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AN EXPERIMENTAL STUDY ON THE DROPLET VAPORIZATION: EFFECTS OF HEAT CONDUCTION THROUGH THE SUPPORT FIBER.

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ABSTRACT

Droplet vaporization process is of interest in energy systems such as diesel and rocket engines, in which the fuel is supplied as a spray of droplets. The classical "quasi-steady" theory has been developed within the context of isolated droplet vaporization studies and is also used in spray models because of its simplicity. This theory predicts a linear evolution of the squared droplet diameter with time and allows estimating the "droplet vaporization rate". The aim of this study is to provide a detailed description of the heat and mass transfer mechanisms occurring in the vaporization of isolated droplets due in particular to the presence of the droplet support fiber in most of the experiments. Most droplet evaporation and combustion experiments have been conducted with the droplet suspended on a support fiber to avoid the experimental difficulties for free-falling droplets, such as for obtaining high-resolution droplets images. The potential influences of the support fiber on the evaporation rate have been pointed out in previous studies, but in the absence of alternative solutions, most researchers continued to employ this method. The literature reports many studies appreciably improving the technique by reducing as much as possible the fiber diameter, others by taking into account in numerical models this phenomenon, then correlating their results with experimental data. It is only very recently that experimental studies, equivalent to the one presented here, could implement extremely fine suspension fibers, allowing the production of new results. In this paper, experimental measurements will be presented to highlight and discuss the effects of heat transfer through the support fiber on droplet evaporation. Different droplet sizes, fiber diameters and orientations, gas temperatures, and fuel volatilities have been tested and analysed.

INTRODUCTION

Droplets gasification is an important process for the performance of liquid-fuelled combustion systems, such as diesel and propulsion engines. In these systems, the fuel is sprayed as a cloud of droplets in the combustion chamber, which then vaporize, mix with the oxydant and burn to release heat. Therefore, the study of the gasification of a droplet via vaporization, which involves heat, mass and momentum transfer processes in gas and liquid phases, and their coupling at the droplet interface, would provide the knowledge basis for better understanding and modeling complex spray flows. The pioneering work of Godsave in the early 1950s [1] has led to the development of a theoretical model that is capable of describing the gasification process of a droplet. This model, which is termed "Quasi-Steady model" and also called d^2-law, demonstrates that during the gasification process, the droplet surface area, represented by the droplet-squared diameter, varies linearly during its lifetime. Although this model is very successful in describing the gasification process of a fuel droplet, the assumptions upon which the model has been developed are subjected to several experimental and numerical analyses and also criticism (see, for example, review articles [2-6]). The most controversial assumptions which are discussed in several publications (see, for example, [3, 4], and references cited therein), are summarized below due to their pertinence for the present study.

(a) Constant and uniform droplet temperature. This assumption has quickly been scrutinized in several studies (see Refs. [7-12] to cite only a few). These studies and others demonstrate the existence of a transient heat-up period prior to the occurrence of the d^2-law. During the initial stage of the droplet lifetime, i.e. the non-steady period, it is discovered that the heat received initially by the droplet is utilized to heat-up the liquid to its equilibrium temperature, i.e. wet bulb temperature. Once this temperature is achieved, then all the heat transferred into the droplet is employed to gasify the liquid. However, the need for experimental data to verify the numerical predictions of the existence and lifetime of the droplet heat-up period complicated the situation, as the fiber (or the droplet suspending material) would induce extra effects, which are not part of the physical problem, and hence alter the droplet heat transfer. In an experimental study of the vaporization process, in general, the droplet is suspended on the tip of a thin fiber. Several experimental and numerical studies have been performed to assess the influence of the fiber, and consequently the corresponding heat transfer (see, for example, Refs. [13-15] and references cited therein). It is proved that the fiber can indeed influence the droplet heat and mass transfer processes. In order to completely eliminate the fiber effect on droplet gasification, a new experimental approach has recently been recently developed [16, 17]. It consists of two micro-sized fibers where the droplet is suspended at their cross point. The results, which are presented below confirm that the d^2-law does not hold during this period of the droplet lifetime.

(b) Spherical symmetry. This means that convection (either natural or forced) is absent and hence droplet remains spherical during its lifetime. This assumption makes it easy to develop the d^2-law. However, under certain practical applications, the droplet deforms during its gasification due to the presence of natural convection or a strong forced flow and thus the spherical symmetry assumption breaks down. Numerous experimental and numerical studies have been undertaken to verify the implications of this assumption. The results are that the d^2-law still holds even under convection

conditions but only once the droplet reaches its thermal equilibrium. It must be recalled that the idea behind this assumption is to avoid a complicated/lengthy numerical solution and rather to develop a simple analytical solution based on spherical symmetry and then correct for the effect of convection by using empirical correlations [2]. In addition, the assumption of spherical symmetry of the droplet is important for ensuring a spherical envelop flame.

(c) The gas-phase quasi-steadiness. This assumption indicates that the gas-phase immediately adjusts itself to the local boundary conditions and droplet size at each instant of time. Although this assumption was considered unrealistic already in the early years of d^2-law, it is only relatively recently that the deficiency of the d^2-law is related to the non-steadiness of the gas-phase surrounding the droplet. (See, for example, [18-20]). It is also pointed out that the effects of this assumption on the d^2-law are not yet completely identified [3].

The principal objective of the present study is to further examine the d^2-law under well-controlled test conditions in normal and micro-gravity environments by putting the main emphasis on the suspension fiber effects.

EXPERIMENTAL SET-UP AND TEST CONDITIONS

The experimental set-up is described elsewhere [17]. Therefore, only a brief presentation is provided here. The experimental test facility consists mainly of a furnace and a droplet's support and formation system. The furnace is essentially a short cylinder with inner diameter of 68 mm and 100 mm height, which results in a volume of 360 cm^3. The furnace is capable of attaining temperatures up to 1200 K, which is generated by Joule effect heating placed in a pressure chamber which envelops the furnace. The droplet, which is supported on a "cross-fiber" system, is formed by injecting liquid *n*-heptane via a piezo-electric injection system, at the intersection point of the two quartz fibers, which are fixed perpendicularly using a metallic frame system. The quartz fibers/wires are 14 µm in diameter. Heptane (C_7H_{16}) has been chosen as the liquid because it has been intensively used in the literature and consequently allows comparisons. The furnace gaseous medium is chosen to be Nitrogen to avoid oxidation. The droplet is initially formed in the lower part of the chamber, and then introduced into the furnace by the aid of a motorized displacement system. Once the droplet is exposed to the hot atmosphere in the furnace, the temporal regression of the droplet surface is recorded by using a high-speed video camera with a frame rate that can be varied between 150 and 750 fps. For each experiment set, approximately 700 images are recorded in order to allow a satisfactory temporal resolution. In addition, at least five experiments are performed for each test conditions to verify the repeatability of the data as well as to remove statistical errors. The images are transferred to a computer and are analyzed by post-processing to deduce the droplet instantaneous surface area and hence its diameter temporal variation. Note that the calculation error in determining the droplet diameter is of the order of ± 3%. As an example, the droplet vaporization rate for T_∞ = 973K is on average of 0.296 mm^2/s with a standard deviation of 1.2%. Two series of droplet vaporization experiments are carried out in the present study; one in normal gravity, and another in microgravity conditions of $10^{-2}g_0$. The latter are realized via parabolic flights aboard of the A300 Aircraft of CNES. Note that the parabolic flight duration is of the order of 22 seconds. In both series of experiments, the pressure in the furnace is kept atmospheric while the temperature is varied in the range between 473K and 748K for microgravity experiments, and between 473K and 973K for normal gravity experiments. The droplet diameter is kept equal approximately to 370 µm for the microgravity experiments, and around 500 µm for normal gravity experiments.

RESULTS

Effect of Natural convection

Under normal gravity, the experimental evolution of the squared diameter of the droplet is linear with time, as is considered by the theory, while under microgravity these curves slow down gradually, depending on the initial diameter. Only droplets having an initial diameter of 250µm or less does not show this phenomenon and its regression evolves linearly throughout the full duration of its vaporization.

The objective of achieving microgravity conditions is to eliminate natural convection effects to obtain spherical symmetry of the droplet and of the surrounding gas parameters. As buoyancy does not exist in microgravity, the time scale for the gas phase is that of the mass diffusion which is slower than natural convection. The fuel vapor produced at the droplet surface is no more evacuated towards infinity but remains in a bounded region, affecting the concentration gradient and thus the phase-change mechanism. This is in poor agreement with the quasi-steady assumption, according to which the gas-phase adapts instantaneously to the size of the droplet and the boundary conditions. However, this assumption becomes valid when the ambient temperature is sufficiently high, hence the mass diffusion coefficient and the Stefan velocity; we indeed observe experimentally that the deviation from linearity of the vaporization curves becomes less important as the gas temperature increases.

The results obtained in terrestrial gravity and those obtained in reduced gravity are compared on Figure 1. On this figure, the rates of vaporization obtained for various temperatures show linear evolutions. A traditional correlation of Ranz-Marshall type thus could be introduced to determine the impact of the natural convection on the rates of vaporization [21]. The effects of the natural convection have been expressed by a simple relation derived from heat and mass transfer analogies for spheres in the convective field. The vaporization rate constant for the natural convection field may be expressed as,

$$K = K_{th}(1 + A \cdot \Pr^m \cdot Gr^n) \quad (1)$$

Where A, m, and n are the constants, and Pr and Gr are the Prandtl and Grashof numbers, respectively. This correlation is shown on Figure 1.

The theoretical rate K_{th} of vaporization as defined here is common to the totality of the experiments, carried out in reduced gravity or normal gravity. The numbers of Grashof and Prandtl were defined for the whole of our experimental conditions, thanks to the simultaneous acquisition of the temperatures and the level of residual acceleration. We then observe on Figure 1, that the correlation which corresponds to our experimental results is obtained by affecting a value of 0.25 for the coefficient A. As for the coefficients m and n, they were preserved with the values usually used in the literature (m=1/3 and n=1/4). It is important to mention here that this A=0.25 coefficient was also given for our experiments with another fuel, the *n*-decane. Although quartz is supposed to have a very low thermal conductivity, a heat transfer by conduction exists through the fibers towards the

droplet center. This results in an increase of the vaporization rate with the fiber diameter. This effect will be examined in details in the next section.

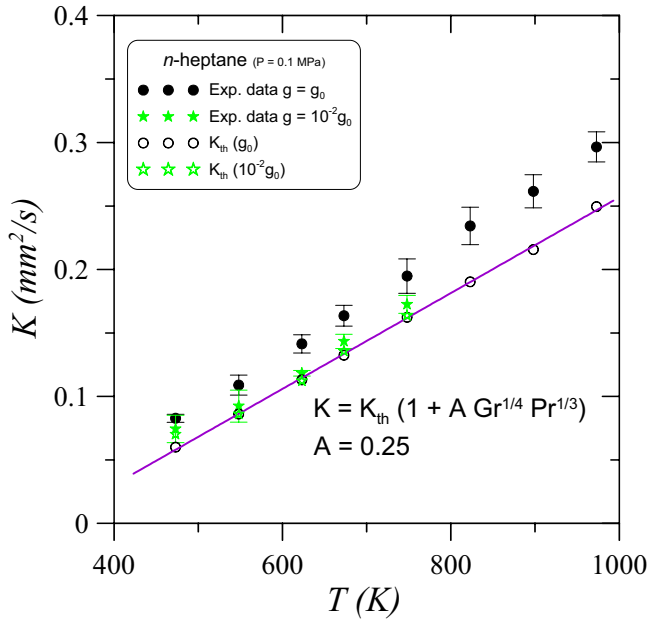
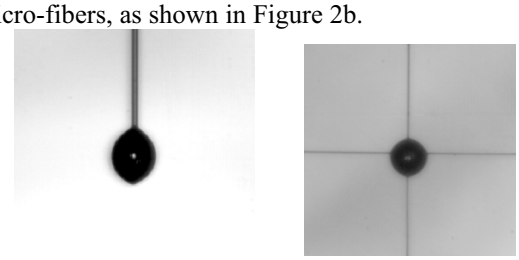


Fig. 1. Vaporization rate of *n*-heptane in normal or reduced gravity conditions, for various temperatures (P_∞= 0.1 MPa).

Effect of the Droplet Suspending Technique

The influence of the fiber size on the d^2-law during droplet evaporation is investigated by conducting experiments at a typical ambient temperature, T_∞ = 570 K, in normal gravity environment. Two different droplet supporting techniques are employed, which are the cross-fiber technique and the classical suspending fiber technique. For the cross-fiber technique, the fiber diameter is 14 µm, whereas for the suspending technique three different diameters of the fiber are tested, which are d_f = 106 µm, d_f = 144 µm and d_f = 181 µm. The initial droplet diameter is kept constant, d_0 = 800 µm, in all experiments to eliminate the effect of the droplet diameter (i.e. buoyancy effect). Figure 2a shows, as expected, that the droplet is ellipsoid in shape when suspended on a classical fiber, whereas it is nearly spherical when suspended on the cross micro-fibers, as shown in Figure 2b.



(a) (b)

Fig.2. Droplet's suspending (a) classical fiber, and (b) cross-fiber technique.

The experiments have been conducted on *n*-decane droplets and have been fully described in reference [22]. Only the conclusions of this previous study will be reported here, in order to prepare the second part. The corresponding droplet average-vaporization rates are plotted in Figure 3 as a function of the squared diameter of the quartz fiber, d_f^2.

This figure shows that the droplet vaporization rate increases linearly with the fiber cross-sectional area (represented by the fiber squared diameter). This implies that the conduction heat flux into the droplet is proportional to the fiber cross-sectional area, and subsequently to d_f^2. Therefore, the extrapolation of the linear relationship between the fiber cross-section and the droplet vaporization rate suggests that the value of K_0 corresponding to d_f^2 = 0 is free from the fiber effect. This value is found practically identical to that obtained by using the cross-fiber technique. This suggests that the droplet supporting cross-fiber technique, which is employed in the present experiments, does not cause any interference with the droplet heat transfer, and hence its evaporation process.

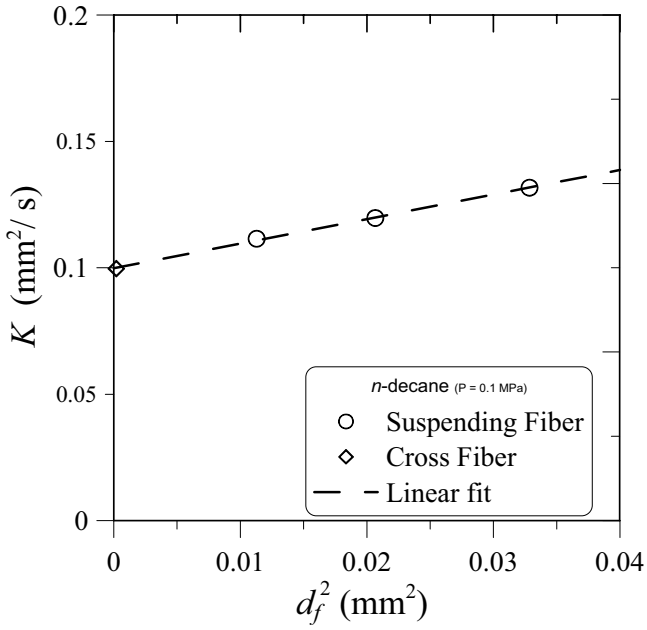


Fig. 3. Evolution of the vaporization rate of *n*-decane droplet versus the diameter squared of the suspending fiber (P_∞= 0.1 MPa, T_∞= 570 K, d_0= 800 µm).

The previous results were obtained with n-decane fuel, and it was quite difficult to compare with the literature because of the lack of sufficient comparable work. This is why the next part of the paper concerns the vaporization of *n*-heptane droplets, for which experimental data are abundant in the literature.

Comparison with the litterature

In the previous paragraph the influence of the suspension was demonstrated, and the use of a cross-fiber system with small dimensions (14µm) enabled us to demonstrate that this configuration is near to be without influence. We will now compare our experimental results with those of the literature. This analysis relies mainly upon the paper of Yang [23]. In this paper the authors analyze carefully the differences between the theoretical and experimental results on droplet evaporation, and propose a complete numerical model allowing to correctly simulate the experimental results, worthy of confidence [11, 24]. To lead to this result, Yang and Wong had to introduce into their numerical model, in addition to taking into account the effects of high pressure on the thermophysical properties, the contribution of heat transfer enhancement to the drop by fiber conduction and the contribution of heat by absorption of the radiation emitted by the furnace walls.

In a similar thought process, we compared our experimental results with those of Nomura [11] and Ristau [24], because the conditions of these experiments were identical to ours, including the range of explored temperatures and conditions of microgravity to eliminate the influence of

the natural convection. Although these studies took into account the influence of the pressure, only the atmospheric pressure case will be compared here. Before comparing the experimental results, it can be noted that the various studies quoted here [11, 24-27], share similar experimental methods. The *n*-heptane droplets are generated in an atmosphere at ambient temperature and suspended at the tip of a quartz fiber, and then the droplet is introduced into a furnace at high temperature, either by displacement of the support in the furnace, or by displacement of the furnace. Dimensions of the various furnaces used are rather similar. The comparison was made here for a pure fuel, the *n*-heptane, common for all the studies. These two last points make it possible to affirm that the effect of the liquid-phase absorption of the radiation from the furnace wall will be similar for all studies and will thus not affect the differences observed on the results.

These various studies of the literature were performed either in normal gravity or in reduced gravity; our experimental results covering also the two conditions, we are also capable to compare the influence of the natural convection.

Therefore the fundamental differences which distinguish these various studies concern mainly the diameter of the support fibers and to a lesser extent the initial size of the droplet. These two parameters are not independent, because the initial size of the droplet depends on the size of the support fiber. Indeed, in our experimental device with the "cross-fiber" technique, droplet initial diameters range from 0.25 to 0.7 mm, whereas the use of traditional fibers (> 120 µm) involves initial diameters higher than 0.6 mm. If the influence of the initial diameter is not to be neglected, it is however less critical than the influence of the size of the support, and it conditions mainly the duration of the phase of pre-heating and the influence of the liquid-phase radiative absorption.

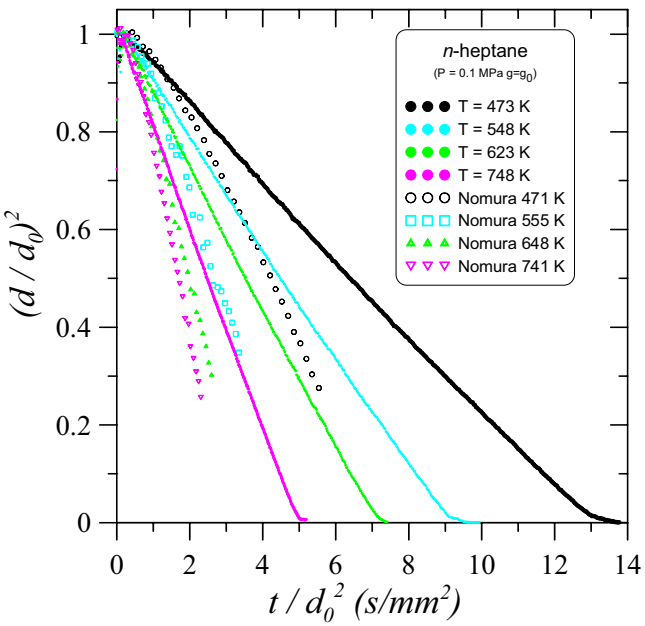


Fig. 4. Comparison of *n*-heptane droplet vaporization, from Nomura and coworkers [11] and this work, for different temperatures. (P_∞= 0.1 MPa, normal gravity).

The first comparison which can be made is related to the normalized temporal evolution of the squared diameter. The experimental data of Nomura and ours have been plotted on Figure 4. It can be noted that the *n*-heptane droplets vaporizes more slowly in our device and this statement is identical for all the explored temperatures. This can be also confirmed by the evolution of the vaporization rates according to the temperature, as plotted on Figure 5.

On Figure 5, many experimental results found in the literature were reported, in order to be compared. Our experimental points obtained with the cross fiber device, in terrestrial gravity and also those obtained in microgravity have been plotted.

The experimental data of Nomura [11] obtained in reduced gravity and Ghassami [25] obtained in normal gravity have been included on this graph. It is immediately obvious to notice the differences which exists between these various results. The data of Morin [27] also were reported in this graph; these experimental data resulting from our group were obtained in terrestrial gravity. Independently of the influence of the natural convection, the present cross fiber experiments revealed quite lower rates of vaporization and this for all the conditions of explored temperatures. The distribution of these data according to the diameter of the support fiber is obvious, knowing that the diameters of the support fiber are respectively of 200µm for Morin [27], 150µm for Nomura [11], 125 µm for Ghassami [25], and 14µm for the present study. This confirms the importance of the effect of the heat conduction through the support fiber, systematically involving an increase in the rate of vaporization. This rate enhancement increases with the temperature. To supplement this comparison the simulation data obtained by the model of Yang [23] have been plotted on this graph, by taking case 1 ignoring both fiber conduction and radiative absorption, being thus more representative of a theoretical or the idealized case. One realizes curiously that our experimental data are still lower than this theoretical simulation.

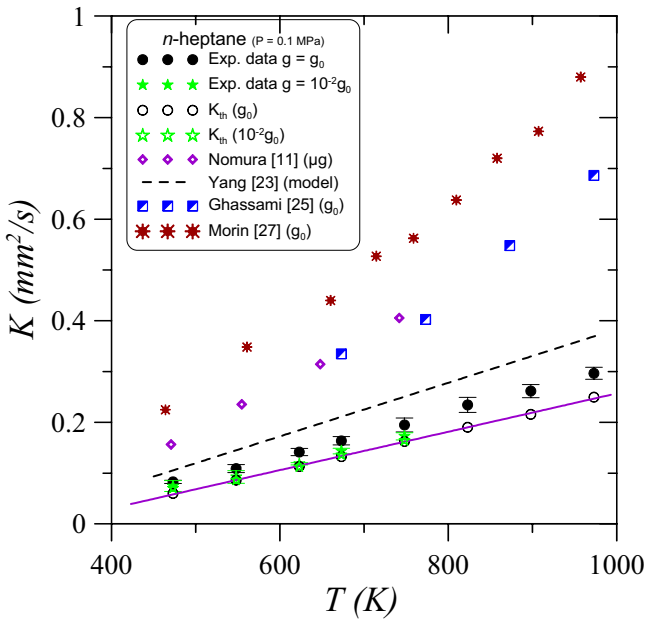


Fig. 5. Comparison of the vaporization rate of *n*-heptane droplets, according to the temperature, for various authors (Nomura [11], Ghassami [25], Morin [27], Yang [23] and this work)

In droplet vaporization it is relatively easy to find effects which increase the experimental rates of vaporization compared to the theory, but it is very difficult to find plausible effects that can reduce the vaporization rates. It is all the more strange to realize that even the experimental case under normal gravity is lower than the simulation data without the influence of natural convection. The assumptions governing these models are perhaps too restrictive and will perhaps require modifications in future studies.

Taking into account these observations, we tried to determine a law which correlates the various experimental results according to the fiber diameters used. We obtained, on Figure 3, a linear law according to df², we thus will try to obtain a linear law on the whole of the results available of the literature, for each temperature. This law can take the following form:

$$K(T) = Cd_f(T) \times d_f^2 + K_0(T) \quad (2)$$

according to the temperature. Cd_f being a coefficient proportional to the temperature, d_f the fiber diameter, and K_0 the value of the idealized vaporization rate without the influence of heat conduction through the fiber. We determined in a first stage Cd_f for each temperature.

For that we have selected two results of the literature employing different fiber diameters and having results at equivalent temperatures, i.e. Morin [27], Nomura [11], and our presents results. The fiber diameters in these studies are respectively 200µm, 150µm and 14µm. The evolution of the vaporization rate, K, according to the square diameter of the quartz fiber, df² has been plotted on Figure 6 for various temperatures.

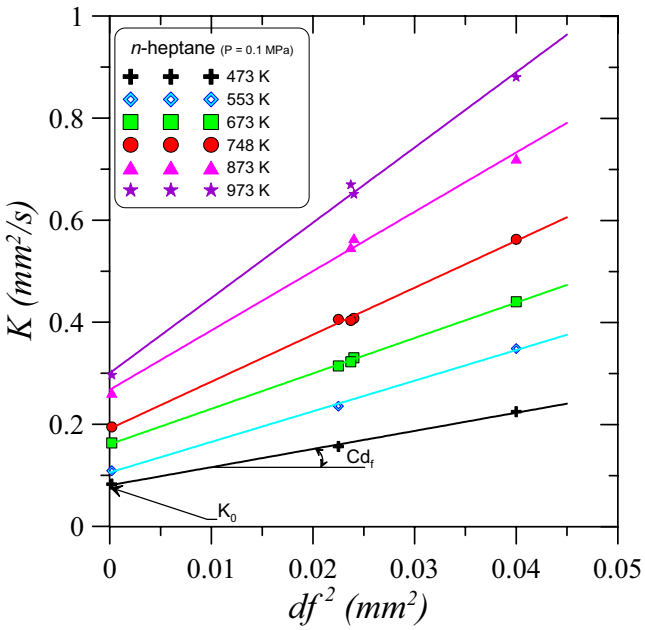


Fig. 6. Evolution of the vaporization rate of *n*-heptane droplets versus the diameter squared of the support fiber (P_∞= 0.1 MPa).

This evolution is observed to be linear which can be justified as follows. Due to the small diameter of the fiber, the conductive heat flux propagating through it can be considered as monodimensional. This means that the heat flux is proportional to the cross section of the fiber, or equivalently to d_f^2. On the other hand, the vaporization rate K, refering to Figure 5, depends linearly on ambient temperature T_∞, both experimentally and theoretically. Since the heat flux, within the context of the quasi-steady theory, is proportionnal to (T_∞- T_s) and the surface temperature T_s is approximately constant, the vaporization rate also evolves in a linear way with the heat flux. We consider a given value of the vaporization rate, called K_0, corresponding to the case in which all the heat is provided to the droplet through its surface, so that no fiber effect occurs. We find that the difference between the actual vaporization rate K and the "ideal" one K_0 is proportional to the heat flux through the fiber, and equivalently to d_f^2. The extrapolation of the linear function passing by the experimental points to $d_f^2 = 0$ provides the value of K_0, free from the fiber effect. This value is very close to that obtained with the cross fiber technique, which means that our experimental configuration causes no disturbance in the vaporization process.

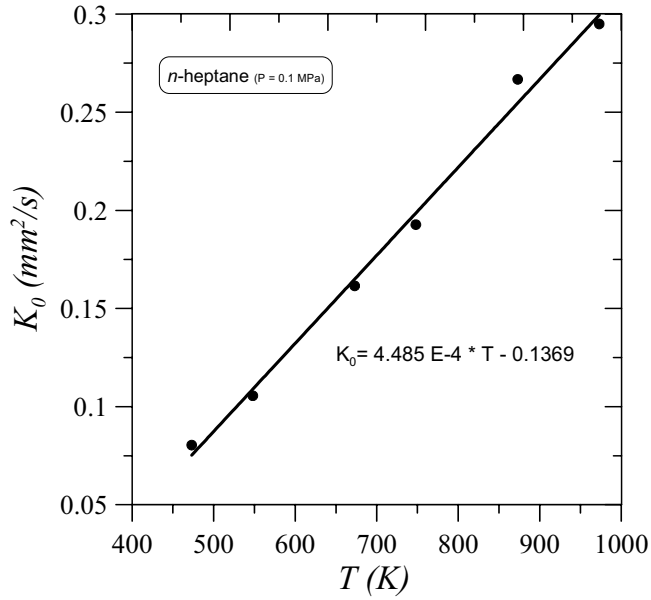


Fig. 7. Idealized vaporization rate of *n*-heptane droplet versus the temperature (P_∞= 0.1 MPa).

For each temperature it is thus possible to determine the linear regression passing through the experimental points. Cd_f is the coefficient of this slope and K_0 corresponds to the value of K extrapolated for a null fiber (d_f=0).

Naturally this value of K_0 is very close to our value of $K_{14\mu m}$, indicating the weak influence of our cross-fiber device. Cd_f and K_0 vary of course with temperature; linear relations can however be accepted for the two cases. The variation of K_0 has been plotted on Figure 7, and the evolution of Cd_f according to T has been determined on Figure 8.

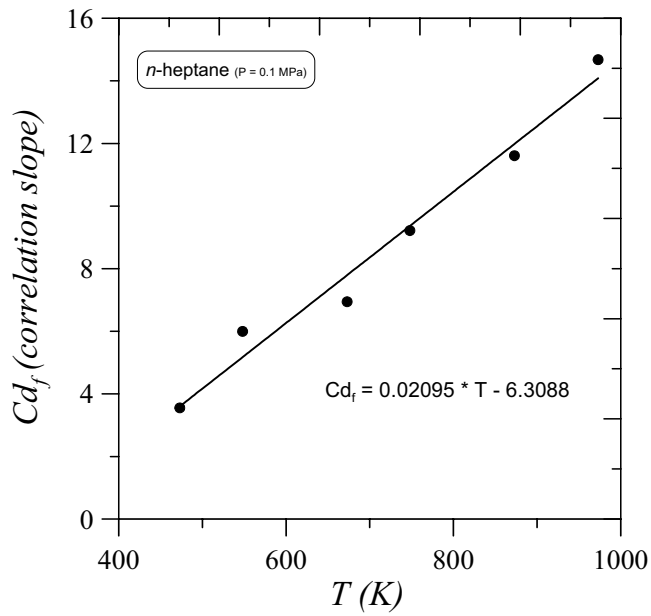


Fig. 8. Variation of the heat flux coefficient versus the temperature, for *n*-heptane droplet vaporization (P_∞ = 0.1 MPa).

As an ultimate check of this correlation, the experimental points of the various authors have been plotted on Figure 9, and the simulated fiber effect correlation according to the

corresponding fiber diameter has been also plotted for each one (continuous line). This figure shows the very good agreement of the correlation with the experimental points, except for the experimental points of Ghassami [25] for which the adapted correlation corresponds to a fiber diameter of 155 µm whereas the authors announce 125 µm.

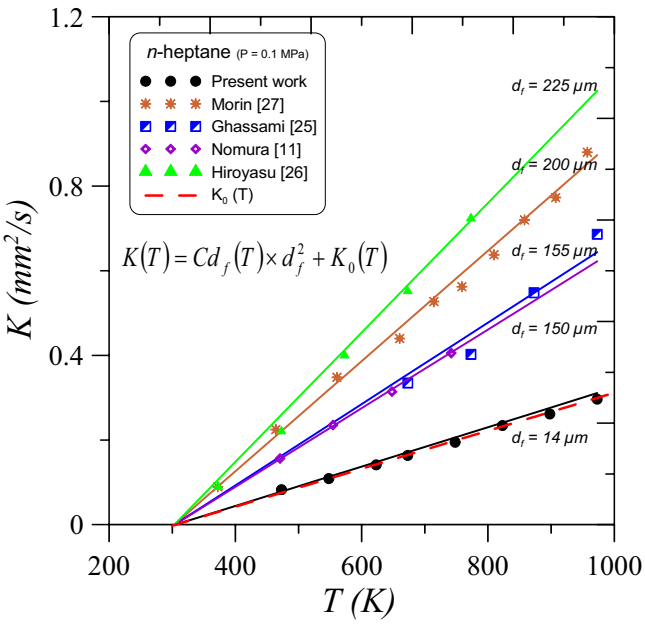


Fig. 9. Comparison of the experimental vaporization rate of *n*-heptane droplets, and the fiber effect correlation, according to the temperature, for various authors (Nomura [11], Ghassami [25], Morin [27], Hiroyasu [26] and this work).

We also plotted on this same figure the evolution of $K_0(T)$ corresponding to the case $d_f = 0$, i.e. without the fiber effect. We again observe that this law merges with our experimental case, which authorizes us to consider that our droplet fiber support introduces no effect on the droplet vaporization rate.

CONCLUSIONS

The present study examines the d^2-law under well-controlled normal and micro-gravity conditions. The effect of gravity is studied by performing experiments in normal gravity and microgravity environments while keeping all other test conditions identical; that is, constant atmospheric pressure, and ambient/furnace temperature in the range up to around 970K. The effect of the droplet suspending technique is eliminated by using a novel cross micro-fiber system. This technique enables to preserve the spherical shape of the droplet throughout the vaporization process in normal gravity atmosphere.

Our original experimental data have been compared with the literature data for the same fuel, *n*-heptane. The vaporization rates measured by us are lower than those measured by all the other authors, even those whose experiments were undertaken under microgravity conditions. It is therefore clear that only the effect of heat conduction through the fiber makes it possible to explain and quantify the increase in the vaporization rate observed in the other studies. A correlation based on the squared diameter of fiber, showed the possibility of unifying a great number of the published results.

The results obtained in this study are important in the sense that they make it possible to clearly show that the effects of the suspension fiber can be very important and can even hide the benefit of the experiments conducted in reduced gravity if the fiber has a too important size. Taking into consideration these results, it would be judicious to revisit the studies carried out previously on the effect of the pressure on the droplet vaporization rates, because all these experiments were conducted with fibers having large sizes, introducing therefore the possibility of a systematic over-estimation of the measured vaporization rates.

ACKNOWLEDGMENTS

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NOMENCLATURE

Symbol	Quantity	SI Unit
P	Ambient Pressure	MPa
T_∞	Ambient Temperature	K
T_s	Droplet surface temperature	K
d_0	Initial droplet diameter	m
d_f	Fiber support diameter	m
K	Vaporization rate	m^2/s
K_0	Idealized vaporization rate	m^2/s
$K_{14\mu m}$	Vaporization rate with 14µm fiber	m^2/s
g_0	Terrestrial gravitational acceleration	m/s^2
µg	Reduced gravity	m/s^2
Gr	Grashof number	dimensionless
Pr	Prandtl number	dimensionless

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