International Journal of Heat and Fluid Flow 70 (2018) 125–130

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Experimental investigations of fuel film evaporation with deposit formation

Philipp Hänichen*, Maximilian van Eyk, Peter Stephan

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

ABSTRACT

A new test rig has been designed to investigate the effect of carbon based deposit layer formation on the hydrodynamics and heat transfer of a thin evaporating methylnaphthalene film, which builds deposits at a hot wall under thermal stress in an oxidative environment. The liquid film is shear driven by a preconditioned air flow, spread on a foil heater (joule heating) and evaporates. With a black and white camera the hydrodynamics of the moving film is visualized, whereas the temperature field below the foil is qualitatively measured with an IR camera. Prior to conducting the measurements the foil is wetted and dried periodically multiple times to form an initial deposit layer. For the main investigations the deposit layer is removed locally. The presented recordings show a direct effect of the deposit layer on wetting and heat transfer, and thus the ongoing deposit formation. Deposit layers are preferably wetted and act as thermal barriers leading to local higher wall temperatures and thus to a reduced foil cooling.

1. Introduction

In combustion engines thin liquid fuel films can develop and spread on hot cylinder walls, the piston, or injector tips. The evaporation of the hydrocarbons in the oxidative atmosphere can lead to deposit formation which has a negative effect on particle emissions, CO and NO_x emissions, fuel consumption, and engine performance (Arters et al., 1999; Arters and Macduff, 2000; Xu et al., 2015; Song et al., 2016). The wall temperature plays an important role for the formation of such deposits. Kinoshita et al. (1999) pointed out that injector tip temperatures above the fuel's T90 value, at which 90 vol% of the liquid fuel has been evaporated, leads to a tip dryout and thus impeds self-cleaning through washing primal deposits away. In contrast Combustion Chamber Deposits (CCD) form when reactive precursors within the gasphase condense on hot walls Cheng (2000). Jorand et al. (2000) stated that the gaseous mixture reacts at temperatures around 300 °C, condense afterwards and undergo further reactions. Richter et al. (2013) observed chemical changes of the fuel after heat treatment at 150 °C for 29 h and stated that these products are precursors for condensation and polymerization reactions which are responsible for the formation of deposits.

Regardless of whether reactive gas phases condense on combustion chamber walls or liquid films dry out at the injector tip, the two phase heat transfer seems to play a major role for the deposit formation process. However, to the best knowledge of the authors, the mutual interaction of the phase change heat transfer phenomena and the deposit formation has not been investigated so far in-situ. Consequently, the knowledge in this field is insufficient and no thermodynamical models are present. Countermeasures aim at using additives or simply adjusting temperature through design changes. The complexity and variety of the deposit formation mechanisms make repeatable and reproduceable engine and vehicle tests almost impossible, as not all of the test conditions are controllable in an accurate way and over a long period of time (Kalghatgi, 2013). In conclusion, a deeper insight in the involved deposit formation mechanisms and their interaction with the two phase heat transfer can only be obtained by generic experiments with controllable test conditions and optical access for high spatio-temporal resolved observation and temperature measurements. For high resolved temperature measurements in the proximity of evaporating films infrared (IR) thermography has been established e.g. in the recent works of Karwa et al. (2014) and Fischer et al. (2015).

In this work we present a generic test rig, which enables in-situ measurements at a heated wall element with visualization of the film formation and local dryout from the top as well as wall temperature profiles applying IR thermography on the backside of the thin wall. First qualitative results of a wetting and dryout event are presented and discussed.

2. Experimental setup and methods

2.1. Test facility

All experiments are conducted in an open loop flow channel according to the process diagram shown in Fig 1. Two compressors (1)

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

https://doi.org/10.1016/j.ijheatfluidflow.2018.02.001
Received 10 December 2017; Received in revised form 1 February 2018; Accepted 5 February 2018

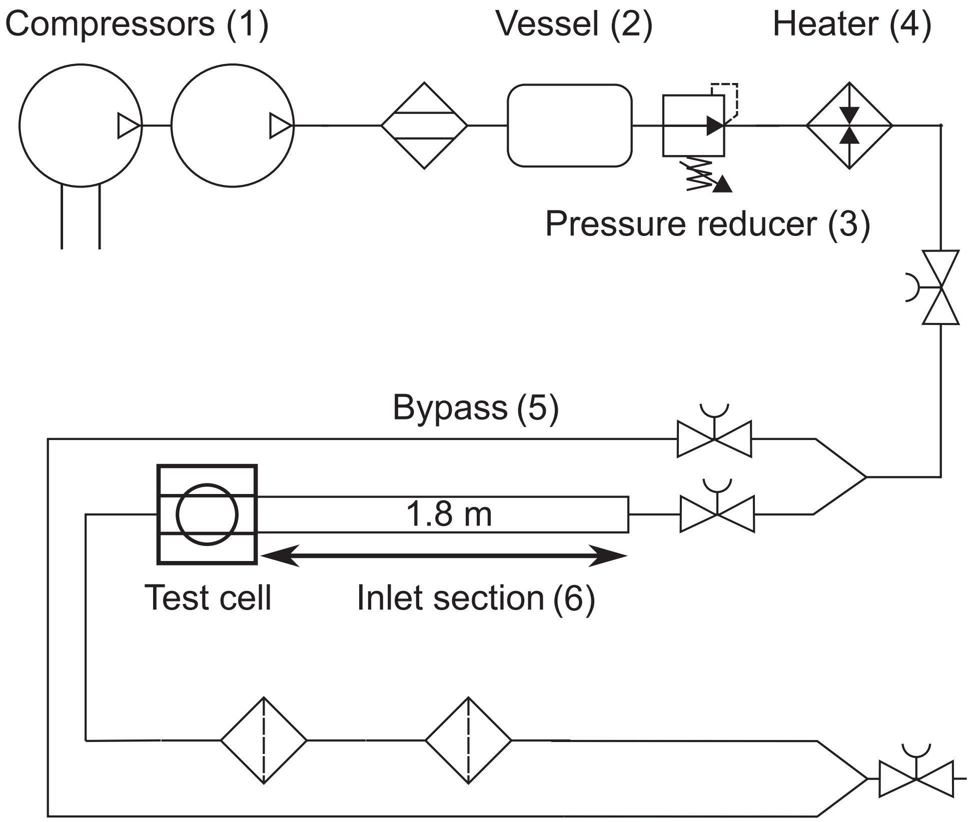

Fig. 1. Process diagram of air supply and conditioning (according to ISO 1219:2012).

Table 1
Operating range of the test facility.

ID	Component	Parameter	Value
(1)	Compressors	$p_{max,\ abs}$	1–13 bar
(2)	Pressure vessel	V	10 m^3
(3)	Pressure reducer	$p_{red,\ abs}$	1–5 bar
(4)	Heater	t_{max}	500 °C
(6)	Inlet section	l	1.8 m

feed a pressure vessel (2) with cold, dry air, which expands in the pressure reducer (3), and is then conducted through the temperature controlled heater (4). The volume flux entering the test cell is adjusted to the settings by control valves and a bypass (5) and is passing an inlet section (6), where a fully turbulent flow is developed. The operating range of the test facility is listed in Table 1.

2.2. Test cell and process conditions

Fig. 2 shows the experimental setup of the test cell. The less detailed schematic on the left hand side shows the air flow along the channel, the perpendicular test fluid supply, the wall heater element with a thin metallic foil, which is observed with a black and white (b&w) camera from the top and a high-speed IR camera from below. The thin metallic foil is integrated smoothly into the channel wall and acts as an electrical resistance heater. The test fluid enters through a small slit and is spread in streamwise direction due to the shear stress of the air flow, thereby forming a thin liquid film on the top of the thin foil heater. The foil heater is a sandwich construction with five layers, shown in detail on the right hand side of Fig. 2. A thermal insulation (a) below the auxiliary heating layer (b) minimizes heat losses through the lower cell body. The foil carrier (c), made out of copper, has a longitudinal nut to bound the liquid film in lateral direction and bears the electrical insulation (d). The stainless steel foil (e) is clamped upstream and kept tense by a spring downstream. For the test runs presented in this work methylnaphtalene, $C_{11}H_{10}$, has been chosen as the test fluid. Own preliminary tests as well as the results of Ashida et al. (2001) show that aromatic hydrocarbons tend to build deposits under thermal stress. The test conditions for the steady state operating mode are listed in Table 2.

2.3. Measurement methods and test procedure

The film motion on the upper side of the heater foil is detected by a b&w camera with a spatial resolution of 35.4 µm/pixel, a field of view of 13.45 mm × 36.25 mm, and a frame rate of 50 Hz. The temperature distribution is measured qualitatively on the backside of the heating foil by a mid-wave IR camera with a sensor size of 256 × 256 pixel, a spatial resolution of 73.5 µm/pixel, a field of view of 18.82 mm × 18.82 mm and also a framerate of 50 Hz. The nonuniformity of the sensor pixels is reduced by a pixel wise non-uniformity correction at one reference point (offset correction). A black coating at the bottom of the foil is applied to get uniform and high emissivity. The IR pictures in Figs. 4 and 5 show the intensity signal, whereas the intensity increases with higher temperatures. The intensity color scale starts from deep blue (lower temperatures) to dark red (higher temperature). Both cameras are aligned to each other and mechanically fixed together so that the center of the IR camera is also visible on the b&w images. A time triggering guarantees the simultaneous recording of the data from the two cameras.

During 60 h and prior to conducting the measurements the heated foil is wetted and dried periodically multiple times to form an initial deposit layer.

3. Experimental results

The results presented in the following are based on test runs including the pre-process for prime deposit formation, followed by one wetting and one dryout event. To compare the instantaneous b&w and