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Characteristics of heating and evaporation of droplets of jet fuel and its surrogates

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The paper presents the results of experimental study of heating and evaporation of TS-1 aviation kerosene and its surrogates (n-decane and SU4) in a high-temperature gas flow (gas temperature range is 450–750 K, gas flow velocity range is 0–6 m/s). The conditions for temperature and gas flow rate are established, under which it is possible to provide good agreement on the time of complete evaporation, the dynamics of changes in the sizes (radii) and average temperatures of droplets of traditional aviation fuels using the example of kerosene TS-1 and its surrogates (SU4 and n-decane). When processing videograms, we used our own image processing algorithms developed in the MATLAB software package.

Keywords: heating, evaporation, aviation kerosene, surrogate fuel.

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Owing to their high calorific efficiency, stable thermodynamic properties, and viscosity characteristics that are retained at low temperatures at altitudes in excess of 9 km, kerosene and its derivatives are the most common types of liquid fuels for combustion chambers of aviation engines. Jet fuel typically contains no less than 40 components, including n-decane, isooctane, isocetane, and toluene [1]. The composition and properties of fuel have a significant effect on the performance of modern aviation engines and anthropogenic emissions [2]. Specifically, such parameters as heating time and evaporation intensity are of the utmost importance for the aviation industry [3]. These are the values that specify the rate of formation, the composition, and characteristics of a fuel–air mixture. A combustion chamber should be designed so as to hold a fuel–air mixture in the mixing zone for a time that exceeds the complete evaporation time and is shorter than the ignition delay [3]. In addition, the rate of evaporation of fuel droplets has an influence on the steady-state combustion limits, combustion efficiency, carbon buildup, smooth operation of fuel pumps, and the tendency to form vapor locks in the fuel system in high-altitude flights [4]. When trying to improve the evaporation characteristics, one needs to take into account the fragmentation of fuel droplets, which is characterized by one key parameter (ratio of the surface areas of liquid before and after the explosive fragmentation of heterogeneous droplets), and the conditions under which this process may be regarded as a steady-state and reproducible one [5]. Aviation fuels have a multicomponent chemical composition [6], which makes for a complex heat and mass transfer in processes involving these fuels. The simulation of heating, evaporation, and ignition in combustion chambers of propeller, jet, and compound engines with the inclusion of specific features of blend compositions of fuels requires colossal amounts of time. The use of surrogate or monocomponent fuels (n-hexane, n-decane, n-dodecane) instead of a traditional one is a common approach to this problem [7]. It is often applied in approximations of traditional fuels (TS-1 kerosene, gasolines, etc.) in commercial software (Ansys Fluent, Comsol Multiphysics, OpenFOAM) [7]. Surrogates are variants of traditional fuels with their composition simplified to optimize the calculation procedure [7]. In most cases, the development of models of surrogates of traditional fuels is centered on the determination of their physical and chemical properties [8]. The key rated parameters of such fuels are their density, saturated vapor pressure, fractional composition, viscosity, and surface tension [9]. No data regarding the heating and evaporation characteristics of these surrogates applied in practice have been published yet. Only the results of theoretical studies into the applicability of such models are known [10]. The aim of the present study is to determine the difference in the parameters of heating and evaporation of droplets of jet fuel (with TS-1 aviation kerosene and its surrogates used as an example) and establish the limits of applicability of surrogates in modeling of heat and mass transfer processes in combustion chambers of engines.

Mass concentration of components for SU4 kerosene surrogate

n-decane	Isocetane	Tetralin	Methylcyclohexane
0.492	0.202	0.104	0.202

The experimental setup shown in Fig. 1 was used to examine the characteristics of heating and evaporation of jet fuels (exemplified by TS-1 aviation kerosene) and

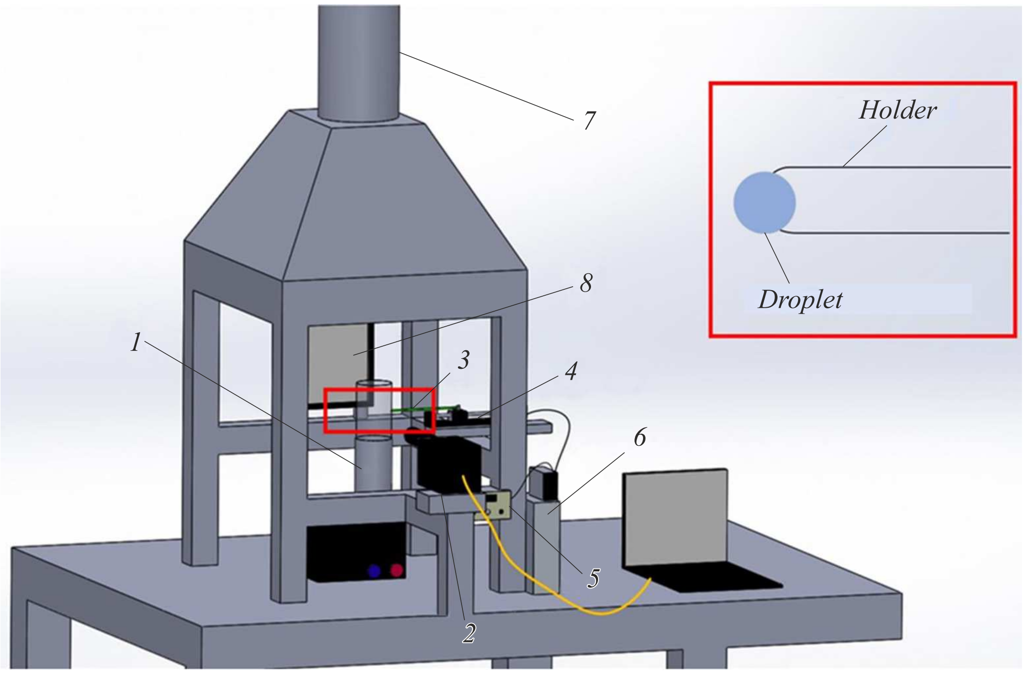

Figure 1. Experimental setup. *1* — Heater and blower of a high-temperature gas flow, *2* — Phantom Miro M310 high-speed camera, *3* — junction of a chromel–alumel thermocouple, *4* — step motor, *5* — microcontroller, *6* — power unit, *7* — ventilation system, and *8* — LED projector.

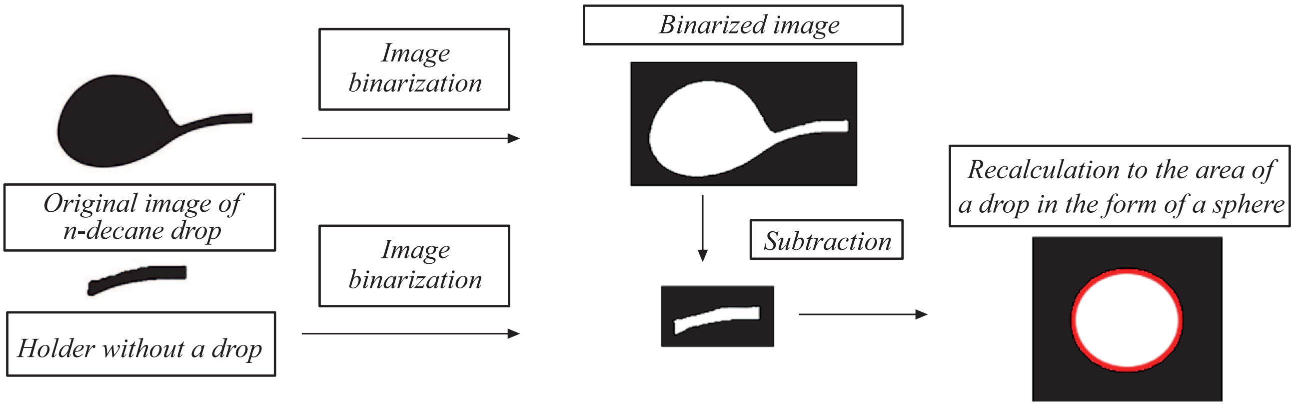

Figure 2. Stages of processing of video frames with images of droplets in MATLAB.

their surrogates (n-decane and SU4; see the table for the mass concentration of its components). A vertically mounted Leister heat gun (the gas temperature range was 450–750 K, while the gas flow velocity varied from 0 to 6 m/s) was used as a heating system and an air blower. The overall errors of determination of the heat gun parameters were ±5 K for the gas temperature and ±0.05 m/s for the gas flow velocity. A thermally insulated cylinder made of quartz glass with a thickness of 2 mm, a diameter of 7 cm, and a height of 20 cm was positioned at outlet of the heat gun to maintain a constant temperature. Two apertures in this cylinder were used to introduce droplets into the heating zone and record evaporation processes. Droplets under study were introduced into the recording area by a coordinate mechanism with a holder in the form of a chromel–alumel thermocouple at the end of it. The temperature in the heating zone was raised to a predetermined level in advance. A droplet remained secured to the holder throughout the entire experiment from the moment of its introduction into the heating zone to its complete evaporation. Initial droplet temperature T_{d0} was measured right before the introduction into the heating zone and was equal to 293 ± 5 K. The recording area was illuminated with a LED projector. The droplet heating and evaporation processes were recorded with a Phantom Miro M310 high-speed video camera. The framing rate in

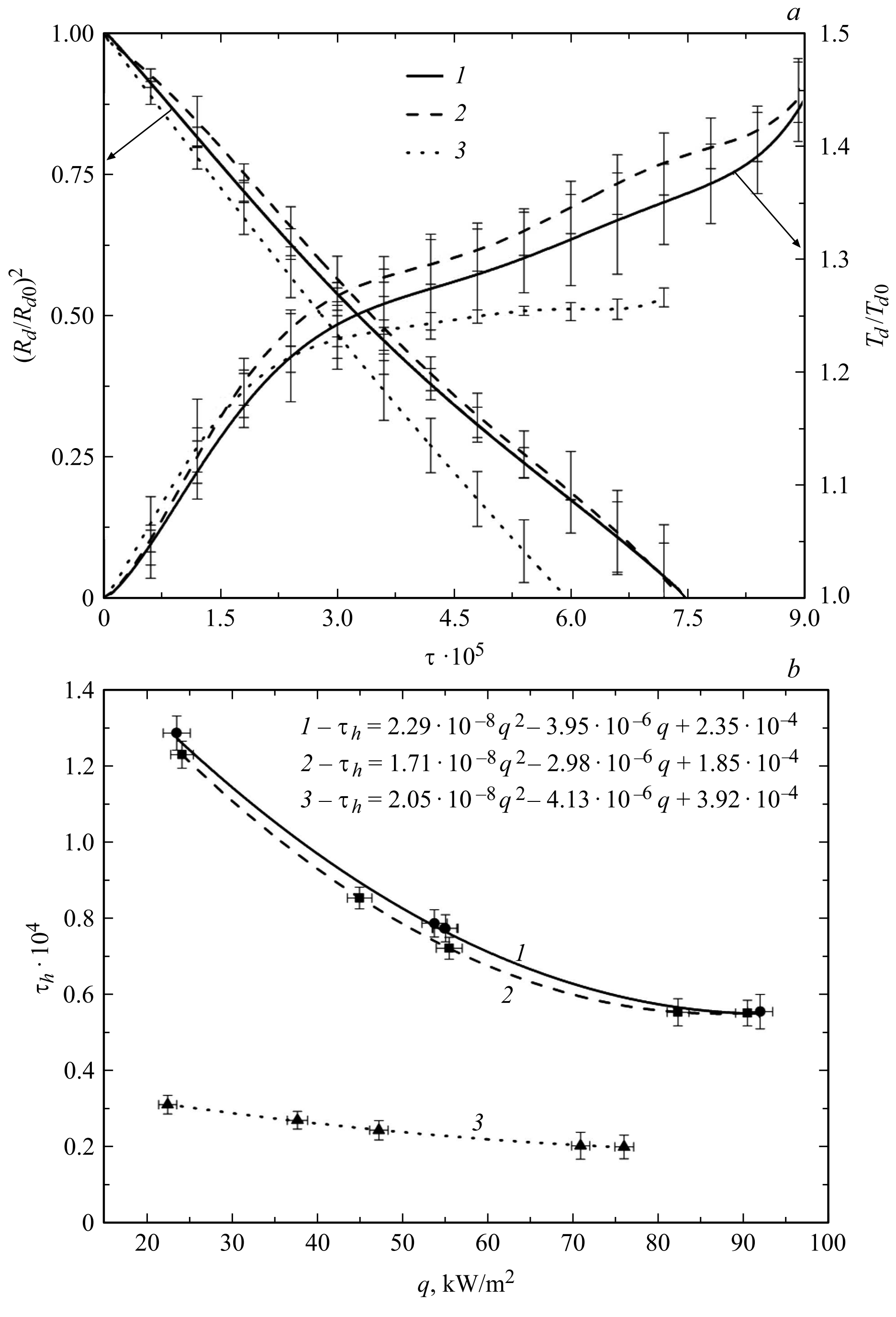

Figure 3. *a* — Dynamics of variation of the size of TS-1 kerosene (*1*), SU4 (*2*), and n-decane (*3*) droplets (in the form of $(R_d/R_{d0})^2$) and their average temperature (in the form of T_d/T_{d0}) at $T_g = 490 \pm 5\,\mathrm{K}$, $U_g = 0.10 \pm 0.05\,\mathrm{m/s}$, and $R_{d0} = 1.00 \pm 0.05\,\mathrm{mm}$. *b* — Dependences of dimensionless complete evaporation time τ_h of TS-1 kerosene (*1*), SU4 (*2*), and n-decane (*3*) on thermal flux q within the ranges of $T_g = 450{-}750\,\mathrm{K}$ and $U_g = 0{-}6\,\mathrm{m/s}$.

experiments was 1000 frames per second at a resolution of 512×512 pixels. The obtained video fragments were processed in Phantom Camera Control and MATLAB with the use of proprietary processing algorithms. The size of a droplet at every instant during its evaporation was determined in MATLAB. Video fragments in AVI format output by Phantom Camera Control were the initial data for processing. The systematic errors of determination of the size (radius) of droplets and their average temperature did not exceed 0.01 mm and 1.5 K, respectively. The initial size (radius) of droplets was measured before their introduction into the heating zone. Figure 2 illustrates the stages of image processing. Droplets obtained in experiments were objects of an irregular shape. The area of these objects was analyzed in the course of processing of the original images. Recalculation to the effective size (radius) of a droplet, which is given by $(S/\pi)^{0.5}$, where S is the area occupied by an irregular-shaped object, is one of the known ways to present the end results of examination of the evaporation dynamics of such droplets.

Figure 3, a presents the results of examination of the dynamics of size variation of n-decane, SU4, and TS-1 kerosene droplets (in the form of $(R_d/R_{d0})^2$) and the dynamics of variation of their average temperature (in the form of T_d/T_{d0}) at gas temperature $T_g = 490 \pm 5\,\text{K}$, gas velocity $U_g = 0.10 \pm 0.05\,\text{m/s}$, and initial droplet radius $R_{d0} = 1.00 \pm 0.05\,\text{mm}$. Dimensionless time τ was determined as $\tau = tD_g/R_{d0}^2$, where D_g is the coefficient of diffusion of the vapor–gas mixture [m^2/s] and t is time [s]. The size (radius) of droplets was chosen so as to fit the limitations of the experimental setup. However, the obtained fundamental test results for large droplets of surrogate fuels provide an opportunity to probe smaller droplets with a radius below $100\,\mu$m in mathematical modeling. The dependences of dimensionless time τ_h of complete evaporation of droplets of n-decane, SU4, and TS-1 kerosene on thermal flux q (Fig. 3, b), which was calculated for a gas temperature range of 450–750 K and a gas flow velocity range of 0–6 m/s, were established. Thermal fluxes supplied to the near-surface layer of fuel droplets were calculated as $q = h[T_g - (\rho_l L(dR/dt))/h]$ ($h = \lambda \text{Nu}/2T_g$ is the convective heat transfer coefficient $[\text{W}/(\text{m}^2 \cdot \text{K})]$, λ is the heat conductivity of the vapor–gas mixture $[\text{W}/(\text{m} \cdot \text{K})]$, $\text{Nu} = 1 + (1 + \text{RePr})^{1/3}$ is the Nusselt number, Re is the Reynolds number, Pr is the Prandtl number, ρ_l is the liquid density [kg/m^3], L is the heat of evaporation [J/kg], and dR/dt is the evaporation rate [m/s]) and varied within the 10–100 kW/m^2 range, which corresponded to a gas temperature range of 450–750 K and a gas flow velocity range of 0–6 m/s. Note that the thermal fluxes supplied to droplets vary in time, but the maximum thermal fluxes at the initial time were used to plot the dependences in Fig. 3. The thermal flux from the holder was disregarded, since it is negligible compared to the convective one. These features have been examined in detail in our earlier studies [11]. The experimental dependences obtained here for SU4 and TS-1 kerosene are in a satisfactory agreement in terms of dynamics of $(R_d/R_{d0})^2(\tau)$ and $\tau_h(q)$ variation. The values of $(R_d/R_{d0})^2$, T_d/T_{d0}, and $\tau_h(q)$ for these fuels stay within the confidence interval throughout the entire time span. The characteristics of n-decane differ by more than 15–20% from the corresponding parameters for TS-1 aviation kerosene. These results reveal the limits of applicability of surrogates in modeling of conditions and parameters of heat and mass transfer in combustion chambers of jet engines. Expressions (Fig. 3, b) allowing one to predict the heating and evaporation characteristics within wide ranges of gas temperatures and flow velocities were derived via mathematical processing of the experimental data. It seems reasonable to continue and advance these studies further by examining the results of heating and evaporation of jet fuel droplets with a size (radius) below $100\,\mu$m under different external heat conditions for the purpose of analyzing the possibility of filling a combustion chamber with a fuel aerosol.

Thus, the reported experiments provided an opportunity to establish the temperature (450–750 K) and gas flow velocity (0–6 m/s) conditions under which the complete evaporation time and the dynamics of variation of sizes and average temperatures of droplets of traditional jet fuel (TS-1 kerosene) and its surrogates remain in a satisfactory agreement. The obtained results should prove helpful in the development of physical and mathematical models of phase transformations of jet fuel droplets in combustion chambers of engines and power plants.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] D. Zheng, W.M. Yu, B.J. Zhong, Acta Phys. — Chim. Sin., **31** (4), 637 (2015). DOI: 10.3866/PKU.WHXB201501231

[2] S. Holz, S. Braun, G. Chaussonet, R. Koch, H. Bauer, Energies, **12** (4), 2835 (2019). DOI: 10.3390/en12142835

[3] B.A. Uglov, *Ekspluatatsionnye svoistva reaktivnykh topliv i nadezhnost' aviatsionnykh silovykh ustanovok* (KuAI, Kuibyshev, 1986) (in Russian).

[4] *Topliva, smazochnye materialy, tekhnicheskie zhidkosti*, Ed. by V.M. Shkol'nikov (Khimiya, M., 1989) (in Russian).

[5] M.V. Piskunov, P.A. Strizhak, Tech. Phys. Lett., **43** (6), 558 (2017). DOI: 10.1134/S1063785017060256.

[6] G.V. Kuznetsov, P.A. Strizhak, Tech. Phys. Lett., **40** (6), 499 (2014). DOI: 10.1134/S1063785014060200.

[7] L. Poulton, O. Rybdylova, I.A. Zubrilin, S.G. Matveev, N.I. Gurakov, M. Qubeissi, N. Al-Esawi, T. Khan, V.M. Gun'ko, S.S. Sazhin, Fuel, **269**, 117115 (2020). DOI: 10.1016/J.FUEL.2020.117115

[8] V.A. Alekseev, J.V. Soloviova-Sokolova, S.S. Matveev, I.V. Chechet, S.G. Matveev, A.A. Konnov, Fuel, **187**, 429 (2017). DOI: 10.1016/J.FUEL.2016.09.085

[9] N.D. Radchenko, *Issledovanie i modelirovanie ekspluatatsionnykh svoistv benzinov* (Tomsk. Politekh. Univ., Tomsk, 2019) (in Russian).

[10] S. Ray, V. Raghavan, G. Gogos, Int. J. Multiphase Flow, **111**, 294 (2019). DOI: 10.1016/j.ijmultiphaseflow.2018.10.002

[11] D.V. Antonov, R.M. Fedorenko, P.A. Strizhak, Z. Nissar, S.S Sazhin, Combust. Flame, **233**, 111599 (2021). DOI: 10.1016/j.combustflame.2021.111599

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