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INVESTIGATION OF THE BURNING OF PARAFFIN DROPLETS

The burning characteristics of pure n-alkanes (n-octadecane and n-docosane) are investigated. Combustion of single and double droplets is studied experimentally, the histories of burning droplets are obtained, and the burning rate constants are determined. Flame transfer is studied in a two- droplet system.

Keywords: n-docosane, n-octadecane, droplet, burning rate.

1. Introduction

Recent investigations in space propulsion are aimed at the development of highly effective and environment friendly rocket fuels. It is well known that the traditional propellants (liquid and solid) are very toxic and highly explosive. Hybrid rocket motors have evident advantages over liquid and solid motors – simplicity of design, exploitation safety, and low cost. The main disadvantage of traditional hybrid propellants is a relatively low regression rate. But, in the late 1990s, researchers of Stanford University demonstrated experimentally that a paraffin-based fuel charge provided a high regression rate. For example, paraffin waxes burn about 3 to 5 times faster than high-density polyethylene (HDPE), which is used in hybrid propulsion systems. Moreover, they are environmentally sound, because the main products of paraffin combustion are water vapor and carbon dioxide [1]. The high regression rate of a paraffin-based charge is explained by peculiarities of heat and mass transfer in a combustion chamber. A thermal radiation from the burning zone heats up a charge surface above the melting point. In such way, a melted layer is formed with low viscosity. This liquid layer is inherently unstable, and surface roll waves are immediately excited on the surface by a high-speed gaseous oxidizer flow [2]. The fuel droplets are formed, entrained by this flow, and then quickly burn out. As a result, the paraffin charge combustion is intensified significantly, and a high regression rate is attained. Thus, the liquefying fuel appeared to be a quite promising alternative fuel for hybrid motors. But the testing showed that if a plane paraffin charge is used, a significant part of the fuel was expelled unburned from the combustor. Consequently, a specific impulse is reduced [3]. Now, researchers are aimed at the development of a fuel composition, which will provide the regression rate control. The main efforts of researches are focused on an improvement of the fuel combustion by the use of highly energetic additives. Light metals (Al, Mg), carbon black, and energetic polymers are considered to be promising fuel components, which can modify heat and mass transfer in a combustion chamber. Another way to intensify the fuel combustion is developed by Prof. V.Ya. Chernyak [4] and his colleagues, who elaborated and tested a plasma-assisted system of paraffin burning by the gliding arc discharge. There is another way to control the burning characteristics of a paraffin-based fuel by varying a fractional composition of paraffin wax itself. It is well known that paraffin wax is a mixture of n-alkanes ($C_{18}H_{38} \div C_{35}H_{72}$) with the melting point between about 45 and 68 °C. The physical properties of alkanes change continuously, as their molecular weights increase. But this fact was ignored till now. So, our research is aimed at investigating the effect of carbon chain length on the burning characteristics of n-alkanes. The main purpose of this work is to study experimentally the burning characteristics of n-octadecane ($C_{18}H_{38}$) and n-docosane ($C_{22}H_{46}$) droplets.

2. Experimental Technique

To investigate the combustion kinetics of paraffin droplets, a special experimental setup was constructed. A scheme of this setup is presented in Fig. 1. It is known that n-alkanes C_nH_{2n+2} with $n > 17$ are solid under standard conditions. So at first, a paraffin sample is melted in a ceramic vessel and drawn up with a syringe. Then droplet (3) is suspended quickly on tungsten filament loop (2) (the filament diameter equals 114 mcm). The droplet is ignited by spark coil (9). During the combustion, the droplet and its flame are observed, by using two cameras. To determine the instantaneous droplet size, we use videomicroscopy: a droplet is continuously imaged by a camera through a microscope objective (×16). The data from both cameras are transferred to computers (5, 6).

We investigated the combustion of pure n-alkanes: n-octadcane and n-docosane. These alkanes were selected, because they have relatively low melting points, so we could easily obtained droplets under room conditions. In addition, these alkanes are widespread components of diesel fuel, including biodiesel, so the data obtained can be used in other industrial applications. The main physical properties of the alkanes are presented in Table 1. It should be noted that the difference in basic thermal characteristics is not great.

3. Results and Their Discussion

Droplet burning rates were obtained, by measuring the temporal evolution of a droplet diameter. For that, the burning droplets were recorded by a videocamera at 30 frames per second (fps). The combustion processes were not very fast, so it was quite enough to process from 10 to 12 frames per second. In Fig. 2, some images of a burning docosane droplet and its flame are presented. We can see that the exact identification of the droplet edges is complicated by the flame radiation. Using a least-squares regression in the calculation of the burning rate would minimize this sort of random errors. The absolute size of a droplet is determined by using the tungsten filament ($d = 0.114$ mm) as a reference scale. The obtained video-files are decoded and processed to define the instantaneous values of droplet diameter $d(t)$, as well as the flame height $h(t)$. At last, a squared diameter $d^2(t)$ is calculated for different droplet initial diameters.

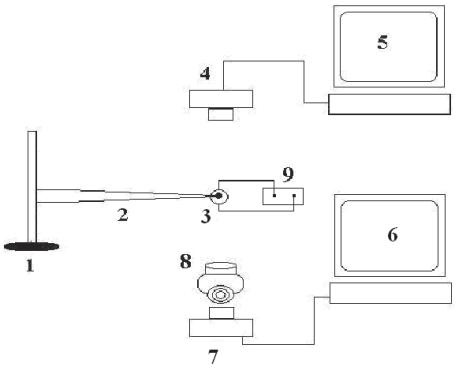


Fig. 1. Scheme of the experimental setup: *1* – droplet support; *2* – thermocouple; *3* – paraffin droplet; *4, 7* – digital cameras; *5, 6* – computers; *8* – objective of a microscope; *9* – spark coil

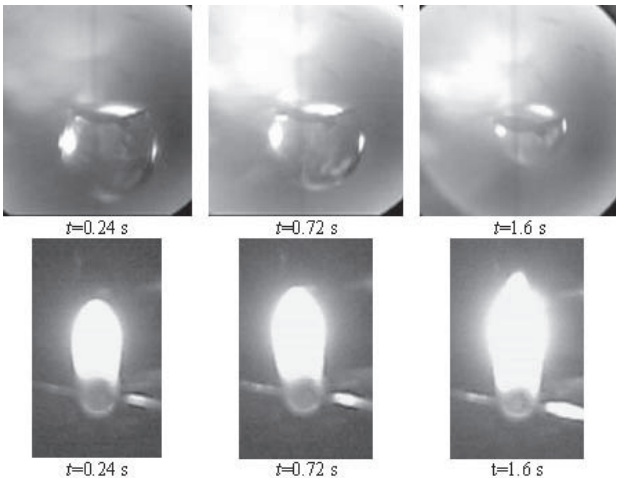
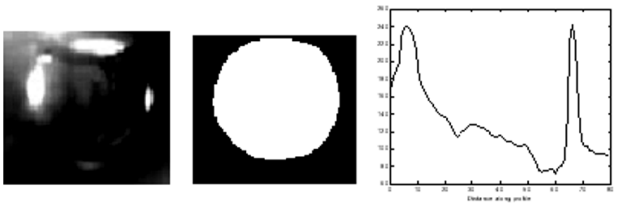


Fig. 2. Images of a burning docosane droplet at successive points in time, $d_0 = 2.04$ mm

Table 1. **Basic thermal properties of n-octadecane and n-docosane**

Alkane	n-octadecane	n-docosane
Chemical formula	$C_{18}H_{38}$	$C_{22}H_{46}$
Molecular weight, g/mole	254.5	310.6
Density, g/ml (at 25 °C)	0.777	0.778
Melting point, T °C	28	44
Boiling point, T °C	316	369
Autoignition, °C	235	NA
Specific heat of combustion, MJ/kg	43.867	44.146
Specific heat of vaporization, kJ/kg	356	399.2



a *b* *c*

Fig. 3. Droplet image processing steps: *a*) initial image; *b*) black-and-white image; *c*) intensity profile across a droplet

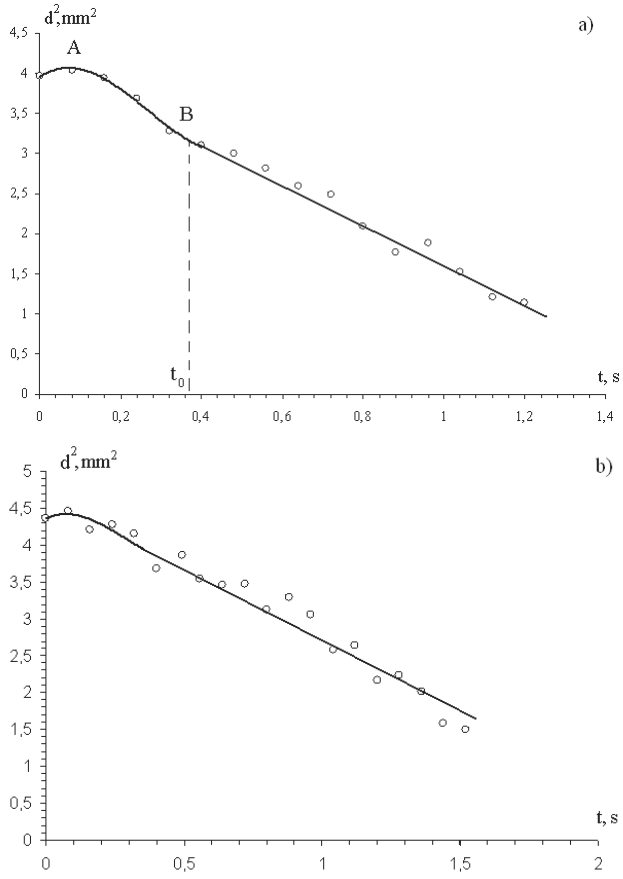


Fig. 4. Burning droplet histories: *a*) n-octadecane, *b*) n-docosane, $T_g = 293$ K

Table 2. **Burning characteristics of n-docosane droplets in still air**

d_0, mm	$K_{\rm bur}$, mm^2/s	$h_{\max}$, mm	$h_{\max}/d_0$
1.87	1.22	21.45	11.5
1.99	1.44	23.09	11.6
2.04	1.61	23.63	11.6

To process the pictures obtained, we used Image Processing Toolbox (MatLab 7.0). The edges of burning droplets turned out to be hardly identified by the standard techniques of binarization and edge detection, so we had to select the droplet outline manually by the "roipoly" procedure (see Fig. 3). Then we could define the equivalent diameter of the selected region that is the diameter of a circle with the same area as the region. To estimate a ratio error of diameter measurement, we build a plot of the intensity profile along a droplet diameter (see Fig. 3, *c*). By analyzing this curve, we found $\delta D = D/D_0 \approx 3/60 = 0.05$; then $\delta D^2 = 2\delta D \approx 0.01$.

In Fig. 4, the histories of burning droplets are presented, i.e., the droplet squared diameter versus the time for octadecane (see Fig. 4, *a*) and docosane (see Fig. 4, *b*). The droplets were selected equal-sized with an initial diameter of 2 mm. We can define two stages of the process. The initial part of the curve (to point A) corresponds to the heating and the thermal expansion of the droplet. It is well known that liquid alkanes exhibit a high volumetric expansion under heating. For example, the volumetric density of liquid n-octadecane decreases by 20%, when it is heated to the boiling point. After the transient period (t_0), the droplet temperature attains a steady-state value close to the boiling point, and then the evaporation only affects the droplet size: a straight line part of the curve corresponds to the droplet burning at a constant rate. It is found that the $d^2(t)$ law is valid for the initial droplet diameter between 1.2 and 2.5 mm. The time interval t_0 is an important characteristic of a large liquid fuel droplet. The value of t_0 is a function of the initial droplet size, temperature of environment, and composition of a droplet [5]. The $d^2(t)$ law validity for the droplet combustion assumes that the chemical reactions of oxidation are fast with respect to the mass transfer process. So, the droplet burning is controlled by the fuel evaporation and the vapor diffusion to the combustion zone. In that case, we can define the burning rate constant by the slope of the straight-line portion in Fig. 4.

The data obtained on the burning characteristics of docosane droplets are presented in Table 2. Here: $K_{\rm bur}$ – burning rate constant, mm^2/s; $h_{\max}$ – maximum flame height, mm; and dimensionless flame height – $h_{\max}/d_0$ for the various values d_0 of droplet's initial diameter. We can resume that an increase in the initial droplet diameter led to a pronounced rise

of the burning rate constant and flame height. The maximum flame height exceeds the initial droplet diameter by a factor of 11.5.

The same experiments are fulfilled with n-octadecane droplets to define the burning rate constants. It is found that the droplet diameter squared decreases linearly with the time. In Table 3, the data are presented for equal-size droplets of n-docosane and n-octadecane. We can see that the burning rate of octadecane exceeds that of docosane distinctly: by 15% for relatively small droplets ($d_0 = 1.87$ mm) and more significantly (about one third) for larger droplets.

In such way, we found that relatively small differences in physical properties may result in significant changes in burning characteristics. This fact is related to a substantial non-linearity of multispecies reaction-diffusion equations. Thus, the burning characteristics of a paraffin-based fuel can be modified by the percentage variation of alkanes with different molecular masses. As stated above, the spray combustion dominates in hybrid rocket motors with liquefying fuel. So, the heat and mass transfer processes are complicated by the interaction of burning droplets. To consider a multidroplet array, we should begin with a simple two-droplet system. A problem under consideration is the flame transfer from one burning droplet to another one. We place two similar droplets of octadecane one under the other, ignite the lower one by a Ruhmkorff coil, and register the process of upper droplet ignition, as well as its diameter change and the flame height. It is shown that the d^2(t) law is true in this case. So, we can determine the burning rate constants as described above.

The experiments were performed for a number of two-droplet systems with different initial diameters, for various interdroplet distances. We determined the burning time ($t_{\rm bur}$) and the maximum flame height ($h_{\max}$) for the upper droplet directly. Then we calculated the burning rate constant ($K_{\rm bur}$) of the upper droplet by the procedure described above.

The video recording of the upper droplet ignition allows us to find the ignition delay $t_{\rm in}$ as a function of the interdroplet distance L (see Fig. 6). We can see that the ignition delay rises with L and amounts to a considerable value when the distance L exceeds 20 mm, in other words, $L/d_0 > 10$.

By analyzing this curve, we make conclusion that the interaction between droplets is pronounced, when the interdroplet distance not exceeds ten droplet di-

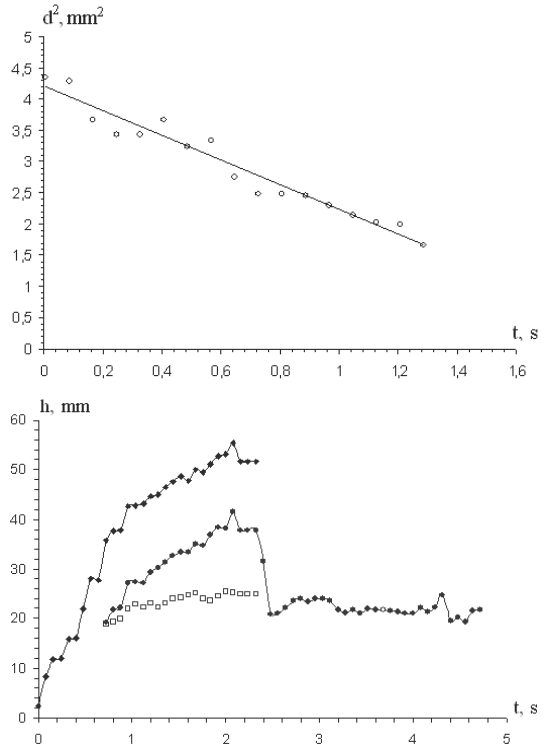


Fig. 5. Upper droplet history ($d_0 = 2.3$ mm) and flame height

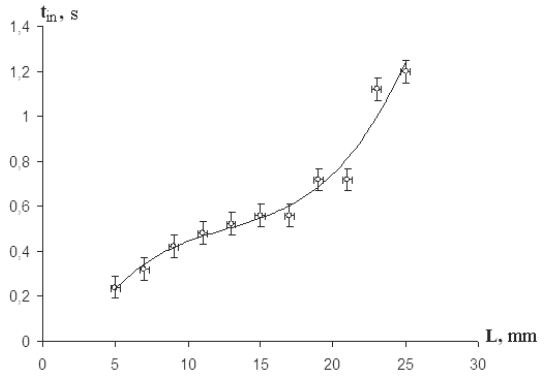


Fig. 6. Ignition delay of the upper droplet (n-octadecane) versus the interdroplet distance

Table 3. **Burning rate constants for droplets of equal initial diameters**

Alkane	$K_{\rm bur}$, mm^2/s	
Initial droplet diameter, mm	1.87	2.04
n-octadecane ($d_0 = 1.87$ mm)	1.43	2.59
n-docosane ($d_0 = 2.04$ mm)	1.22	1.61

Table 4. **Burning characteristics of the upper droplet of octadecane versus the interdroplet distance L**

L, mm	d_0, mm	$h_{\max}$, mm	$t_{\rm bur}$, s	L/d_0	$K_{\rm bur}$, mm^2/s
7	2.09	35.7	3.60	3.3	1.46
9	2.43	40.4	4.48	3.7	1.67
11	2.30	55.3	4.72	4.8	1.98
15	2.40	31.3	4.80	6.3	1.63
19	1.76	47.9	2.80	10.8	1.79
21	2.17	35.1	4.08	11.6	2.61
23	1.96	25	4.00	11.73	0.94
25	2.15	21.7	4.48	11.62	0.98

ameters; otherwise, it could be neglected. In case of horizontally placed droplets, it is found that the burning droplet caused the melting and the evaporation of another droplet, when the interdroplet distance is at most two diameters. This fact correlates with the results reported by J. Sangiovanni and M. Labowsky [6]: for the droplet distance of the order of two droplet diameters, the strong droplet interaction is observed. They asserted that an increase in the droplet burning time due to the droplet interaction depends universally on the droplet spacing and not on the fuel type, droplet size, or ambient conditions.

4. Conclusions

It is found that the droplet squared diameter is determined by the concurrence of the thermal expansion and the paraffin vaporization: it distinctly increases at the initial stage, attains a maximum value, and then decreases linearly in the course of time. The burning rate constants are determined by the slope of the linear portion of the $d^2(t)$ curve. We have established that the burning characteristics of n-octadecane and n-docosane (single droplet) differ distinctly. So, there is a possibility to control the combustion of a paraffin-based fuel by varying its fractional composition. Then we have investigated the flame transfer in a simple two-droplet system and have determined the burning rate constants of each droplet separately under normal conditions. It is found that the burning rate of separate droplets is higher than that of a two-droplet system. The ignition delay is determined as a function of the interdroplet distance. It is concluded that the interaction between droplets is appreciable at small interdroplet distances. So, it can be neglected in a hybrid combustion chamber, where the concentration of droplets is rather small.

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ДОСЛІДЖЕННЯ ГОРІННЯ КРАПЕЛЬ ПАРАФІНУ

Р е з ю м е

В роботі вивчаються характеристики горіння окремих крапель парафінів (н-октадекану та н-докозану) та з'ясовуються закономірності їх взаємовпливу при горінні в системі подвійних крапель. Доведено, що на стадії стаціонарного горіння крапель квадрат їх діаметра зменшується лінійно з часом горіння. Встановлено, що швидкість горіння крапель октадекану помітно перевищує швидкість горіння докозану. Досліджено процес поширення полум'я в системі з двох крапель. Встановлено, що помітна взаємодія між краплями має місце при невеликих відстанях, яка дорівнює двом початковим діаметрам краплі при горизонтальному розташуванні, та не перевищує десять діаметрів при вертикальному розташуванні крапель.

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ИССЛЕДОВАНИЕ ГОРЕНИЯ КАПЕЛЬ ПАРАФИНА

Р е з ю м е

В работе изучены характеристики горения отдельных капель алканов (н-октадекана и н-докозана) и исследовано их взаимовлияние при горении системы двух капель. Показано, что на стадии стационарного горения капель квадрат их диаметра линейно уменьшается с течением времени. Установлено, что скорость горения капель октадекана заметно превышает скорость горения капель докозана. Исследован процесс распространения пламени в системе из двух капель. Наблюдается выраженный эффект взаимовлияния в случае, когда межкапельное расстояние не превышает два начальных диаметра при горизонтальном расположении капель. При размещении капель по вертикали происходит воспламенение верхней капли от горящей нижней при расстоянии не более десяти диаметров.