

# EXAMINING EVAPORATION CHARACTERISTICS OF TYPICAL AVIATION FUELS INCLUDING JP-4, JP-5, JP-7, RT, Jet A-1 AND TS-1

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## Abstract

This work numerically studies the evaporation characteristics of 6 typical gas turbine fuels (JP-4, JP-5, JP-7, RT, Jet A-1, and TS-1, respectively). In this work, the influence of ambient temperature and liquid properties on the droplet lifetime is examined. At the same initial conditions (e.g. fuel temperature  $T_{s0} = 300$  K, droplet diameter  $D_0 = 1$  mm and atmospheric pressure  $p = 101.33$  kPa) and low ambient temperature (e.g. 500 K), significant differences in evaporation characteristics among these fuels are observed. JP-4 has the longest droplet lifetime while JP-7's is the shortest. However, at high ambient temperature (e.g. 2000 K), the droplet lifetimes of the fuels are almost identical. Under critical temperature, it is shown that the fuel properties remarkably impact the evaporation rate.

**Keywords:** Aviation fuel; drop evaporation; drop evaporation rate; drop lifetime.

## 1. Introduction

The evaporation process of liquid fuels comprises of simultaneous heat and mass transfer processes in which the heat for evaporation is transferred to the liquid surface by conduction and convection from the surrounding hot gas environment, and vapor is transferred by convection and diffusion back into the hot gas stream. Fuel evaporation characteristics significantly affect the fuel and air mixing quality. Improving evaporation processes can, therefore, directly enhance combustion efficiency, which is crucial for heat engines including aviation counterparts. In this work, drop evaporation is characterized for 6 different aviation liquid fuels including JP-4, JP-5, JP-7, RT, Jet A-1 and TS-1. These fuels are typically used in both civil and army aviation gas turbine engines in which TS-1 is commonly used in Vietnam Airforce.

Droplet evaporation is a fundamental phenomenon in nature and has implications in different industries and research areas, thus, this phenomenon has been intensively studied for decades [1, 2]. Compared to a monocomponent droplet, evaporation of a

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multicomponent droplet is more practical and common but involves much more complicated mechanism. Therefore, scientists have been attracted to this area and efforts have been made to understand the underlying physical mechanisms of multicomponent droplet evaporation utilizing experimental and numerical methods [3].

One of the earliest numerical studies on multicomponent droplets done by Newbold and Amundson [4] has characterized the evaporation processes for a multicomponent droplet under a temperature condition close to the drop boiling point. Later, a number of models based on different approaches, such as expanded diffusion limit model [5], distillation curve model [6], continuous distribution model [7], and continuous thermodynamics model [8], has been developed in order to describe and predict multicomponent droplet evaporation rate. Meanwhile, experimental studies have been carried out under different environmental conditions to understand the mechanism of multicomponent evaporation, including vaporization in an electric field [9], free falling in a temperature gradient field [10], sitting on heated or non-heated flat surface [11], evaporating in heated air flow [12] and at elevated pressure and temperature conditions [13].

According to our knowledge, studies on comparison of multicomponent droplet evaporation for typical aviation fuels like the ones investigated here, are scarce. This paper adopted numerical approach developed earlier in [14] to predict droplet evaporation rate and droplet lifetime for six different commercial aviation fuels. Enhancing knowledge on the evaporation characteristics for these fuels may help to improve the evaporation quality and this in turn improves mixing and combustion processes for aviation engines.

## **2. Mathematical Modeling**

Mathematical modeling used to characterize droplet evaporation will be discussed in this section. In this model, a stationary drop is placed in a hot gaseous environment and the drop lifetime is to be estimated. This is based on theory earlier reported in [14] and this section will summarize the mathematical correlations. The following assumptions are made:

- (i) The drop is spherical.
- (ii) The fuel is a pure liquid having a well-defined boiling point.
- (iii) Radiation heat transfer is negligible.
- (iv) Lewis Number of unity is obtained (i.e. diffusivities of heat and mass are equal).
- (v) Drop temperature is uniform (i.e. drop surface and center temperature are equal).

(vi) Heat-up stage is negligible (i.e. the drop surface has attained its wet-bulb temperature and all of the heat reaching the surface is utilized in providing the latent heat of vaporization)

The rate of fuel evaporation is obtained as:

$$\dot{m}_F = 2\pi D_S \frac{k_g}{c_{p_g}} \ln(1 + B_T) \quad (1)$$

where  $\dot{m}_F$  is rate of evaporation of a fuel drop (kg/s);  $D_S$  is drop diameter (m);  $k_g$  (J/m.s.K) and  $c_{p_g}$  (J/kg.K) are thermal conductivity and specific heat capacity of the mixture air-vapor, respectively;  $B_T$  is heat transfer number. Accuracy of this expression is very dependent on the choice of values of  $k_g$  and  $c_{p_g}$ . According to Hubbard et al. [15], best results are obtained using the one-third rule of Sparrow and Gregg [16], where the average properties are evaluated at the following reference temperature and composition:

$$T_r = T_S + \frac{T_\infty - T_S}{3} \quad (2)$$

$$Y_{Fr} = Y_{Fs} + \frac{Y_{F\infty} - Y_{Fs}}{3} \quad (3)$$

$$\text{and } Y_{Ar} = 1 - Y_{Fr} \quad (4)$$

where  $T$  is temperature (K),  $Y_F$  is mass fraction of fuel vapor,  $Y_A = 1 - Y_F$  is mass fraction of air and subscripts  $r$ ,  $s$ , and  $\infty$  refer to reference, surface, and ambient conditions.  $Y_{Fs}$  is obtained as:

$$Y_{Fs} = \left[ 1 + \left( \frac{p}{p_{Fs}} - 1 \right) \frac{M_A}{M_F} \right]^{-1} \quad (5)$$

where  $p$  is ambient pressure (Pa),  $p_{Fs}$  is fuel vapor pressure at the drop surface (Pa),  $M_A$  and  $M_F$  are the molecular weights of air and fuel, respectively. For any given value of surface temperature, the vapor pressure of fuel is estimated as:

$$p_{Fs} = 10^{\left( a - \frac{b}{T_s} \right)} \quad (6)$$

Values of  $a$  and  $b$  for the fuels studied in this work are reported in Tab. 1.

As the fuel concentration at an infinite distance from the drop is assumed to be zero, Equation (3) becomes:

$$\Upsilon_{Fr} = \frac{2}{3} \Upsilon_{Fs} \quad (7)$$

and 
$$\Upsilon_{Ar} = 1 - \Upsilon_{Fr} = \frac{\Upsilon_{Fs}}{3} \quad (8)$$

Equations (2), (7), (8) are used to calculate reference values which are showed in the following expressions:

$$c_{pg} = \Upsilon_{Ar} (c_{pa} at T_r) + \Upsilon_{Fr} (c_{pv} at T_r) \quad (9)$$

$$k_g = \Upsilon_{Ar} (k_a at T_r) + \Upsilon_{Fr} (k_v at T_r) \quad (10)$$

where subscripts *a* and *v* refer to air and vapor, respectively. At normal atmospheric pressure,  $p = 101.33$  kPa, specific heat and thermal conductivity of air are calculated by the following equations [17]:

$$c_{pa} = 1.9327E - 10T_r^4 - 7.9999E - 7T_r^3 + 1.1407E - 10T_r^2 - 4.489E - 3T_r + 1.0575E3 \quad (11)$$

$$k_{pa} = 1.5207E - 11T_r^3 - 4.8574E - 8T_r^2 + 1.0184E - 4T_r - 3.9333E - 4 \quad (12)$$

The variation of specific heat and thermal conductivity for hydrocarbon fuel vapor with temperature is described by the relationships:

$$c_{pv} = (363 + 0.467T_r)(5 - 0.001\rho_{F0}) \quad (13)$$

where  $\rho_{F0}$  is fuel density at a temperature of 288.6 K.

$$k_v = 10^{-3} [13.2 - 0.0313(T_{bn} - 273)] \left( \frac{T}{273} \right)^n \quad (14)$$

$$n = 2 - 0.0372 \left( \frac{T}{T_{bn}} \right)^2 \quad (15)$$

where  $T_{bn}$  is fuel normal boiling temperature that is defined as the temperature in which the vapor pressure of the liquid equals to the normal atmospheric pressure, 101.33 kPa.

The heat transfer number  $B_T$  in Equation (1) is calculated by following expression:

$$B_T = \frac{c_{pg} (T_\infty - T_S)}{L} \quad (16)$$

where  $L$  is latent heat of vaporization (J/kg) which given by [18] as:

$$L = A(B - T_s)^{0.4} \quad (17)$$

In this expression, values  $A$  and  $B$  for the fuels investigated here are listed in Tab. 1, here  $B = T_{cr}$  (K) (fuel critical temperature).

During evaporating process, the drop diameter diminishes with time according to relationship:

$$\lambda t = D_{s0}^2 - D^2 \quad (18)$$

or 
$$\lambda = \frac{d(D)^2}{dt} \quad (19)$$

where  $D_{s0}$  is initial drop diameter (m);  $D$  is drop diameter at time  $t$  (m);  $\lambda$  is evaporation constant (m<sup>2</sup>/s); and  $t$  is time (s). In addition, the rate of evaporation could be calculated as:

$$\dot{m}_F = \frac{dm_F}{dt} = \frac{d(V_F \rho_F)}{dt} = \frac{\rho_F d \left( \frac{\pi D^3}{6} \right)}{dt} = \frac{\pi}{4} D \rho_F \frac{d(D)^2}{dt} = \frac{\pi}{4} D \rho_F \lambda$$

hence

$$\lambda = \frac{4\dot{m}_F}{\pi D \rho_F} \quad (20)$$

At the end of the evaporation process, drop diameter is assumed to be zero, substituting for  $D = 0$  into Equation (18) gives:

$\lambda t_d = D_{s0}^2$  and as such the droplet lifetime,  $t_d$  could be estimated:

$$t_d = \frac{D_{s0}^2}{\lambda} \quad (21)$$

where  $t_d$  is drop lifetime (s).

### 3. Model Prediction

#### 3.1. Fuel selection

Six different aviation fuels have been selected in this study (TS-1, RT, JP-4, JP-5, Jet A-1 and JP-7). The evaporation rate of these fuels depends on their application area and supply. Both TS-1 and RT are adopted in Russia, TS-1 is typically used in military aircraft while RT is typical civil gas turbine engine fuel. Remaining fuels including

JP-4, JP-5, Jet A-1 and JP-7 are standard liquids used for specific purposes in America. The wide-cut JP-4 is the primary fuel that meets operational requirements and reflects a broad availability. The U.S. Navy, particularly for aircraft carrier safety, relies on JP-5, a high flash-point fuel. JP-7 is used by the Air Force for specific applications in which high thermal stability is required. And Jet A-1 is the primary commercial fuel outside the US. The more details about the selected fuels availability is directed to [19, 20].

The important properties of the selected fuels are shown in Tab. 1 [19, 20]. Table 1 also shows constants used in the mathematical model presented in previous section, they were calculated by using data from [19, 20]. As can be seen from the Tab. 1, the average number of C atoms contained in the fuels ranges from 7 to 12 and this may cover most of the fuels currently used in civil air crafts as well as military airforce.

Tab. 1. Fuel physical properties

Fuel	TS-1	RT	JP-4	JP-5	Jet A-1	JP-7
Approximate Formula	$C_{7.21}H_{13.2936}$	$C_{10.8}H_{21.6}$	$C_{8.5}H_{17}$	$C_{12}H_{22}$	$C_{12}H_{21}$	$C_{12}H_{25}$
Density $\rho_{F0}$ (kg/m <sup>3</sup> )	782.456	781.32	765.15	812.5	801.36	793.68
$a$ in Equation (6)	19.02	18.18	17.32	21.75	18.87	21.75
$b$ in Equation (6)	5605.02	5279.52	4204.5	7500.8	5978.6	7500.8
A in Equation (17)	34680.91	33510	36902.66	37218.31	36146.6	31208.69
B in Equation (17)	639.77	659.24	603.15	617.46	683.15	688.34

### 3.2. Model validation

Fig. 1 shows the predictions and experimental results for Jet A-1 fuel. The theoretical graph shows a straight-line relationship between diminishing ratio of droplet diameter squared versus time. However, experimental inspection reveals that the slope of the  $(D/D_0)^2/t$  line is almost zero in the first stage of evaporation and then gradually increases with time until the drop attains its wet-bulb temperature, in which the temperature inside the drop is uniformed and the slope of the  $(D/D_0)^2/t$  line remains fairly constant throughout the remainder of the drop lifetime. Therefore, the vaporization process can roughly be separated into the transient or unsteady state and

the steady state. Fuel drops finally reach their wet-bulb temperature asymptotically with time, and for almost fuels, the drop generally spends only a very small portion of its time in the unsteady state; thus in this work, we only considers the steady state. Also, as mentioned in assumption (vi) that heat-up stage is negligible in this model but this is not practically true. As such this is also a limitation of the model shown here and we will look up these issues in the future to consider the first stage of evaporation. As illustrated in Fig. 1, the slope of second part of experimental graph and that of theoretical line are almost identical and as such we are confident to use the model to predict the droplet lifetime. The discrepancy in droplet lifetime for the experimental case is formed because of inclusion unsteady state period.

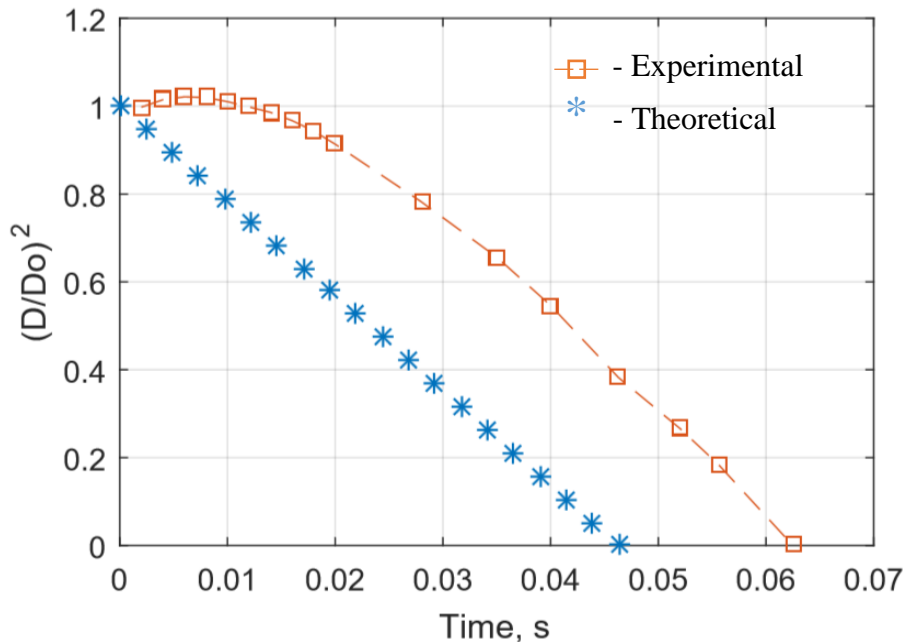


Fig. 1. Comparison between the predictions and experimental findings [21] for the  $(D/D_0)^2$  versus time for Jet A-1 fuel. Initial conditions:  $T_\infty = 800$  K,  $T_{s0} = 300$  K,  $D_0 = 100$   $\mu$ m and  $p = 101.33$  kPa.

### 3.3. Influence of fuel properties on evaporation process

Variations of diminishing ratio of droplet diameter squared with time for several gas turbine fuels are illustrated in Fig. 2. The figure clearly shows the influence of fuel properties on droplet lifetime. JP-4 shows its longest lifetime while JP-7's evaporates quickest. The difference amongst the fuels tested here may due to the differences in

their physical and thermal properties as shown in Tab. 1. The influence of fuel properties on evaporation will be discussed further in this section.

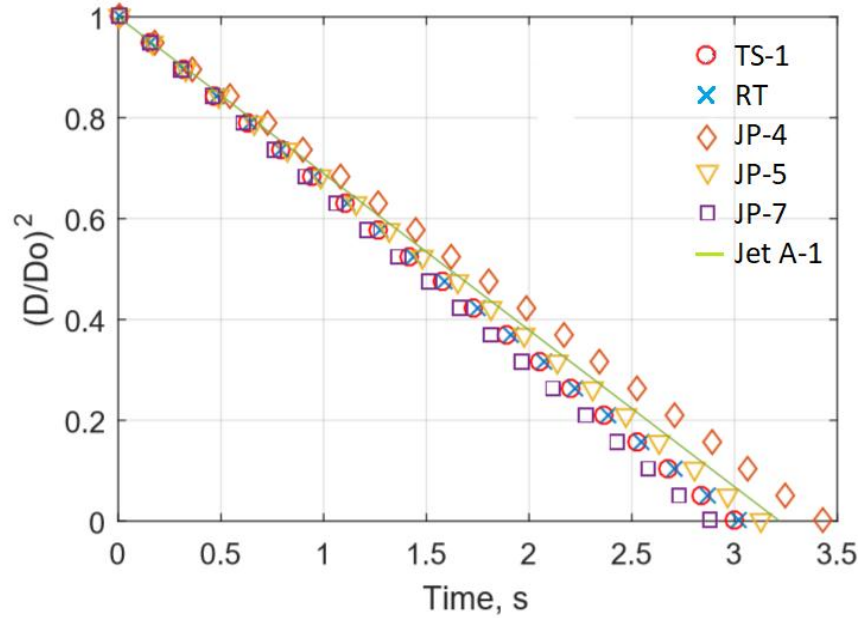


Fig. 2. Variation of  $(D/D_0)^2$  with time during evaporation process for several fuel. Initial conditions:  $T_\infty = 800 \text{ K}$ ,  $T_{s0} = 300 \text{ K}$ ,  $D_0 = 1000 \mu\text{m}$  and  $p = 101.33 \text{ kPa}$ .

Influence of initial fuel temperature on evaporation process is shown in Fig. 3 for TS-1 and JP-4 fuel at ambient temperature  $T_\infty = 1000 \text{ K}$  (bigger than TS-1 and JP-4 critical temperature:  $T_{cr}$  for TS-1 = 639 K, and for JP-4 = 603 K). As the fuel temperature rises, the fuel vapor formed at the drop surface has two impacts: (1) part of the heat transferred to the drop is needed to furnish the heat of vaporization of the liquid and (2) the outward flow of fuel vapor impedes the rate of heat transfer to the drop. This tends to diminish the rate of increase of the surface temperature, so there is a part of the graphs (where initial temperature is smaller than fuel normal boiling temperature) drop lifetime grows up according to the increase of fuel temperature. When initial temperature nearly attains normal boiling point ( $T_{bn}$  for TS-1 = 431 K, for JP-4 = 372 K) which corresponds to distillation temperature 50% recovery, the influence of the outward flow decreases. Eventually, droplet lifetime is diminished with increasing initial fuel temperature from  $T_{bn}$  to  $T_{cr}$ . This figure also reveals that as the fuel asymptotically reaches its critical temperature, the droplet lifetime approaches to zero.



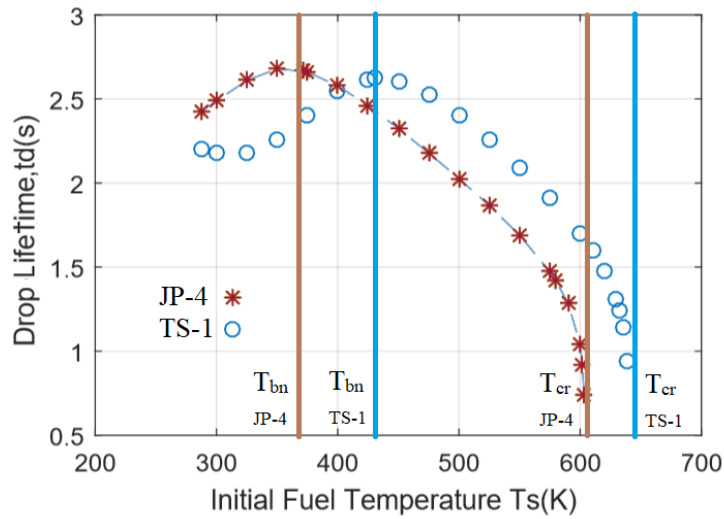


Fig. 3. Influence of initial fuel temperature on drop lifetime for TS-1 and JP-4 fuel.

Initial conditions:  $T_{\infty} = 1000 \text{ K}$ ,  $D_0 = 1 \text{ mm}$  and  $p = 101.33 \text{ kPa}$ .

The variation of the fuel temperature also affects liquid properties such as: heat of evaporation, density, and specific heat. Fig. 4 correlates the heat of evaporation and droplet lifetime as the initial fuel temperature rises from  $T_{bn}$  to  $T_{cr}$  for several fuels. This figure reveals that heat of evaporation and droplet lifetime become zero at  $T_{cr}$ , and for this condition drop lifetime grows up according to increasing direction of  $L$ .

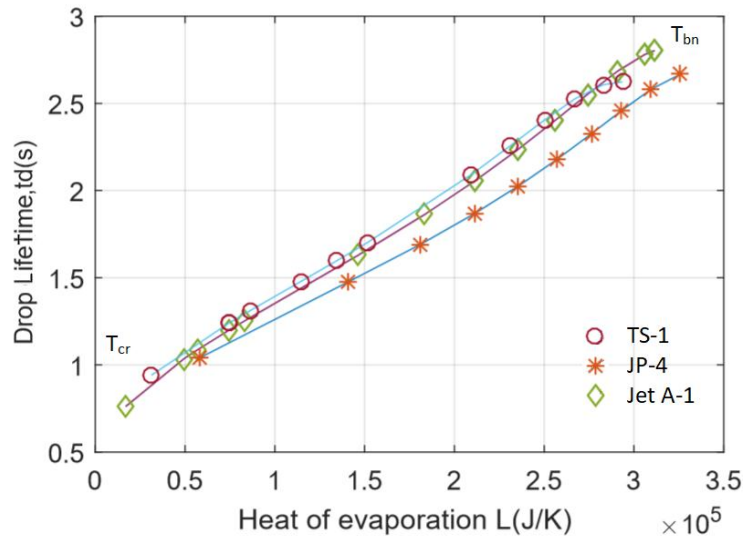


Fig. 4. Influence of heat of evaporation on droplet lifetime as the initial fuel temperature

rises from  $T_{bn}$  to  $T_{cr}$  for several fuels. Initial conditions:  $T_{\infty} = 1,000 \text{ K}$ ,

$D_0 = 1 \text{ mm}$ , and  $p = 101.33 \text{ kPa}$ .

### 3.4. Influence of ambient temperature on evaporation process

Fig. 5 shows drop lifetime versus ambient temperature. The figure clearly indicates that the time decreases remarkably with an increase in ambient temperature. Moreover, at low ambient temperature, difference in drop lifetime amongst the fuels studied here is significant but the difference is smaller with high temperature and the drop lifetime is almost identical amongst the fuels studied here at 2,000 K.

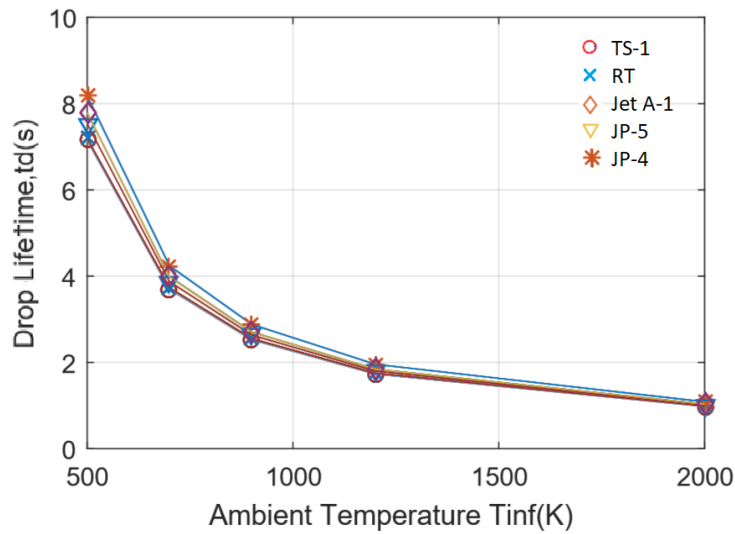


Fig. 5. Influence of ambient temperature on fuel evaporation process. Initial conditions:  $T_{s0} = 300$  K,  $D_0 = 1$  mm, and  $p = 101.33$  kPa.

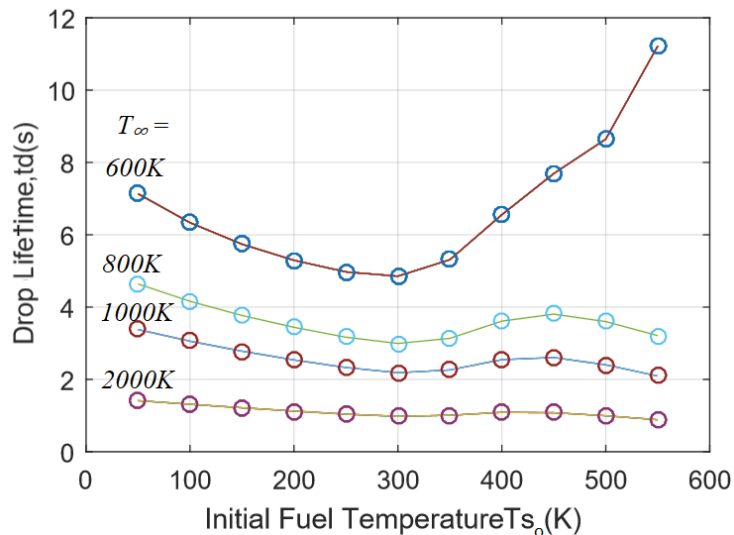


Fig. 6. Influence of initial fuel temperature to drop lifetime at varied ambient temperature for fuel TS-1. Initial conditions:  $D_0 = 1000$   $\mu$ m, and  $p = 101.33$  kPa.

It is shown earlier in Fig. 3 that with an increase in initial fuel temperature to  $T_{cr}$  drop lifetime reduces to zero. However, this thing only corresponds to predetermined condition, in which ambient temperature is greater than the fuel critical temperature,  $T_{cr}$ .

Fig. 6 shows the influence of initial fuel temperature to drop lifetime at varied ambient temperature for fuel TS-1. At ambient temperature higher than fuel critical temperature  $T_{cr}$  (for TS-1  $T_{cr} = 639$  K), when initial fuel temperature approaches to  $T_{cr}$ , drop lifetime reduces to zero; whereas at ambient temperature smaller than fuel critical temperature, as initial fuel temperature approaches to  $T_{cr}$ , drop lifetime increases to infinite.

#### **4. Conclusion**

In this paper, evaporation of different aviation fuels has been successfully investigated. The influence of fuel properties and ambient temperature on evaporation is examined. It is observed that the fuel properties significantly affect the evaporation characteristics. All of fuel evaporation processes are remarkably affected by ambient temperature and initial fuel temperature. At the same initial conditions ( $T_{s0} = 300$  K,  $D_0 = 1$  mm and  $p = 101.33$  kPa) and low ambient temperature (500 K), difference in evaporation rates amongst those fuels tested here is significant. JP-4 has the longest droplet lifetime while JP-7 shows its fastest evaporation time. However, under a high ambient temperature condition (2000 K), these values are almost identical. As fuels' temperature approaches to their critical values, the evaporation is strongly affected by the fuel properties.

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## NGHIÊN CỨU ĐẶC TRƯNG BAY HƠI CỦA CÁC LOẠI NHIÊN LIỆU HÀNG KHÔNG BAO GỒM JP-4, JP-5, JP-7, RT, Jet A-1 VÀ TS-1

**Tóm tắt:** Bài báo nghiên cứu đặc tính bay hơi của 6 loại nhiên liệu tua bin khí điển hình bao gồm JP-4, JP-5, JP-7, RT, Jet A-1 và TS-1. Bài báo tập trung đánh giá ảnh hưởng của nhiệt độ môi trường và đặc tính nhiên liệu đến tốc độ và thời gian hóa hơi. Ở cùng điều kiện ban đầu (ví dụ: nhiệt độ nhiên liệu là  $T_{s0} = 300$  K, đường kính hạt  $D_0 = 1$  mm, áp suất khí quyển  $p = 101.33$  kPa) tại nhiệt độ môi trường thấp (khoảng 500 K), sự khác biệt về tốc độ bay hơi giữa các nhiên liệu là rất rõ ràng, trong đó JP-4 có thời gian hóa hơi dài nhất trong khi thời gian hóa hơi JP-7 là ngắn nhất. Tuy nhiên, ở môi trường nhiệt độ cao (2000 K) những giá trị này lại xấp xỉ gần như nhau. Khi nhiệt độ môi trường tiến đến giá trị tới hạn, tốc độ bay hơi của nhiên liệu phụ thuộc lớn vào đặc tính nhiên liệu.

**Từ khóa:** Nhiên liệu hàng không; quá trình bay hơi; tốc độ bay hơi; thời gian bay hơi giọt nhiên liệu.

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