



Brief Communication

Effect of additional heat transfer modes on measured evaporation and combustion rates of isolated hydrocarbon droplets

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A B S T R A C T

This work addresses the impact of different additional heat transfer modes on the evaporation behaviors extracted from single droplet experiments. Conduction of heat through the support filaments, absorption of radiation and external convective effects can induce significant deviations from the targeted canonical problem, where the only heat transfer mode is usually assumed to be conduction through the droplet-gas interface. When these additional modes are not duly accounted for, those deviations should be considered as experimental artifacts. This work is an extension of a previous study describing a theoretical framework to estimate the magnitude of each experimental artifact by means of dimensionless numbers. Whereas the method had been validated with high-temperature evaporation data obtained for alcohols droplets, this assessment is now extended to cover situations of practical relevance including hydrocarbon fuels (dodecane and Jet A) vaporizing under both oxygen-free and oxidizing atmospheres. Results from a total of 352 tests support the use of the proposed method also for hydrocarbons and droplet combustion scenarios, allowing for an inexpensive estimation of the different experimental artifacts in single droplet tests, as required for the correct interpretation of droplet evaporation/combustion experimental data.

1. Introduction

The isolated droplet setup can be considered as the most common reference framework for the detailed study of liquid fuel evaporation and combustion. The relative simplicity of this problem has enabled the development of a wide range of theoretical descriptions, from pioneering analytical expressions [1,2] to more complete models accounting for additional effects (e.g., see [3]). From the experimental point of view, different setups have been used to reproduce this simplified configuration, yielding detailed data for liquid fuels: droplets suspended on fibers, free-falling, levitating, or even floating in the absence of gravity (e.g., see [4]). The different experimental setups usually aim to reproduce the canonical, idealized scenario targeted by most theoretical descriptions: spherical symmetry problem where all the heat input to the droplet is due to conduction through the gas-droplet interface.

However, it is clear that deviations from this ideal scenario occur in real-life experiments, and therefore these differences must be assessed to correctly interpret test data. Partial aspects have been addressed in several works, in particular regarding the conduction of heat through the supporting fibers (e.g., see [5–8]). Also, the absorption of thermal radiation by the liquid can become very relevant when big-sized droplets are tested close to hot radiating surfaces (e.g., see [9]). Finally, convective flows (either forced or buoyancy-induced) can also

significantly enhance the heat and mass exchange between droplet and surrounding gas.

A recent work [10] proposed a novel theoretical approach to estimate the impact of additional heat transfer modes (which, unless duly quantified, constitute experimental artifacts) by means of dimensionless numbers. The method was validated with high-temperature evaporation data obtained for alcohols droplets. The current work aims to extend this study to hydrocarbons fuels, while also exploring oxidizing conditions where the droplet is surrounded by an envelope flame, as a way to validate this method for a much broader range of conditions of clear interest for combustion applications.

2. Materials and methods

A total of 352 tests were carried out in a suspended droplet facility (SDF), described in detail elsewhere [10]. Among these, 191 tests correspond to a high-temperature evaporation scenario (ambient temperature of 1336 K, without oxygen), whereas 161 experiments were conducted for a combustion case (similar ambient temperature, with 10 % vol. of oxygen in the gas coflow). The radiative heat flux at the droplet location was measured as 23.5 kW/m², while estimated Reynolds number was ~0.5 for a 500 μm droplet.

The droplets were suspended on two fiber materials, namely silicon carbide (SiC, $d_f = 15 \mu\text{m}$) and platinum (Pt, $d_f = 25 \mu\text{m}$). For SiC, the

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Nomenclature		ρ	Density, [kg m ⁻³]
CN	Convection number, [-]	σ	Stoichiometric O ₂ -to-fuel mass ratio [-]
C_p	Heat capacity at constant pressure, [J kg ⁻¹ K ⁻¹]	<i>Subscripts</i>	
d	Diameter, [μm]	0	Initial
FN	Fiber number, [-]	b	Boiling
k	Thermal conductivity, [W m ⁻¹ K ⁻¹]	c	Combustion
K	Droplet evaporation rate, [mm ² s ⁻¹]	can	Canonical case
L_v	Latent heat of vaporization, [J kg ⁻¹]	f	Fiber
Q	Enthalpy of reaction, [J kg ⁻¹]	g	Gas phase
RN	Radiation number, [-]	l	Liquid phase
t	Time, [s]	pyr	Pyrolysis
T	Temperature, [K]	v	Vapor
Y	Mass fraction, [-]	∞	Ambient

droplet was deployed at the intersection of two single crossed fibers (2 × 1) and of two bundles of 3 fibers (2 × 3), so as to evaluate the effect of increasing the effective cross section of the suspending filament. As for the platinum wire, the droplet was suspended on a single filament bent in a U-shape.

A wide range of initial droplet sizes were tested ($d_0 \sim 250$ to 1200 μm). Two different liquid hydrocarbons were studied, namely n-dodecane (99 % purity) and a commercial Jet A sample, whose main properties can be found in [11].

3. Results and discussion

Fig. 1 displays the droplet evaporation curves obtained for dodecane and Jet A droplets with similar initial sizes ($d_0 \sim 400$ μm) under evaporation (0 %O₂) and combustion (10 %O₂) conditions when using different supporting elements. Even though the experimental curves may not exactly follow the d^2 -law, following common practice, results are presented in terms of the temporal evolution of the droplet diameter squared (d^2).

For a given fuel, the suspension fiber causes clear differences in the evaporation behaviors displayed in Fig. 1. For instance, when increasing the number of SiC fibers from 2 to 6, the initial heat-up transient is delayed, with a slower evaporation and larger droplet sizes during the first instants. This slightly delayed evaporation is compensated by an enhanced evaporation rate (K) during most of the droplet lifetime, causing similar or even slightly shorter droplet consumption times for the 2 × 3 SiC cases. This behavior is quite consistent for both fuels, being

also observed for both evaporation and combustion cases. If the ceramic SiC fibers are changed to Pt25, the evaporation characteristics are completely modified. The larger cross section and the much higher thermal conductivity of platinum significantly increases the fiber temperature, enhancing heat transfer to the liquid droplet. This additional heat input dramatically increases the evaporation rate, disturbing the vaporization curves to a point where the d^2 -law is not followed anymore, with a clear fluctuating evaporation even for a pure compound such as dodecane. This behavior is ascribed to the nucleation of fuel vapors at hot spots on the fiber, creating bubbles that disrupt the otherwise smooth evaporation curves (as it was analyzed in detail in [10]).

Droplet evaporation curves obtained for dodecane droplets suspended on platinum wires are displayed in Fig. 2 for different initial droplet sizes. As d_0 increases, the evaporation process becomes smoother, and closer to the theoretical d^2 -law. For 0 %O₂, this increase in d_0 leads to a progressive reduction in K and a transition to a smooth evaporation process. This is fully consistent with the impact of the suspension fibers being related to the fiber-to-droplet diameter ratio, as concluded in [6,7,10]. A convergence in terms of consumption time seems to be reached for sufficiently big droplets (e.g., $d_0 = 853$ –1000 μm, $d_0/d_f = 34$ –40). Despite this apparent convergence and the smooth curves in Fig. 2a, it is worth noting that Pt25 fibers still have a notable impact by enhancing K , as it will be detailed further on. Similar trends can be extracted for the combustion scenario in Fig. 2b, although in this case the curves are further away from the d^2 -law even for droplets > 1 mm. This is ascribed to the higher fiber temperatures for this combustion case, which would increase heat transfer between fiber and droplet,

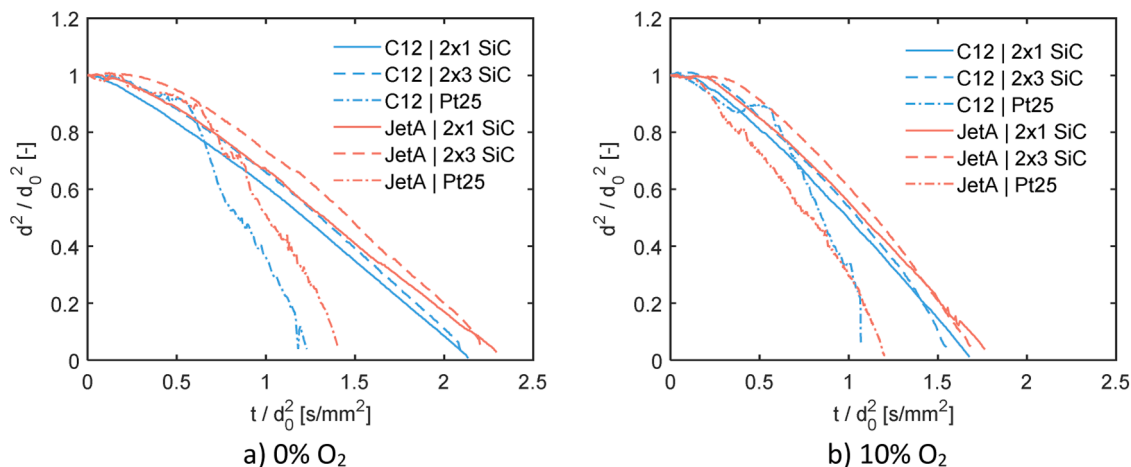


Fig. 1. Evaporation curves for dodecane (C12) and Jet A droplets suspended on different fiber arrangements, with oxygen-free (a) and oxidizing (b) atmospheres. All tests were performed with $d_0 \sim 400$ μm, except for the combustion cases with Pt25, where $d_0 > 550$ μm due to practical reasons.

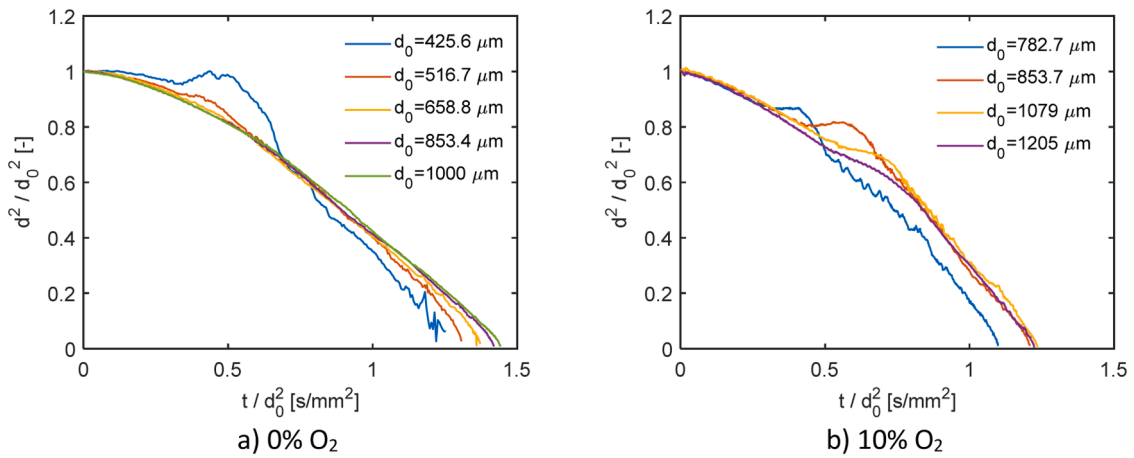


Fig. 2. Evaporation curves for dodecane droplets suspended on a Pt25 filament with oxygen-free (a) and oxidizing (b) atmospheres.

inducing therefore a stronger fluctuating behavior.

A more general assessment can be obtained from Fig. 3, where the quasi-steady evaporation rate ($K = -d(d^2)/dt$) is plotted in terms of d_0 for the different fibers, fuels and oxygen conditions tested. This averaged K is calculated as the slope of a straight line fitting the experimental points between $(d/d_0)^2 = 0.6$ and 0.2 in the evaporation curves shown in Figs. 1 and 2.

Ideally, K should be independent from fiber properties. Therefore, the variations observed in Fig. 3 can only be due to experimental artifacts caused by the presence of the fiber, and hence inherent to suspended-droplet tests, that need to be duly identified and assessed. Overall, the dependency of K on fiber typology, d_0 and oxygen level is found to be perfectly consistent for both dodecane and Jet A, following

also the behavior reported in [10] for pure evaporation of alcohol droplets. Namely, as bigger droplets are tested, the impact of forced and natural convection increases, enhancing the evaporation rate. This, in addition to increased radiative heating for larger surface areas, explains the sustained rise in K with d_0 for cases where the impact of the suspension filaments is small enough (i.e., experiments with $2 \times \text{SiC}$). However, for sufficiently thick and/or conductive fibers, heat transfer due to conduction along the fiber may become significant. In those cases, the fiber-to-droplet diameter ratio becomes a controlling parameter. Thus, an increase in d_0 induces a sustained decrease in K , as it can be assessed in Fig. 3 for experiments using Pt25. This decrease is slowed down by the aforementioned higher impact of radiative and convective heating for larger droplets so that, even for quite large ones ($d_0 \sim 1 \text{ mm}$),

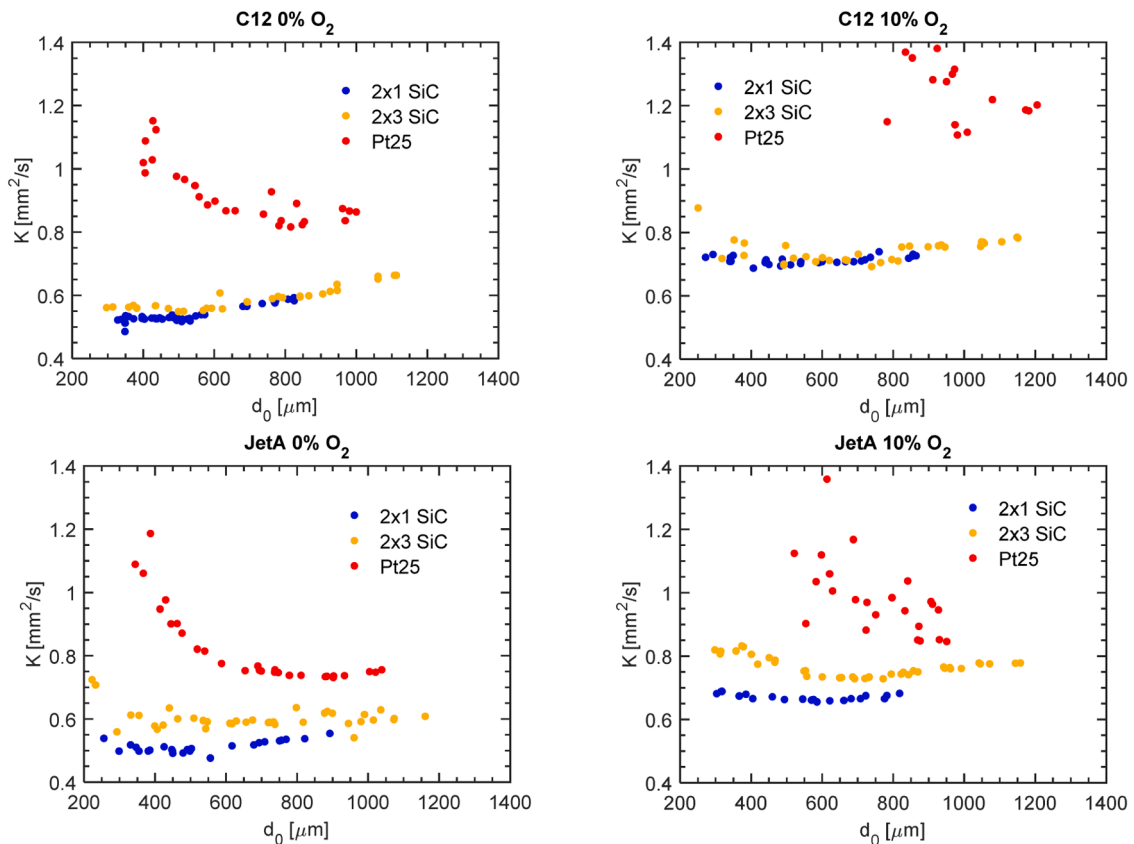


Fig. 3. Experimental evaporation rates measured for dodecane (C12) and Jet A for oxygen-free (0 % O₂) and oxidizing (10 % O₂) atmospheres using different fibers and initial droplet sizes.

the evaporation rates using a platinum wire significantly exceed those obtained for SiC fibers. Finally, it is worth to note the significant scattering of the experimental data obtained for Pt25 under combustion conditions, due to the fluctuating behavior displayed in Fig. 2b.

This work is an extension of a previous study [10], which proposed a novel approach to quantify deviations from canonical conditions (K_{can}) as:

$$K = K_{can} + \Delta K(FN, RN, CN) \quad (1)$$

Being FN , RN and CN dimensionless numbers related to fiber conduction, radiative heating and convective effects, respectively, as defined in [10]. As for K_{can} , it represents the evaporation rate under ideal conditions (i.e., the conduction of heat through the liquid-gas interface is the only heat input to the droplet). For small departures from this ideal case, the following functional form was proposed [10]:

$$K/K_{can} = 1 + FN + RN + CN \quad (2)$$

This approach was validated in [10] for pure evaporation of alcohols. However, it is not evident if those conclusions are equally applicable to other liquids (e.g. dodecane and Jet A as representative of hydrocarbon fuels) or conditions (oxidizing atmospheres) of relevance for practical applications. The dimensionless numbers FN , RN , CN have been therefore estimated as detailed in [10] for all the experiments displaying smooth evaporation curves (i.e., no internal boiling and disruptive evaporation). For combustion conditions (10 % O_2), the ambient temperature in the original formulation of RN has been replaced by the flame temperature (as estimated by the classical theory of droplet combustion, [12]).

In contrast to the alcohols tested in [10], the hydrocarbons studied in this work have been reported to thermally decompose when exposed to the high temperatures used in this work, noticeably lowering the evaporation rate [13]. Similarly to [11], this additional effect can be accounted for in a simplified manner in the calculation of K_{can} by adding a term related to the pyrolysis enthalpy (Q_{pyr}) to the Spalding heat transfer number. Thus, K_{can} can be readily estimated as follows for evaporation and combustion cases, respectively:

$$K_{can} = \frac{8 k_g}{\rho_l C_{p,v}} \ln \left(1 + \frac{C_{p,v}(T_\infty - T_b)}{L_v + Q_{pyr}} \right) \quad (3)$$

$$K_{can} = \frac{8 k_g}{\rho_l C_{p,v}} \ln \left(1 + \frac{\frac{Y_{O_2,\infty} Q_c}{\sigma} + C_{p,v}(T_\infty - T_b)}{L_v + Q_{pyr}} \right) \quad (4)$$

Q_{pyr} is adjusted from experiments using a free-falling droplet facility with minimal impact of experimental artifacts, as detailed in [11]. In a

first approximation, Q_{pyr} is assumed to be constant for a given fuel, and independent of the oxygen condition. As such, the value reported in [11] for the evaporation of n-dodecane in a high-temperature and inert atmosphere (0.205 MJ/kg) will be used in this work for both oxygen conditions. Liquid properties are evaluated at the boiling point, since the droplet quasi-steady temperature is assumed as T_b in this simplified estimation. The gas properties are evaluated by following the widely employed 1/3 rule [14] between the droplet surface and the far field (0 % O_2) or the flame (10 % O_2). The resulting K_{can} values obtained for dodecane for the conditions used in this work are 0.424 and 0.542 mm^2/s for 0 and 10 % O_2 atmospheres, respectively. As for Jet A, such simplified estimations are not possible for this complex multicomponent fuel. Thus, in a first approximation and in view of its closeness to dodecane (see Fig. 1), K_{can} for Jet A is assumed to be that of dodecane. Following this procedure, results from 286 experiments (163 for 0 % O_2 , 123 for 10 % O_2) with smooth evaporation curves are plotted in Fig. 4.

The new experimental data for dodecane and Jet A are found to clearly follow the trends presented in [10], with a defined linear tendency in Fig. 4 and within the range of the results reported for alcohols. Only the data for tests with platinum wire display larger deviations, again confirming the greater disturbance caused by highly-conductive fibers. Overall, the data plotted in Fig. 4 are considered to confirm that the approach proposed in [10] is also perfectly suitable for the high-temperature evaporation of hydrocarbons and real fuels such as dodecane and Jet A.

Furthermore, the data displayed in Fig. 4(b) reveal very similar behavior under combusting conditions, indicating that similar deviations in measured burning rates, compared to ideal conditions, can be expected when fiber conduction, radiation and/or convective effects are not negligible in isolated droplet combustion tests. Likewise, the method proposed in [10] seems to provide a suitable framework to estimate such deviations also in combustion tests with hydrocarbon fuels.

4. Conclusions

The effect of different additional heat transfer modes on the evaporation of isolated droplets has been investigated for liquid hydrocarbons (dodecane and Jet A) under oxygen-free / oxidizing conditions (0/10 % vol. of O_2), extending the analysis presented in a previous work for pure evaporation of alcohols to a much broader range of conditions of practical relevance. The suspension filament is found to significantly modify the droplet vaporization curves, especially when platinum wires (25 μm , about the thinnest available) are used. In several cases, the nucleation of fuel vapors inside the droplet induces a fluctuating evaporation, in clear divergence with the d^2 -law. This shift is more marked for combustion

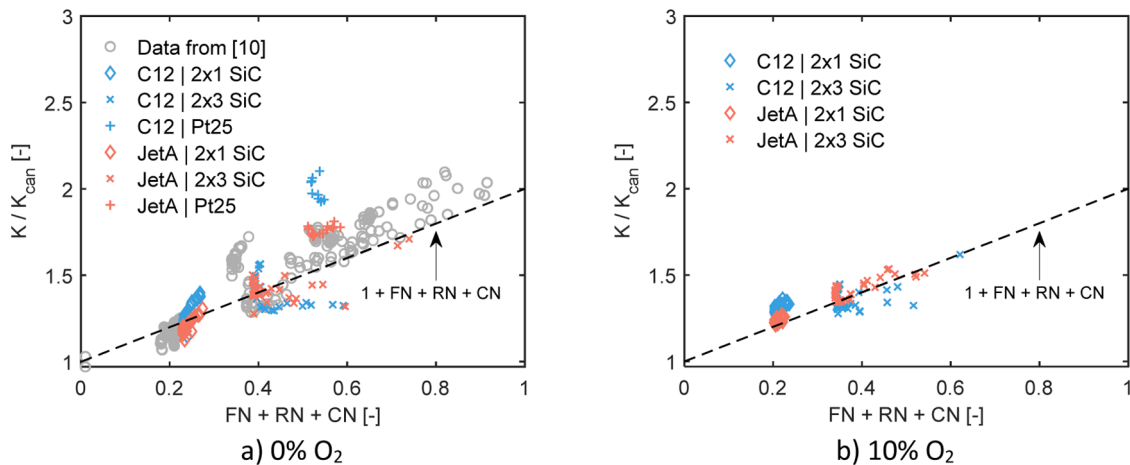


Fig. 4. K/K_{can} as a function of $(FN+RN+CN)$ for dodecane (C12) and Jet A under oxygen-free (a) and oxidizing (b) conditions. Only experimental points without fluctuating evaporation are included.

experiments, in agreement with the higher temperatures of the fibers for these cases. Current results are perfectly consistent with the aforementioned previous work, and clearly indicate that the use of metal wires or thermocouples embedded inside droplets needs very careful consideration, as they can cause drastic disturbances in high-temperature evaporation and combustion tests. For tests with a lower impact of experimental artifacts, a clear correlation has been observed between experimental conditions and changes in measured evaporation rate. The magnitude of the three additional heat transfer modes evaluated here (conduction of heat through the supporting fibers, absorption of thermal radiation, convective effects) is estimated by means of dimensionless numbers, as proposed in a previous work. The results obtained for dodecane and Jet A are remarkably consistent with those previously reported for the evaporation of alcohol droplets, supporting the extended use of the proposed approach for hydrocarbons and real fuels, both for high-temperature evaporation and combustion scenarios.

Novelty and significance statement

Real experiments on high-temperature evaporation and combustion of isolated droplets often undergo noticeable departures from ideal conditions, with additional (and typically undesired) heat transfer modes that can modify the droplet vaporization behaviors. These modifications can be substantial, in terms of enhanced droplet evaporation rate or even inducing a fluctuating evaporation caused by the nucleation of fuel vapors at solid-liquid interfaces (for droplets suspended on filaments). This work extends a previous study where a novel approach was proposed and validated to estimate the magnitude of these departures for the high-temperature evaporation of alcohol droplets. The current study extends the analysis to hydrocarbon droplets vaporizing in both oxygen-free and oxidizing atmospheres.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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