Leidenfrost evaporation of a single droplet of gasoline blends of ethanol

Tadeusz Orzechowski[*]

Kielce University of Technology, Al. Tysiąclecia PP7, 25-314 Kielce, Poland

Abstract. The increase in energy consumption is observed since the middle of the 20th century. At the same time, the International Energy Agency (IEA) forecasts a 50% increase in energy consumption by 2030. One of the ways to reduce the consumption of such fuels are small additions received from natural gas and renewable energy sources. Mixtures of alcohols with gasoline and diesel oil are produced. Their small additions allow for a certain share of energy from renewable sources without a noticeable change in the combustion characteristics of such fuels. The paper presents the studies on the evaporation of drops of gasoline with a total composition C_nH_{n+2}, where n = 5 to 7. Its components are distillation products of crude oil with a low flash point. It is a colourless liquid mixture which main components are: n-heptane, neohexane and cyclopentane. The evaporation characteristics of such a drop with the addition of ethanol are also given. The result of the conducted research is the loss of mass during the drop carried above the surface with temperature above the Leidefrost point.

1 Introduction

Relatively low price, high power density in a unit, accessibility, availability and well-developed technology decide about common use of fossil fuels. At the same time, their resources become depleted, and their exploitation has negative effect on the environment. The increase in energy consumption is observed since the middle of the 20th century. In the years 2008-2017 it was 1.7% per year on average, to reach even 2.2% in 2017 [1]. This high consumption is the reason for imposing various restrictions, including legal ones [2]. One of the key consumers of fossil fuels is transportation, for which in quoted Directive the European Commission has set the share of energy from renewable sources to be no less than 10% in 2020. In order to meet these standards it is required both to develop technologies allowing production of these fuels [3], [4], and to adapt equipment for their combustion [5]. This applies in particular to the ICE engines.

The tests of methylnaphthalene combustion discussed in the study [6] indicate negative impact of the deposit layer, which forms a thermal barrier thus inducing local surface temperature rise. In petrol engines it is observed that rising surface temperature is accompanied by the tendency to reduce deposit formation [7].

Ethanol added to fuels has positive effect of reduced emissions to the atmosphere. Tests of commercial diesel fuel emulsion with added 20% water-ethanol blend show extended sprayed liquid penetration length with more hydrated ethanol added and reduction of soot in flame [8].

Some additives are insoluble in fuel. This can be e.g. water, which forms an emulsion when added. The n-decane fuel with a volume ratio of 0.2 obtained in this way is characterised in [9]. The evaporation measurement carried out for droplets installed at the tip of a fine thermocouple allowed distinguishing its three stages: droplet heating, inflation/puffing and pure evaporation. Moreover, it has been observed that evaporation rate during the pure evaporation stage and droplet lifetime is not dependent on pressure, but only on ambient temperature. As shown in the study [10], air temperature rise from 373 K to 573 K results in droplet lifetime reduced by 70 %, whilst pressure impact is insignificant.

The mechanism of boiling in the droplets during fuel combustion is even more complex [11]. The observations of fuel containing different volumes of ethanol indicate that inner micro-explosions occur at low (~10%) ethanol content, while they are not seen at higher concentrations. The authors suspect that the reason for this is insufficient number of nucleation centres or poor fuel mixing.

Boiling is a complex process, in which heat and mass exchange take place simultaneously. Various investigations conducted into the subject focus on the physics of the phenomenon, which depends strongly on the liquid and its components [12], thermal and flow conditions [13], [14], or interaction with the surface [15], [16].

The need to reduce fossil fuel consumption imposes the search for new combustion blends. The fuels, which are most often used for that purpose, are petrols and diesel oils with alcohols added. Blends prepared in this way only slightly modify the combustion process; additionally, they induce reduced carbon dioxide emission into the atmosphere. In case of mixtures, in which pure alcohol is the prevailing constituent, higher flashpoint and higher lubricity is ensured. Fuel type change demands that the equipment is adapted to their combustion process, which

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[*] Corresponding author: todek@tu.kielce.pl

also makes it necessary to gather possibly complete knowledge on their evaporation processes. The aim of this study is to provide the analysis of heat transfer between a gasoline droplet and its blends of ethanol at atmospheric pressure, and a hot surface at a temperature higher than Leidenfrost one.

2 Experimental procedure

The purpose of this study is to analyse heat exchange between the surface at a temperature higher than the Leidenfrost point and the droplet suspended above it. The temperature difference between them induces mass evaporation. At preset and constant surface temperature mass decrement in time depends both on physical parameters of liquid and droplet size. Quantities needed to characterise the heat and mass exchange processes have been measured using a setup consisting of five independently working systems: recording of heating surface and droplet temperature, mass measuring in time, power supply, photographic evidence, and data acquisition and processing station.

The tested droplet is installed above the surface of a cylindrical heating element made of copper, which is shown in Fig. 1. It consists of a copper base, made hollow in order to reduce mass, so as to ensure steady inflow of heat to its upper surface. Electric band heater has been installed on its external surface. A 1-mm diameter hole has been drilled in the cylinder axis, inside which a K-type sheathed thermocouple has been soldered to position its measuring component at the surface level. A cylindrical cover forms upper part of the heating element. Its top surface has the shape of a bowl with very large curvature radius, which makes it easier to keep the tested droplet in its central position.

The heating element is a part of the system with an electric autotransformer, which allows pre-setting voltage to adjust heater power. Applied power is controlled by voltage at the equipment terminals. Constant heating surface temperature is maintained in this way. Its value is collected in time at preset intervals by the data acquisition system, which is provided with an external analogue-digital station.

The complete heating block was placed on special-purpose electronic scales that have the maximum load of 500g, sensitivity of 0.001g and accuracy of 0.01g. It is equipped with RS-232C interface for remote control and measurement data transmission. The data are collected in RAM, and on completion of the measurement, they are recorded on the disc. Under stationary or slow-varying conditions, the scales reading is only transmitted when three successive readings in the device internal system are identical. This function can be switched off, and if that is the case, due to technical issues related to analogue-to-digital signal conversion, the signals can be recorded under non-stationary conditions at the maximum frequency of 5 Hz.

Three support pins were fixed to the heating block. Those supported the cylinder with the heater, upholding it at approx. 2 cm above the surface, which prevented excessive heating of the substrate. Additionally, two screws were installed on pin ends, as seen in figure 2. The tightening and loosening of the screws allowed precise levelling of the measurement system so that the central position of the droplet could be maintained.

In drop mass measurement, power is supplied to the heater, which is connected to the mains using an earthed wire. The system was switched on at least a few hours before the measurements in order to eliminate the impact on the scale readings of the power and compensation wires. Before starting measurements, the scales and surface temperature readings were observed for approx. 10 minutes. The duration of observations was always over twice as long as the expected time of the drop evaporation. The measurements started if both parameters, i.e. the scales and thermocouple readings, remained stable.

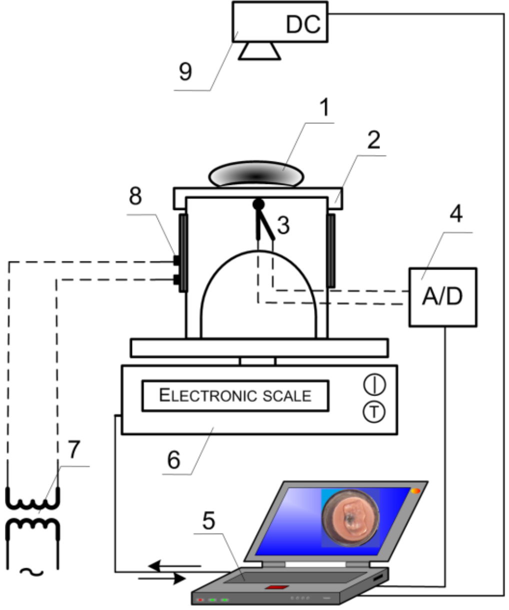

Fig. 1. Experimental set-up: 1 - droplet, 2 - cylinder, 3 - thermocouple, 4 - A/D station, 5 - data acquisition station, 6 - scale, 7 - autotransformer, , 8 - heater, 9 - digital camera.

Conducted measurements have been documented using a digital camera equipped with a 24 Mpx matrix. Photo 2 shows petrol droplet suspended over a heated surface, here ellipsoidal in shape. The detailed description of the measurement procedure, together with the analysis of uncertainties is presented in [17], [18].

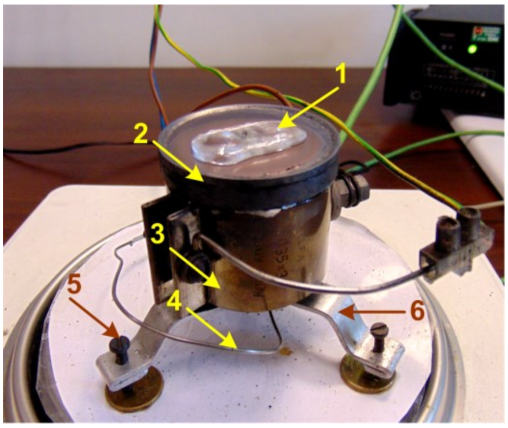

Fig. 2. Side view of the experimental set-up: 1- droplet, 2- cylinder, 3- heater, 4- thermocouple, 5- screw, 6- supporting pin.

3 Droplet evaporation phenomenon

The paper presents the studies of evaporation of drops of gasoline with a total composition C_nH_{n+2}, where n = 5 to 7. Its components are distillation products of crude oil with a low flash point. For comparison purposes, phthalic petrol available in the market has been chosen, as it is slightly heavier due to the number of carbon atoms (between 10 and 16), whereas, both liquids are characterised by almost identical boiling point.

The investigations outcome is a continuous measurement of the mass of evaporating droplet deposited on the upper surface of the heating cylinder (see Fig. 2), the temperature of which is higher than Leidenfrost temperature. An exemplary set of measurement data is shown in Fig. 3. These are curves showing the change in mass of five ethanol droplets in time with initial mass ~1.35g. During the tests the heating surface temperature has been kept close to 327°C. It is an average temperature of the values, which have not differed from each other more than ±2°C in individual measurement series.

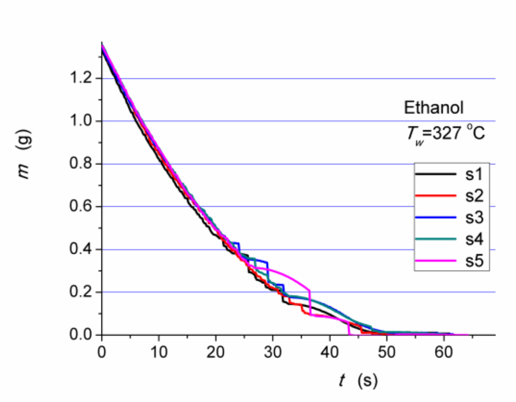

Fig. 3. Evaporation of the ethanol droplets on the wall of the temperature T_w=327°C.

The curves visible in Fig. 3 do not overlap, although in each case evaporation time is almost the same. Their visible uniqueness results from randomly occurring mass fluctuations during growth and release of steam bubbles from upper surface of a droplet. Deviation values can be evaluated after determination of the mean line and calculation of residues in each of the measured points. These calculations have been performed for all five curves, and the result is shown in Fig. 4.

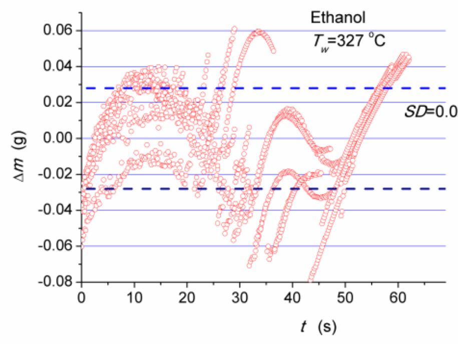

Fig. 4. Residuals of measurement points with respect to the mean line.

High number of registered points allows assessing the random nature of evaporation with standard deviation value that has reached here SD=0.028 g.

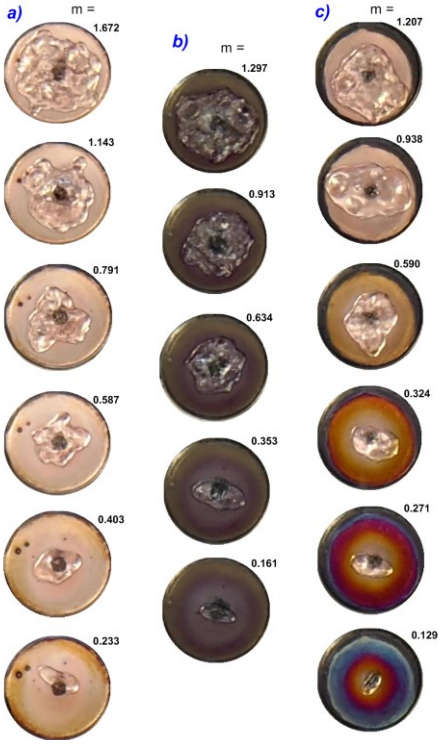

Fig. 5. Forms of droplets: a) ethanol, b) phthalic petrol, c) 25% ethanol in phthalic petrol.

Droplets carried in the Leidenfrost conditions get complex shapes [19], other than for ethanol, which proves to have unstable character when laid on a hot surface. A lot of bubbles form on the side of heating surface. Their uneven distribution and different formation times are the reasons for irregular shapes. Much the same as in [20], it is observed that inner boiling of liquid takes place during evaporation of alcohol, but it is not sufficiently rapid to throw its mass outside. Quite regular shapes occur only for droplets under 0.3 g, initially in the form of oblong ellipses, which become round with decreasing mass. Their selected examples are shown in Fig. 5a.

Comparative tests on the evaporation of droplets with ethanol added have been carried out using the example of petrols with constitution determined by the number of carbon atoms in these compounds. One of them is a gasoline with number of carbon atoms 5-7, and the other: 7-12. Fig. 6 shows evaporation curves for droplets of pure ethanol, gasoline, phthalic petrol and blends from the surface kept at the temperature of Tw~267°C.

Boiling point of both petrols specified in material safety data sheets is ca. 140°C. Similar values of physical parameters are the reason why curves illustrating mass changes for droplets of these liquids (shown in Fig. 6) almost overlap. It is much the same in case of other surface temperature values. The addition of alcohol induces a shift of evaporation curves towards the curve for ethanol at the same temperature, which is adequate to concentration. It is much the same with total evaporation time, which is lowest and almost the same for both petrols, and highest for ethanol, which proves to have much lower boiling point.

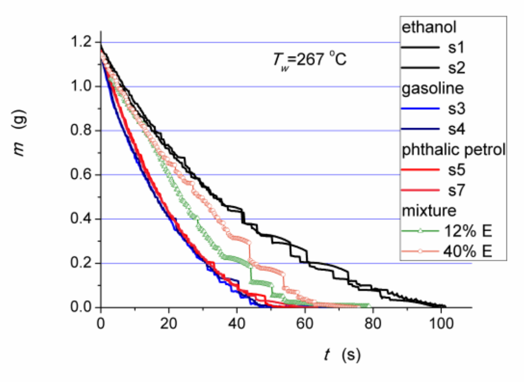

Fig. 6. Evaporation of droplets from the surface with temperature T_w~267°C.

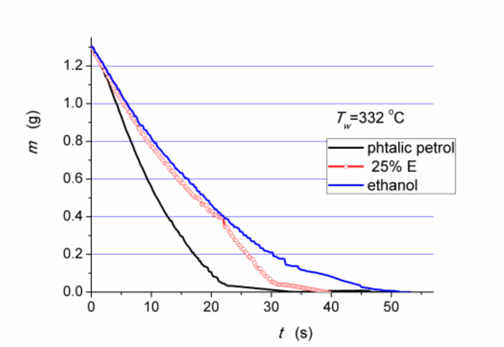

Fig. 7. Evaporation of droplets of ethanol, petrol and its mixture with ethanol.

Physical parameters of blends do not reach values proportional to blend constitution. They always require individual check. In Fig. 6 it can be observed that at the beginning of the process, the change in time of droplet mass for a petrol-ethanol blend is close to that of ethanol droplet, which evaporates faster. This phenomenon can be observed even more clearly in Fig. 7, which presents analogical tests at heating surface temperature T_w=332°C. Earlier ethanol evaporation is also confirmed in Fig. 5, which shows heating surface condition. At high temperatures copper gets covered with a thin dark grey layer of copper oxide. Ethanol vapours contacting the surface covered with copper oxide reduce oxygen, and copper keeps its orange-red colour permanently (see Fig. 5a.). Both petrols do not have these oxidising properties, therefore dark shade of substrate remains permanently during their evaporation. The substrate colour can be assessed in Fig. 5b. Evaporation of petrol droplet with 25% of ethanol added is shown in Fig. 5c. Ethanol vapours escaping first reduce oxide from the surface, which is proven by its bright colour. Ethanol content in petrol drops in time, and copper starts to oxidise gradually and its grey shade successively intensifies with increasing distance from the droplet.

4 Concluding remarks

The study presents the research on the evaporation of droplets of chemically pure ethanol, petrol containing 5-7 atoms of carbon, phthalic petrol with 7-12 atoms, and their blends. The tests have been carried out using a setup placed on a high precision and responsiveness balance, allowing accurate droplet mass recording. The key component of the equipment is a copper heating cylinder. Its constant temperature was controlled using a thermocouple installed under the surface. The measurements were carried out at high temperatures exceeding the Leidenfrost point. At these parameters copper gets covered with a thin layer of dark grey oxide, which is reduced by ethanol vapours contacting the surface to an extent dependent on their concentration (see Fig. 5).

At the same heating surface temperature, the evaporation curves of both petrols overlap to a good extent. The addition of alcohol induces shift of evaporation curves towards the one appropriate for ethanol, which is adequate to concentration. Due to faster evaporation of ethanol, which has much lower boiling point, this shift is visible at the beginning of the process (see Fig. 7). It is much the same with total evaporation time, which is lowest and almost the same for both petrols, and highest for ethanol.

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