Features of heat transfer to hydrocarbon fuel at bubble and film boiling

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Abstract. The article presents the results of a study of heat transfer from a heater to a RT grade hydrocarbon fuel. A number of features of heat transfer during boiling of hydrocarbon fuel in bubble and film modes were discovered. The presence of self-oscillations occurring during heat transfer is noted.

1. Introduction

Intensification of heat transfer during fuel boiling is one of the actual problems of aircraft engine building, while heat transfer depends on the boiling mode. In the bubble boiling mode, the heat flux is ten times greater than in the film one at the same temperature of wall surface. Previously, a fundamentally new method was proposed for intensifying heat transfer during boiling of liquids under heated to the saturation temperature \cite{1}. This method allows to increase the stability of the “heater-liquid” system by using the optimal heat load \cite{1–6}.

The issues of heat transfer during fuels boiling are of great interest in the design of aircraft. The scientific and technical literature addresses issues related to the formation of deposits in fuel systems of power plants \cite{7} and to the fuels bubble boiling \cite{8,9}, however, despite the importance of the problem, systematic research in the field of heat transfer during fuels boiling under high heat fluxes was not detected.

In the present work, the process of heat transfer during fuel boiling under superintense bubble boiling (SBB), as well as in other modes under conditions of high-density heat flow, was studied \cite{1–6}. The aim of the research was an experimental study of the heat transfer characteristics of hydrocarbon aviation fuel in a wide range of temperatures of the heated surfaces.

2. Objects of Study

The object of the study was the RT grade hydrocarbon fuel (GOST 10227-86), used in modern aviation GTE. This fuel is a mixture of hydrocarbons with a distillation temperature in the range from 135\degree C to 280\degree C.

3. Experimental technique

The electrothermographic method was chosen as the main research method. The heater, in addition to its intended purpose, is used as a resistance thermometer. The heater was made of...
platinum wire with a strong dependence of the electrical resistance on temperature. The wire was heated using a constant electric current. By fixing its current-voltage characteristic during the experiment, one can obtain information on the magnitude of the heat flux and surface temperature. Thermal power was supplied to the heater in the mode of stabilized average-integral resistance, whereby the mode of constant temperature of the heater was simulated [1]. A stabilizer of average integral resistance based on a proportional-integral-differential (PID) regulator was used to implement this mode [1].

The experimental setup is shown in figure 1. Electrodes, representing insulated copper wires with a diameter of 2 mm, with a soldered platinum wire of 1.4 cm length and 0.1 mm diameter (heater) were introduced into a three-necks 50 ml round bottom flask through the central neck and immersed in the liquid under study. The heater was installed at a distance of 0.5–1 cm from the bottom of the flask. Through the side necks, a reflux condenser and a mercury thermometer were installed. All connections were sealed. The volume of the test liquid was 15 ml. The flask was placed in a thermostat with adjustable temperature. A two-channel “ADVANCEST 6452A” multimeter and a “KEITHLEY 2000” precision multimeter were used to measure the heat transfer parameters to the fuel. A laptop and the “IEEE-488.2 GPIB” interface were used to collect data. Additionally, optical isolation modules “Q-SHUTTLE-KEL KIS-81GP000B-P” were used. The program written in the graphical programming system displays all measured data in a multi-window mode with the waveform vs time analysis and the histograms of specific power and temperature calculation. The boiling curve is displayed in a separate window.

4. Discussion of results
Since the experiments were carried out in the mode $R = \text{const}$, the maximum resistance of the system to thermal perturbations is achieved. This allows you to most accurately determine the
value of the first critical heat flux [1]. The transition boiling branch in this case is a mode of mixed boiling, which means the simultaneous coexistence of bubble and film boiling. Figure 2 shows a summary graph of boiling curves obtained for three temperatures of the RT grade hydrocarbon fuel.

![Boiling curves of RT grade hydrocarbon fuel. Fuel temperature: ○ – 18°C, ◢ – 98°C, ◆ – 185°C.](image)

As can be seen from the figure when boiling on the wire with underheating occurs (at a fuel temperatures of 18°C and 98°C), the maximum heat flux is significantly higher than when boiling on the wire of a saturated liquid occurs (at a fuel temperature of 185°C). Moreover, during boiling with underheating, it is possible to achieve the regime of superintense bubble boiling (SBB) [1].

Figure 3 shows in more detail the bubble boiling branch for a liquid temperature of 18°C. It is noteworthy that three different modes can be marked in the bubble boiling branch. The CD branch corresponds to the mode when the entire heater is covered with a layer of fixed bubbles. This mode is critically replaced by the EF mode in which the bubbles are set in motion, moving along the wire. And finally, the FG mode, it corresponds to the superintense bubble boiling (SBB) mode [1]. This behavior of the bubble boiling branch is observed for the first time; in all the individual liquids studied earlier [1–6], this branch depended linearly on the heater temperature, and the observed regimes gradually transformed into each other. As the underheating decreases, this feature gradually degenerates and the curve takes on a traditional appearance.

Another characteristic feature in the behavior of the system was identified in the region of mixed boiling. This area is located behind the critical heat flow (point G in figure 3) and continues to film boiling mode.

Figure 4 shows in more detail the mixed fuel boiling branch of the RT grade hydrocarbon fuel at a temperature of 95°C, obtained in a separate series of experiments. When the thermal power control mode is selected, the mixed boiling region is a temperature domain that first increases its temperature (section AB), and then, when the equilibrium heat flow is reached, it begins to spread along the heater (section BC). The CD section is an area of film boiling regime, which
Figure 3. Bubble boiling branch of RT grade hydrocarbon fuel for 18°C. AB is a branch of free-convection heat transfer, CDEF is a branch of bubble boiling, FG is a branch of superintense bubble boiling (SBB).

Figure 4. View of the mixed fuel boiling region of RT grade hydrocarbon fuel for 95°C.

for the considered object of study, as well as the BC area, is poorly reproduced. In all previously studied systems, the areas of mixed and transitional boiling are reproduced with great accuracy, and their behavior is described by mathematical equations [1–6]. At a fuel temperature of 95°C, these regions demonstrate a large scatter of experimental points and a critical phenomenon – the
BCD bend – which is not reproducible with high accuracy in subsequent experiments. It should be noted that each experimental point on the graph represents the averaging of one hundred measurements performed in automatic mode.

Measurement of the dynamic characteristics of the system allowed us to identify the reasons for the low reproducibility of measurement results in areas of mixed boiling. It turned out that in these areas self-oscillations of power are observed, leading to non-reproducible parameters and a critical phenomenon – the bending of BCD. The type of self-oscillations observed is shown in the screenshot of the registration program of experimental parameters in figure 5. The right side shows the normal distribution of the results of power density measurement. As follows from the figure, the frequency of the self-oscillation process increases with increasing temperature of the heater. Note that in practice, self-oscillations are a periodic change in the linear dimensions of the temperature domains at the heater surface. Such behavior was not observed in any of the previously studied systems [1–6].

Figure 5. Self-oscillating heat transfer mode in the mixed boiling region. The average integral temperature of the heater: a – 300°C, b – 420°C, c – 487°C.

5. Conclusion

Thus, we carried out a systematic study of heat transfer from a heated heater to a RT grade hydrocarbon fuel. It was found that in the bubble boiling regime the magnitude of the maximum heat flux depends significantly on the temperature of the liquid. The uncharacteristic behavior of a bubble boiling branch and the existence of a mixed boiling region of a self-oscillating heat-transfer mode are revealed. We assume that the described features of the boiling curve are determined by the fact that the hydrocarbon fuel under investigation is a mixture of hydrocarbons with different boiling points and that during the heating of the heat-transfer surface some of the low-boiling hydrocarbons evaporate, which makes it difficult to establish a steady-state heat transfer.
Acknowledgments
This work was performed in accordance with the state tasks, state registration Nos. 0089-2015-0221 and 0089-2014-0019.

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