Heat transfer under high-power heating of liquids. 4. The effect of water admixtures on the heat transfer in superheated hydrocarbons

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ABSTRACT

The *a priory* unknown peculiarities of heat transfer in superheated hydrocarbons with water traces have been studied experimentally. The approach was based on the relative version of the method of controlled pulse heating of a wire probe at constant current mode. The pulse duration was varied in the range of 1–120 ms. A region of probe temperature rise was limited from above by the value of spontaneous boiling-up temperature of a substance. The objects of study were *n*-hexane, *n*-decane, and *n*-hexadecane. The water content was varied in the range from 5 ppm (initial sample) to 35 ppm (watered sample). A sharp increase in the heat transfer intensity for watered sample with respect to that of initial one has been revealed. The observed effect was manifested solely at temperatures close to the values of boiling-up temperature of watered sample.

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1. Introduction

The processes of high-power heat release in fluids are characteristic of the modern engineering [1–3]. As applied to hydrocarbons, such processes are observed in friction units with oil lubrication, in the cycles of preparation and combustion of fuel in engines and rocket installations. As a rule, hydrocarbons in technical applications are a part of a multicomponent working fluid. Water and its vapor are one of the ubiquitous working fluid components disturbing technologists [4,5]. Numerous works have been carried out to study the effect of water admixtures on properties of oils and fuels and through them on the equipment efficiency and durability, as sited in [6]. Water exhibits an extremely high chemical activity at elevated temperatures. This circumstance leads to an intensive corrosion of details in the course of still insufficiently studied chemical reactions. It is known that water, having comparatively high values of specific heat capacity and thermal conductivity [7] and, under particular conditions [8], extremely high heat flux density is able to significantly alter the thermodynamics of

the processes in heat engines even at low concentrations. In this regard, its allowable content in working fluids is enshrined in the international and national standards. Despite the efforts of technologists to clean oils and fuels, the presence of traces of water in hydrocarbons is virtually irremovable. It has been often considered that water in low concentrations (at a level of 0.01%) does not significantly affect the technological processes, including the working fluid thermal stability and heat transfer intensity. At the same time, it is known that increasing the solution temperature may be accompanied by the liquid–liquid phase separation phenomena [9]. This circumstance leads to changes in the intensity of heat transfer in the system as well.

The present paper is devoted to investigation of characteristic features in the behavior of saturated hydrocarbons with micro-admixtures of water under conditions of a high-power local heating. The main task was to clarify the effect of water traces on the intensity of unsteady heat transfer in a wide temperature range, including temperatures above the temperature of normal boiling of the components. The objects of study were *n*-hexane, *n*-decane and *n*-hexadecane. The water content varied from 5 to 35 ppm. Additives of water were introduced from a vapor phase through the free surface of a base liquid. The essence of thermophysical measurements of the pulse-superheated (with respect to the liquid–vapor equilibrium temperature $T_s(p)$ at a given pressure p) fluids was presented elsewhere [10–13].

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2. Experimental

2.1. Materials

We used *n*-hexane, *n*-decane and *n*-hexadecane (reagent grade all) that were kept over silica gel for 24 h. The residual water content in thus prepared samples (specified as initial samples) was determined by the classic titration method of Karl Fischer and was 5 ± 1 ppm. The watered samples were prepared by saturating base liquid with water vapor through the free surface up to 30–35 ppm. The initial and watered samples proved to be visually transparent. According to the spectrometry studies, water at such concentrations in saturated hydrocarbons is generally in the dissolved state [14].

2.2. Choice of approach

Following [10–13], the approach to our investigation is based on the pulse heating of a wire probe-resistance thermometer immersed in the substance under study. The probe was made of a platinum wire of 20 μm in diameter. Its length was from 5 to 15 mm depending on the task. A sensor for temperature in the bulk liquid T_0 was a part of the probe module, see Fig. 1. This temperature value was used to calculate the temperature of the pulse-heated probe by the measured time dependence of its resistance. The probe calibration was carried out on substances with known properties, as previously described [12].

The voltage drops on the probe and standard resistor as the time functions are the values measured directly in experiment. From these data, the calculation of average weighted probe temperature T and heat flux density across its surface q for any time moment t was performed. The average heating rate, the characteristic temperature of the probe at the end of a pulse, and the content of water in the sample were the experimental parameters. A region of temperature rise, $\Delta T(t) = T(t) - T_0$, was limited from above by the value of spontaneous boiling-up temperature T^* of substance. This temperature is the individual substance parameter at the given parameters of experiment [15]. Along with the pressure dependence, the T^* value depends on the heating rate in the region of temperatures exceeding the $T_s(p)$ value [15–17]. In our experiments, the probe heating rate ranged from 2×10^4 to 10^3 K/s.

In general, the methods of pulse heating of a wire probe are characterized by high sensitivity to small changes in the properties of a thin heated layer of the studied substance [10,11,18]. These changes manifest themselves in perturbations of the time dependences of weight-average temperature of a probe and the heat flux density through the probe surface, which accompany a change in the experimental parameter, in our case, the water content in the sample. In our experiments we used a relative version of the method of controlled heating of a wire probe at constant current mode [19]. For solving the problem, this mode showed a higher resolving power than those used in [10–13]. A quasi-linear nature of the probe temperature rise in the substance was an additional
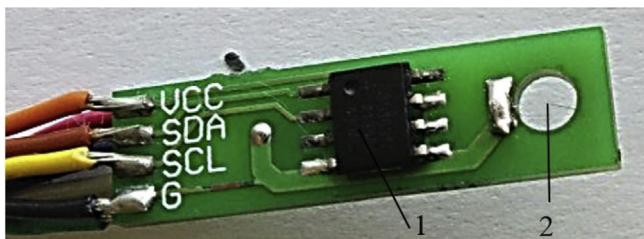

Fig. 1. Photograph of the probe module: 1 – bulk temperature sensor, 2 – platinum wire probe.

advantage of such an approach. Invariability in properties of the probe in a series of measurements was monitored in a test experiment, as previously described [10,11].

The intensity of unsteady heat transfer in a system can be characterized by the instantaneous values of thermophysical parameters of the process, in particular, thermal resistance of the substance for a given heat release, $R_h(t) = \Delta T(t)/q(t)$, or the inverse, heat transfer coefficient, $K_h(t) = q(t)/\Delta T(t)$. The higher the heating curve at a given heat release is located, the lower the heat transfer coefficient is. Discussion of the experimental results for the samples under investigation is based on a comparison of the instantaneous $K_h(t)$ values in the similar thermal modes.

2.3. Single pulse experiments

The chosen approach was applied to the design of experiments on comparing the intensity of the heat transfer in the samples mentioned above. The apparatus allows us to track changes in the probe temperature with an accuracy of a fraction of a degree in the millisecond time range. The amount of water in the sample under given conditions of heating served as the experimental parameter. The first series of experiments was performed by a single pulse of constant current mode. The pulse amplitude was varied in the range of 0.1–0.6 A; its duration, 10–120 ms. The series consisted of experiments on verification of repeatability of the results at given heating parameters and the basic experiments on a comparison of intensity of heat transfer by the samples with different water content.

The results obtained for all samples (*n*-hexane, *n*-decane, and *n*-hexadecane) proved to be similar. As an example, the results for *n*-decane with water content of 5 ppm (initial sample) and 35 ppm (watered sample) are shown on Fig. 2. One can see that at a heating rate of about 10^4 K/s and a time of about 25 ms, the probe is heated to 255 °C almost linearly; then the spontaneous boiling-up process with a characteristic increase in the intensity of heat transfer to the environment occurs. The boiling-up results in a sharp decrease in the temperature of the probe under the given conditions of heating. In our experiments, the probe weight-average temperature T evolution over time t was tracked. For reasons of convenience, in this paper we will take the probe temperature T at the moment of spontaneous boiling-up of the substance as the temperature T^* of its spontaneous boiling-up. For *n*-decane $(T_s(p = 0.1$ MPa$)$ = 174 °C), the T^* value was from 220 to 260 °C depending on the heating rate, see Fig. 2. In general case, the true values of temperature T_t^* of spontaneous boiling-up can be obtained taking into account the corrections for temperature distribution along the probe length, as it was previously described [15–17].

Fig. 2 shows the heating curves for the initial and watered samples at four values of the current in the probe circuit I. Reducing the current value was accompanied by a decrease in the heating rate, an increase in the product of the volume of the superheated $(T > T_s)$ sample by the corresponding observation time, and consequently a decrease in the spontaneous boiling-up temperature [15,16,20] for both types of samples. Boiling-up of *n*-decane in the entire range of heating rate changes was characterized by a sharp increase in the intensity of heat exchange of the probe with the sample, which in turn leads to a sharp decrease in the probe temperature.

A comparison of heating curves in Fig. 2 for the initial and watered samples shows that water addition significantly perturbs the values of both boiling-up temperature and heat transfer intensity. Increasing the temperature of the probe was accompanied by a small but reproducible excess of the heat transfer intensity in the initial sample with respect to the watered one, see inset in Fig. 2. This result is consistent with the fact of reducing the thermodynamic compatibility of the components of a water–hydrocarbon