic compounds to be one of the major functional groups of the deposits. Similar observations have been done by Ashida et al. [5], who also stated that the alkyl substituents influence the formation of injector deposits.

Recently numerous experimental investigations on a laboratory scale have been performed. Richter et al. [6] conducted a 70-h long-term experiment, in which Diesel fuel probes were heated up to 110 °C and 150 °C. The authors detected oxidized aromatic compounds, which are thought to be responsible for the carbon based deposit layers on injector components. Song et al. [7] investigated the effects of deposits on spray behavior of a gasoline direct injector. The coral shaped deposits with particle sizes of less than 5 µm lead to an increased spray cone angle and to a decrease of the spray particle size in combination with a higher standard

---

* Corresponding author.
E-mail address: haenichen@ttd.tu-darmstadt.de (P. Hänichen).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.102
0017-9310/© 2018 Elsevier Ltd. All rights reserved.

deviation. Generic experiments have been done by Arifin et al. [8,9], who investigated the deposit formation of single diesel and bio-diesel drops impinging and evaporating on a hot plate. Deegan et al. [10] firstly reported of capillary flows inside sessile drops carrying dispersed solid particles from the bulk to the edge region. The resulting ring deposits are often referred to as the coffee stains. As liquid evaporates mainly at the triple line, particles accumulate in that region. Similar deposit phenomena are observed for evaporating solutions. Due to the high local heatflux, the saturation concentration is reached initially at the triple line and solutes mainly precipitate or crystallize close to the edge of sessile drops. Schmid et al. [11] investigated this crystallization process for evaporating urea-water drops on heated surfaces and observed a significant heat release when the urea concentration reached the supersaturated conditions at the triple line. Drops evaporating on heated walls without deposit formation have been investigated by various authors. Crafton and Black [12] investigated experimentally evaporation of water and *n*-heptane droplets on copper and aluminum substrates. They found that the evolution of diameter, height, and contact angle vary radically for the two fluids. Picknett and Bexon [13] derived an expression for the evaporation rate based on the solution of the Laplace equation for the vapor concentration as a function of the contact angle. Hu and Larson [14] solved the evaporation problem in the absence of deposit formation numerically and Schönfeld et al. [15] found an approximate solution for the drop volume evolution for pinned drops. Popov [16] derived an analytical expression for the evaporation rate for arbitrary contact angles. Saada et al. [17] used numerical simulations to show the importance of the substrate dimensions and the buoyancy flow in the gas phase for the evaporation rate of the drops for substrate temperatures higher than the environment temperature. The thermal effects of the heat transfer in the substrate on the evaporation process was considered by Sobac and Brutin [18]. They showed that the importance of the substrate on the evaporation process increases with temperature. Lopes et al. [19] developed a numerical model for the transient heat conduction in a droplet, the substrate and the vapor diffusion in the gas phase. They reported that the local temperature distribution at the liquid-gas interface is governed be the transient heat transport. Sefiane and Bennacer [20] incorporated thermal effects of the substrate induced by evaporative cooling at the liquid-vapor interface into the correlation for the evaporation rate of pinned drops. Sodtke et al. [21] studied theoretically and numerically evaporating drops on heated substrates in a pure vapor atmosphere. No studies have been found considering deposit formation and associated varying wettability in the numerical simulation of the evaporation process.

The cited literature shows that surface temperatures and evaporation play a major role in fuel derived deposit formation. In this work, the main focus is to investigate experimentally the evolution of the apparent contact angle and the drop volume for single fuel drops during evaporation depending on the substrate temperature and the presence of deposit. The work is focused on the influence of deposits on wetting and evaporation and vice versa but not on the chemical reactions.

Furthermore, the dependence of the deposited mass as well as deposit shape and structure on the wall temperature are evaluated. The correlations for drop evaporation evolution found by previous authors are applied to evaporating hydrocarbons with deposit formation. The results are compared to the experimental data.

The rest of this paper is structured as follows: Firstly the experimental setup, measuring technique and test conditions are presented in Section 2. Section 3 gives an overview of the physico-mathematical model used. The experimental results regarding drop impingement, evaporation and deposit formation are summarized in Section 4 before they are compared to the model (Section 5). A discussion of the major findings can be found in Section 6. Finally, a summary and conclusion are given (Section 7).

2. Experiment

2.1. Test cell and equipment for repeatable drop evaporation experiments

The test cell (1) and the experimental equipment for the repeatable drop evaporation experiments are shown in Fig. 1. A temperature controlled, electrical heater (2) conducted to power supply 1 is used to heat the aluminium (AlMg3) substrate. The arithmetic average roughness for the substrates R_a is between 0.122 and 0.351 μm. Within the substrate a thin thermocouple is mounted to measure the temperature 0.5 mm below the surface. To reduce the heat losses from the substrate heater to the test cell and the environment, additional electrical heaters are placed in the test cell corners. A controllable syringe pump (3) is used to feed the injector needle with an outer diameter of 0.4 mm, which is positioned 3.4 mm above the substrate surface. Condensation on the side view windows and a change of the atmospheric composition due to evaporation are avoided by the application of a slight air flow ($20\,\mathrm{g\,h^{-1}}$) entering at the cell head. Numerical investigations of the isothermic flow field show no major influence of the flow on the substrate (see supplementary material). The maximum Rayleigh number in the investigated scenarios is $Ra = 1.15$. Additionally, the vapor transport in the gas phase under the influence of forced convection and diffusion was considered. The results show that the effect of forced convection on the vapor transport and, thus, on the drop evaporation process is negligible. A detailed description of the simulation can be found in the supplementary material. Thus, a still environment in the area close to the drop is assumed. The supply of fresh air is monitored with a coriolis flow meter (4) and set by a pressurestat.

Condensable reactants are collected inside a condenser (5) before the waste air is led to the filter system. The drop shape is detected with a CMOS monochrome camera.

2.2. Test conditions and methods

The experiments are conducted with the double aromatic hydrocarbon methylnaphthalene, $C_{11}H_{10}$, as the test fluid. Preliminary drop evaporation experiments with different fuels and hydrocarbons and with wall temperatures close to the saturation point of each test fluid have shown a higher deposit formation tendency for aromatic hydrocarbons and especially for the double aromatic hydrocarbon, $C_{11}H_{10}$ (in comparison with Fig. 2). The generated deposits are similar in morphology to real engine deposits formed by evaporation of fuel found on pistons and injector tips.

The experimental procedure is as follows: After preheating the substrate and the test cell, 500 single fluid drops are impinged on the substrate surface and evaporated. The time scale of the deposit formation process is much larger than the time scale of the individual drop evaporation. Therefore the deposit pattern, which is formed from an individual drop evaporation is negligible and a large number of drops is needed. The drop frequency f_{drop} is set to values ensuring that the next drop impinges the surface after the complete evaporation of the previous drop: $\Delta\tau_{\mathrm{drop}} = 1/f_{\mathrm{drop}} > \Delta\tau_{\mathrm{evap}}$. The number of drops is calculated from the feed volume and the feed rate of the syringe pump with an estimated error of ±5 drops. The procedure is executed for five wall temperatures, where three temperatures are below saturation (180 °C, 200 °C, 220 °C), one temperature is close to the saturation of methylnaphthalene (240 °C) and one temperature is above the saturation point

Download English Version:

https://daneshyari.com/en/article/10139852

Download Persian Version:

https://daneshyari.com/article/10139852

Daneshyari.com