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Technical Note

Interactive influences of convective flow and initial droplet diameter on isolated droplet burning rate

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Abstract

In quiescent ambiences the burning rate of an isolated liquid fuel droplet varies with the droplet's initial diameter d_0 due to the close surrounding of the droplet in the flame and the subsequent strong action of flame heat, in balance with its loss to ambience, on burning. Suppressing the influence of d_0 on burning rate was recognized in this communication through burning the droplet in a forced convective flow that sweeps the flame off the droplet to weaken the action of flame heat on burning. The d_0-dependent k_0, however, affected the correlation $k = k_0(1 + C \cdot Re^{0.5})$ for the burning rate in convective flows, where k_0 and k are the burning rate constants, respectively, in the equi-temperature quiescent and convective-flow ambiences, and Re is the flow's Reynolds number with respect to d_0. Different correlation constants C were acquired when using different d_0 and its corresponding k_0 to fit the correlation. In hot conditions (633 K in this article) k_0 is bigger for larger d_0, causing a smaller constant C when taking a larger d_0 for the correlation. Against this, k_0 is lower for larger d_0 in room-temperature ambiences, which resulted in the mutual compensation of the effects from k_0 and d_0 on C such that C is basically independent of the values of d_0 and k_0. Besides, the communication showed that C was larger for the gas flow with a higher temperature, revealing an increase in the effect of Re on burning with raising the gas temperature.

Keywords: Microgravity combustion; Droplet burning; Burning rate; Flame radiation; Convective flow

1. Introduction

In a convective flow at a velocity V_s the burning rate constant k of an isolated liquid fuel droplet was demonstrated to adhere to the correlation of [1–3]

$$k = k_0(1 + C \cdot Re^{0.5}), \quad (1)$$

where k_0 is the burning rate constant for the case without convection, C is a correlation constant or coefficient, and Re is the Reynolds number estimated by $Re = \rho V_s d_0/\mu$ (ρ: gas density, μ: gas viscosity, d_0: initial droplet diameter). The value of k_0 is generally determined through burning a droplet of the same fuel in a microgravity quiescent ambience at the ambient temperature equaling to the flowing gas temperature. Fig. 1 plots some literature data of such a kind of k_0 for differently sized n-decane droplets at different ambient temperatures T_c. The plotted data were based on Refs. [4,5]. Although there are many literature data regarding the burning in room-temperature quiescent ambiences [6–11], Refs. [4,5] reported the only set of data for the heated quiescent ambience. An important result revealed in Fig. 1 is that the rate constant k_0 is functions not only of temperature T_c but also of diameter d_0. Surely as it is, a higher T_c causes a higher k_0 for both droplet burning and droplet

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vaporization (if oxygen not limiting the burning). The temperature T_c also works with the influence of d_0 on k_0 such that k_0 respectively, decreases or increases at low (room) or high ambient temperatures with raising d_0. About these inverse influences of d_0 on k_0 in cold and hot quiescent ambiences a primary analysis was presented in Xu et al. [4,5]. What we like to stress here is that the d_0-dependent k_0 would affect the correlation (1). That is, the different k_0 for different d_0 may complicate the dependence of the correlation constant C on the selected d_0 and k_0. As we know, the use of the equation asks for a choice of d_0 and its corresponding k_0. For the ideal case that k_0 is independent of d_0, the value of C is smaller when d_0 is larger, which makes $C \cdot d_0^{0.5}$ independent of d_0 so that the equation can be rewritten into

$$k = k_0(1 + C \cdot Re^{0.5}) = k_0\left[1 + C \cdot d_0^{0.5}(\rho V_s/\mu)^{0.5}\right]. \qquad (2)$$

By using $C \cdot d_0^{0.5}$ instead of C the arbitrary choice of d_0 is thus possible. When k_0 varies with d_0 as shown in Fig. 1, the situation is different. The interactive influences of initial droplet diameter and convective flow on droplet burning rate may cause both C and $C \cdot d_0^{0.5}$ to vary with the selected d_0 and k_0. It is thus necessary to clarify how the correlation constant C varies with d_0 and its corresponding k_0 from the viewpoint of facilitating the practical use of Eq. (1). On the other hand, the initial diameter influence itself may change with the interaction. This creates another necessity of clarifying how the initial diameter influence on droplet burning rate behaves when a convective flow is present around the droplet. Suekane et al. [12] observed that the droplet's burning rate in a convective flow is little dependent on d_0 but they did not generalize the result through correlation with the burning in quiescent ambiences.

Moreover, the Eq. (1) was so far examined exclusively for droplet burning in flows at room temperature [3,13–15] or for droplet vaporization in slightly heated-gas flows [16]. Therefore, extension of the examination to droplet burning in hot-gas flows would be necessary and valuable because actual droplet burning occurs in this way. In order to address all the above-mentioned problems, this communication burned droplets of n-decane in convective airflows at two different temperatures (room temperature and 633 K). Further, microgravity conditions were employed to minimize the actions of natural convection.

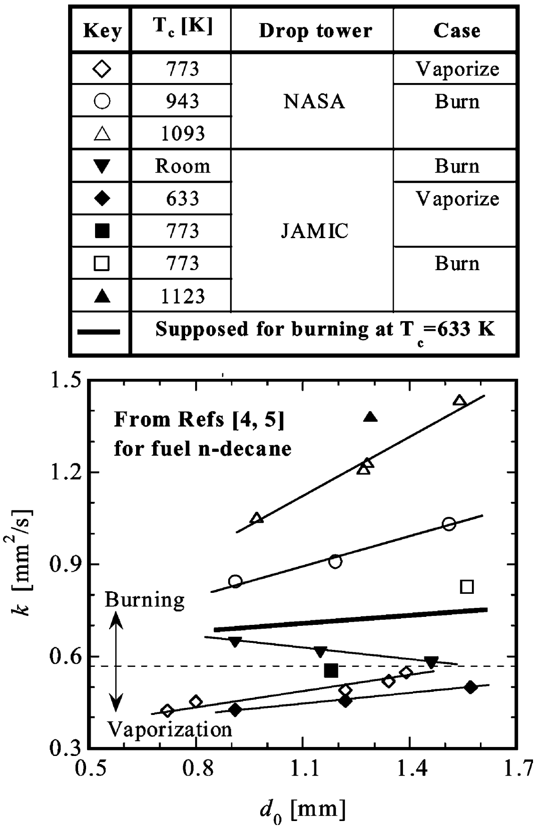

Fig. 1. Dependence of droplet's burning (vaporizing) rate on initial droplet diameter in quiescent-air ambiences with different temperatures.

2. Experimental

Fig. 2 shows a schematic diagram of the employed experimental apparatus. The convective gas flow was

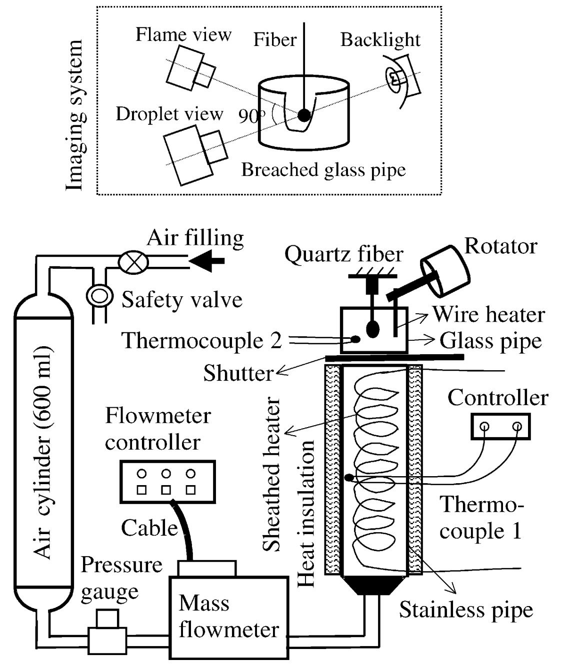

Fig. 2. A schematic diagram of experimental apparatus for testing droplet burning in forced convective airflows with adjustable temperatures.

generated by passing an airflow from an air cylinder through an internally heated stainless steel pipe of 400 mm in length and 22 mm in diameter. For that, a coiled sheathed-heater (Ni–Cr wire) of 1000 W in capacity and 340 mm in length was deployed inside the pipe to make the pipe into a piper heater. At about the middle point of the coiled heater, a K-type thermocouple of 0.3 mm in diameter was located between the heater and the pipe wall to measure the inner temperature of the pipe heater, and the temperature was then controlled using a PID controller. A layer of heat insulation wools was wrapped around the pipe heater to reduce heat loss. The air cylinder, working at a pressure of 1.0 MPa, provided 6.0 l of atmospheric air for experiment. The flow rate of air was controlled with a mass flowmeter, and ahead the flowmeter a pressure gauge was mounted to switch down the cylinder pressure (1.0 MPa) to the flowmeter working pressure of 0.05 MPa. In order to uniform the flow from the pipe heater, a netlike mesh was sintered at the outlet of the pipe heater. A quartz-fiber of 110 μm in diameter suspended the droplet just beyond (about 13 mm) the pipe heater exit. Around the droplet a glass pipe of 22 mm in I D and 25 mm in length was mounted to guide the gas flow. There was a solenoid-controlled shutter between the glass pipe and the pipe heater. Before the shutter was opened, the gas flow overflowed from the interstices below the shutter. The actual temperature of the airflow was measured using another K-type thermocouple in the vicinity of the droplet. Both the piper heater temperature and the volumetric airflow rate controlled this temperature. In the case testing droplet burning, a Cr–Ni wire was placed aside the droplet to start the fire. The wire igniter had an electric resistance of 1.2 Ω and worked at a constant current of 0.5 A. An electrically insulated bar carried the wire, and the bar was up-and-down moved by a step-motor-controlled rotator. The image method was illustrated in the dashed-line box of Fig. 2. Both droplet (backlight) and flame views were simultaneously available. While the droplet view was taken through a breach on the glass pipe, the pipe had affected little the flame view due to the view's low magnification. The camera data were sent to two digital VCRs, and the VCR data were further transferred into image (AVI) files through a frame grabber card.

Experiment was started from turning on the pipe heater at 3–5 min before the onset of microgravity. The drop shafts in the NASA John H. Glenn Research Center (2.2 s) and the Japan Microgravity Center (JAMIC, 10 s) were used to create the microgravity conditions. The airflow was usually started at 50 s before the capsule drop, which was then succeeded by the droplet formation at about 40 s. Turning on the wire igniter occurred at the capsule drop in JAMIC and at about 1.5 s, i.e. between the time-counts 2 and 1, in NASA. This operation for the NASA drop tower was wished to ensure an enough-long time for droplet burning during microgravity. A timer controlled the electrifying time for the igniter, and the end of the timing activated the shutter to open and the igniter to withdraw (to rotate up). The electrifying time was normally between 1.3 and 1.7 s (longer for larger droplet). Hence, the droplet ignition, igniter withdrawal and shutter open could all occur just around the capsule drop in NASA, whereas these took place during capsule dropping in JAMIC. The capsule drop stopped the electricity supply to the pipe heater. When testing droplet burning in room-temperature airflows, the operation procedure was the same but all electricity commands for the pipe heater induced dummy actions.

All image (AVI) files were framed at a rate of 60 Hz in data reduction. In this report only the droplet size d was measured from the droplet image to determine the droplet's burning rate. For that, a time t of burning was defined by counting the time from the moment turning on the igniter. The initial droplet diameter d_0 was measured around $t = 0$. All stated sizes refer to the equivalent values determined as (droplet width)$^{2/3}\times$(droplet length)$^{1/3}$. It was demonstrated that this size is very near to the volume-equivalent diameter. The tested fuel in the article was n-decane, and the examined d_0 varied between 0.8 and 1.6 mm.

3. Result and discussion

Fig. 3 shows the typical curves of d^2 vs. t for droplet burning in a room-temperature airflow of 13.15 cm/s in velocity (V_s being the value at the tested gas temperature T_c). The bold-line crosscut point for each curve annotates the onset of the airflow with the shutter opening. Hence, only the droplet sizes after the crosscut point were correlated to determine the burning rate constant k, as is illustrated in the figure by the straight lines.

The three curves in Fig. 3 correspond to three differently sized droplets. The figure allows thus the accurate identification of the initial diameter influence on droplet's burning rate without recourse to the values of the burning rate constant k (the determination of k involving usually some uncertainties so that a slight initial diameter influence being hard to be identified). For this, three lines with the same slope were drawn to correlate the data for every individual droplet in Fig. 3. The lines well fitted the data, showing thus a burning rate independent of d_0. The result is different from the demonstration in Fig. 1 where the constant k for room-temperature quiescent ambience (▼) gradually decreased with increasing d_0. Essentially, the difference reveals that the influence of droplet's initial diameter, as shown in Fig. 1, was completely suppressed by the application of a convective flow to the burning droplet. In a wider rage of d_0 Fig. 4 corroborated this further. There, some fluctuations are shown for the

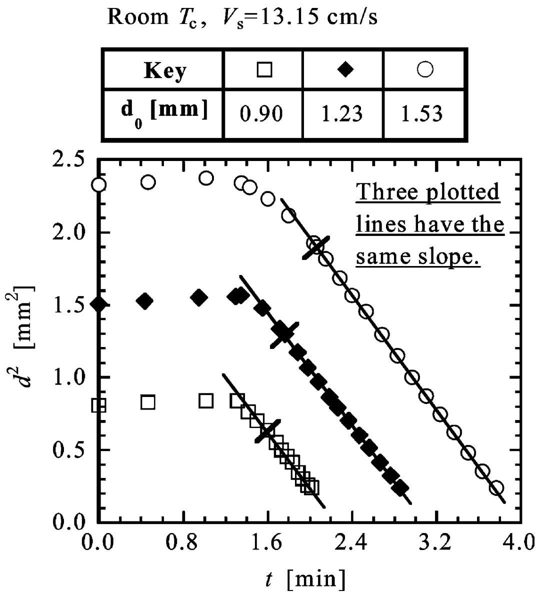

Fig. 3. Typical plots of d^2 vs. t for burning an isolated droplet in forced convective flows (from the test in the NASA drop tower, bold-line crosscut point indicating the onset of gas flow).

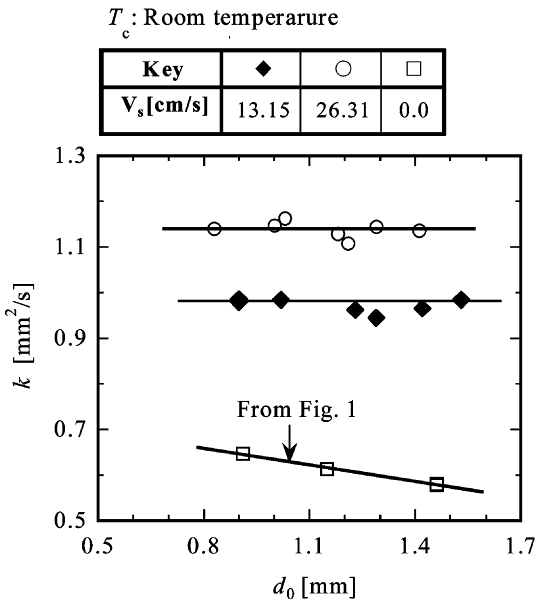

Fig. 4. Demonstration of initial diameter influence on droplet burning rate in forced convective airflows (from the test in the NASA drop tower).

measured burning rate constant k, but the value of k is obviously independent of d_0 for a specified V_s (either 13.15 or 26.31 cm/s in the figure).

The examined situations in Figs. 3 and 4 were for room airflows only, but we can expect that the acquired result is generally valid to the convective flows at arbitrary temperatures. Hence, there must be a negligible effect of d_0 on burning rate in actual spray burners, because the relative velocity between gas and droplets is usually 10s cm/s there [17]. Nevertheless, the investigation of the initial diameter influence on droplet's burning rate in quiescent ambiences is fundamentally necessary to the understanding of the flame's action on burning in balance with its heat loss to ambience [4,8].

For quiescent ambiences in microgravity, the burning products (soot, CO_2 and steam) evenly present around the fuel droplet. This, as a consequence, forms a close flame surrounding around the droplet to strongly affect the droplet's burning and in turn to result in the initial diameter influence on burning rate clarified in Fig. 1. The initial diameter influence denotes a flame-scale effect [4,5], where the flame scale is equivalent to the amount of burning products present around the droplet. Literature studies have demonstrated that the major cause for the initial diameter influence is the different radiations from the burning products, called the flame radiation, to both ambience and droplet for initially differently sized droplets [4,8,18,19]. An initially larger droplet generates a larger flame so that it has more soot, CO_2 and steam around the droplet and, in turn, emits more radiation to affect the droplet's burning. This makes then the differently sized droplets likely have different burning rates. If a convective flow is applied to the flame, soot particles and gaseous burning products may be swept off the droplet to considerably reduce the action of flame radiation on burning. In this case, the flame radiation is still different from droplet to droplet, but the weakened action of the radiation on burning would decrease, even completely suppress, the influences originated from the droplet's different radiations. Reflecting in burning rate it becomes just the demonstration of Figs. 3 and 4 where the convective flow completely suppressed the initial diameter influence on k. In addition, the convective flow allows a lower soot formation during burning [20,21], which would decrease the flame radiation to lower the initial diameter influence as well.

Fig. 5 correlates the burning rate constants k with convective velocity V_s measured at two different gas temperatures T_c, the room temperature (◆) and 633 K (▲ and □). The tests were conducted in the drop towers of JAMIC and NASA for the hot-gas flow and room-temperature airflow, respectively. It was confirmed that at different T_c the droplet size evolutions during burning featured the similar variations of d^2 with t, allowing thus k to be commonly determined with the method illustrated in Fig. 3. The hot-gas flow test was carried out also in normal gravity conditions (□), due to the limited drops we had in JAMIC for microgravity experiment. The lowest velocity V_s examined for the hot-gas flow was 13.15 cm/s in Fig. 5. The reason for this is that to realize the gas temperature of 633 K using the experimental

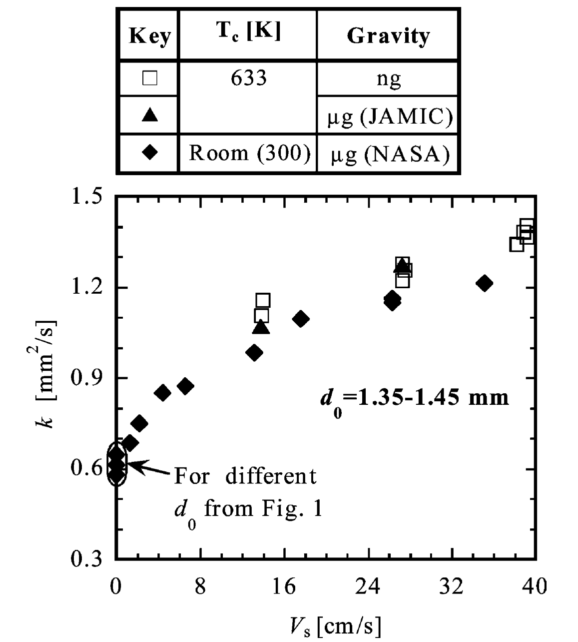

Fig. 5. Droplet's burning rate constant varying with convective velocity of airflows at two different gas temperatures (ng: normal gravity).

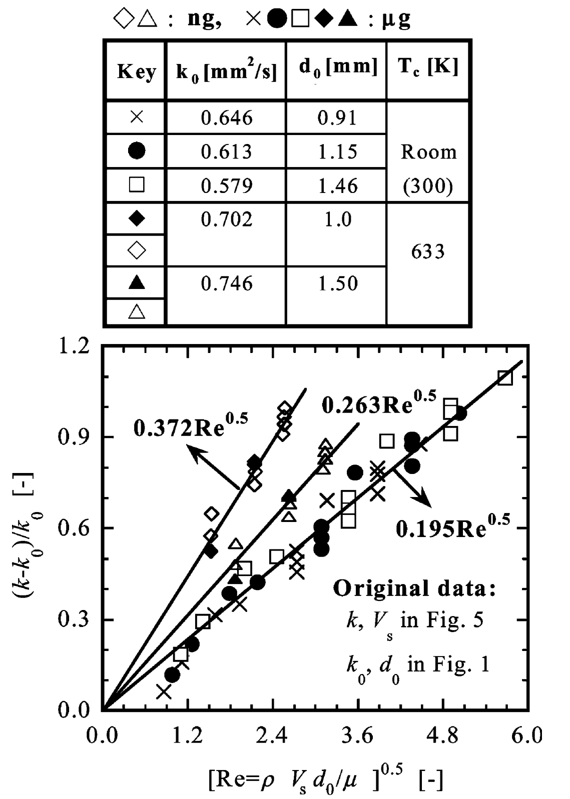

Fig. 6. Correlation of burning rate constants k in Fig. 5 with their corresponding Reynolds numbers Re by adopting different d_0 and k_0 as the quiescent standard.

apparatus sketched in Fig. 2 required velocities above such a value. From Fig. 5 we can see that at these relatively high convective velocities the burning rate constants k were little different between microgravity (▲) and normal-gravity (□) conditions. This enabled the analysis of the data, as is done below, without recourse to the gravity level. Further, it is noteworthy that the encircled k in Fig. 5 were from Fig. 1 (▼) because the value of k at $V_s = 0.0$ is just the same as k_0.

Irrespective of gas temperature, the burning rate constant k gradually increased with increasing the velocity V_s and the increment with respect to unit change in gas velocity, i.e. $\mathrm{d}k/\mathrm{d}V_s$ (δ: differential calculator), was lower at higher V_s. This refers to a commonly recognized result [3,17], but the figure clarified further that the burning rate depended also on the gas temperature. That is, at a given V_s the value of k was slightly higher for the hot airflow at $T_c = 633$ K than for the room-temperature airflow. Theoretically, we may expect that the result is generally valid to gas flows at rather higher temperatures, provided the oxygen dilution by raising T_c does not inhibit the burning. Fig. 1 revealed that the oxygen dilution with raising temperature did not seriously inhibit the burning of an isolated fuel droplet even up to 1123 K for quiescent ambient airs.

The burning rate constants k shown in Fig. 5 are further correlated with the Reynolds number Re in Fig. 6 according to Eq. (1). The relevant properties of air are $\rho = 1.1764$ kg/m^3 and $\mu = 1.87 \times 10^{-5}$ Pa s for 300 K (i.e. room temperature), and $\mu = 3.30 \times 10^{-5}$ Pa s for 633 K. The gas density at 633 K was estimated based on the ideal gas law. For room-temperature airflow the three different sets of d_0 and k_0 shown in Fig. 1 were used as the quiescent standard for fitting the equation. As Fig. 1 showed, k_0 decreases with increasing d_0 at this temperature. There was not directly measured k_0 for $T_c = 633$ K in Fig. 1. An inferential plot (bold line) of k_0 vs. d_0 was thus made for this T_c according to the data at other nearby temperatures, such as 300 K (▼), 773 K (□) and 943 K (○). From this plot we determined then the two sets of d_0 and k_0 mentioned in Fig. 6. Fig. 1 shows that k_0 slightly increased with raising d_0 at 633 K. We believed this variation tendency because the same dependence of k_0 on d_0 was experimentally demonstrated for droplet evaporation at the same T_c (◆ in Fig. 1).

Regardless of gas temperature, the burning rate constants k in convective flows are well correlated with Eq. (1). At room temperature, the choice of k_0 and d_0 is little influential to the correlation. This allowed the same correlation constant C of 0.195 for the three different groups of k_0 and d_0 (×, ● and □). The result, however, is hardly applicable to the case of hot-gas flow. As Fig. 6

shows (such as △ vs. ◇), the greater k_0 for larger d_0 in hot conditions caused a smaller C for Eq. (1). Thus, the little differentiated C for room-temperature airflow represented a particular case where the lower k_0 for larger d_0 allowed mutually compensated actions on C from k_0 and d_0. That is, while the lower k_0 led to a higher C, the corresponding larger d_0 i.e. a larger Re, induced a lower C. The interaction between both the effects caused then the correlation coefficient C to be independent of k_0 and d_0. Generally, we may see that the choice of k_0 and d_0 would differentiate the correlation. In order to facilitate the use of Eq. (1), it is thus necessary to specify a standard d_0 and its k_0 in estimating the coefficient C. For example, we may adopt the unity-size of $d_0 = 1.0$ mm as the quiescent standard, which enables then a unique C for every specified gas temperature, such as $C = 0.195$ for $T_c = 300$ K and $C = 0.372$ for $T_c = 633$ K in Fig. 6. This C can be used to calculate the burning rate constant k from Eq. (1) only for the droplet with d_0 equaling to 1.0 mm (using k_0 corresponing to this d_0). Its resultant k, however, is just the burning rate constant for any other droplets under the conditions of practical spray combustion because in this case d_0 is little influential to the droplet's burning rate (see analyses about Figs. 3 and 4).

Fig. 6 exhibited higher correlation constants C for the hot airflow, indicating a bigger action of the Reynolds number Re on the burning or vaporizing rate constant k at the higher gas temperature T_c. The result is related to the increased kinetic viscosity μ/ρ of the convective gas at a higher gas temperature, as it lowers the value of Re for the same V_s. The tendency of a larger C for a higher gas temperature was indicated also in the calculation of Dietrich et al. [13] who got a correlation constant of $C = 0.4$ for a convective flow at 1280 K. Law and Williams [2] had predicted that the convective effects would decrease with increasing gas temperature, based on a specified constant C of 0.276 for Eq. (1). The present result from Fig. 6 reveals that the actual situation may be different, as we have variations of C with gas temperature.

Another noteworthy point shown in Fig. 6 is the experimental data that are lower than the linear correlation values at smaller $Re (< 1.5)$ for room-temperature airflow. This was similarly shown in the literature studies [3] ($Re < 1.5$) and [14] ($Re < 1.0$). In addition, our data at room T_c had a constant C of 0.195, slightly lower than the value of 0.3 presented in Ref. [3]. Experimental data from Fujita et al. [15] for *n*-nonadecance droplets had led to a constant C that is also smaller than 0.3. As for the droplet burning in room-temperature airflows there are several other values of C reported, such as 0.28 for ethyl alcohol [1], 0.20 for *n*-butyl alcohol [1], 0.276 for an empirical setting based on the data from droplet evaporation [2], and 0.4 for methanol [13]. Hence, how to unify these correlation constants C entails further studies.

4. Concluding remarks

In quiescent ambiences there exist inverse influences of initial droplet diameter d_0 on burning rate at low and high ambient temperatures. While an initially larger droplet has a lower burning rate in the former case (such as at room temperature), it takes inversely a higher rate when the ambient temperature gets higher than a certain value, say, above 580 K or so based on Ref. [4]. A necessary condition for the prevalence of the identified initial diameter influences is the close surrounding of the droplet in the flame, i.e. in the burning products (soot particles, CO_2 and steam), such that the flame heat, in balance with its loss to the ambience, can substantially work on the droplet's burning. In light of this the article demonstrated that the initial diameter influence could be completely suppressed by applying a forced convective flow at the enough high velocities (>10 cm/s) to sweep the flame (burning products) away the droplet and to reduce the action of flame heat (mainly radiation) on burning. As a result, the article suggested that in actual spray burners there should be negligible initial diameter influence on burning rate because the slip velocities between gas and droplets are usually 10s cm/s there [17].

The burning rate constant k in convective airflows was well correlated with Eq. (1), irrespective of the flowing gas temperature. The correlation, however, had higher correlation constants C at higher gas temperatures (633 K compared to room-temperature in this work). This revealed a greater action of the Reynolds number on burning rate for the hotter gas flow. The utilization of Eq. (1) requires a necessary choice of d_0 and its corresponding k_0. The article found that the d_0-dependent k_0 for burning in quiescent ambiences influenced the correlation constant C. For hot-gas flows the value of C was smaller when selecting a larger d_0 that has a bigger k_0. Corresponding to this, the lower k_0 for larger d_0 in room-temperature situation allowed mutually compensated effects of k_0 and d_0 on C such that C little varied with the values of k_0 and d_0. This, however, refers just to a particular interactive case between the influences of initial droplet diameter and convective flow on droplet's burning rate. Generally, the d_0-dependent k_0 for burning in quiescent ambiences would surely differentiate the correlation constant C of Eq. (1). As a consequence, the article urged to specify a commonly acceptable standard d_0, such as the unit droplet size of $d_0 = 1.0$ mm, and its corresponding k_0 to facilitate the application of Eq. (1).

Acknowledgements

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References

[1] G.A. Agoston, H. Wise, W. Rosser, Dynamic factors affecting the combustion of liquid spheres, In: 6th Symp. (Int.) on Combust., The Combustion Institute, Pittsburgh, 1957, pp. 708–717.

[2] C.K. Law, F.A. Williams, Kinetics and convection in the combustion of alkane droplets, Combust. Flame 19 (1972) 393–405.

[3] S. Okajima, S. Kumagai, Experimental studies on combustion of fuel droplet in flowing air under zero- and high-gravity conditions, In: 9th Symp. (Int.) on Combust., The Combustion Institute, Pittsburgh, 1982, pp. 1021–1027.

[4] G. Xu, M. Ikegami, S. Honma, K. Ikeda, X. Ma, H. Nagaishi, D.L. Dietrich, P.M. Struk, Inverse influence of initial droplet diameter on droplet burning rate in cold and hot ambiences: a thermal action of flame in balance with heat loss, Int. J. Heat Mass Transfer 43 (2003) 1155–1169.

[5] M. Ikegami, G. Xu, S. Honma, K. Ikeda, H. Nagaishi, D.L. Dietrich, P.M. Struk, A few new fundamentals of isolated droplet burning demonstrated in microgravity conditions, 2001's Report on International Cooperative Research between NEDO and NASA on Advanced Combustion Science Using Microgravity, NEDO, Tokyo, 2002, pp. 1–59.

[6] G.S. Jackson, C.T. Avedisian, J.C. Yang, Observations of soot during droplet combustion at low gravity: heptane and heptane/monochloroalkane mixtures, Int. J. Heat Mass Transfer 35 (1992) 2017–2033.

[7] G.S. Jackson, C.T. Avedisian, The effect of initial diameter in spherically symmetric droplet combustion of sooting fuels, Proc. R. Soc. Lond. A 446 (1994) 255–276.

[8] K-O. Lee, S.L. Manzello, M.Y. Choi, The effects of initial diameter on sooting and burning behavior of isolated droplets under microgravity conditions, Combust. Sci. Technol. 132 (1998) 139–156.

[9] C.T. Avedisian, J.H. Bae, Combustion of sooting mixture droplets at low gravity, 6th International Microgravity Combust. Workshop, NASA GRC, Cleveland, 2001, pp. 249–252.

[10] F.L. Dryer, A. Kazakov, B.D. Urban, Some recent observations on the burning of isolated *n*-heptane and alcohol droplets, 6th International Microgravity Combust. Workshop, NASA GRC, Cleveland, 2001, pp. 233–236.

[11] F.A. Williams, Experiments on droplet combustion in spacelab and space station: planning, data analysis and theoretical interpretations of results, 6th International Microgravity Combust. Workshop, NASA GRC, Cleveland, 2001, pp. 229–232.

[12] T. Suekane, K. Yasutomi, S. Hirai, Study on combustion behavior of single droplet in free fall generated by using ultrasonic levitation technique, In: 38the Symp. (Japan) on Combust., The Combustion Society of Japan, Tokyo, 2000, pp. 191–192.

[13] D.L. Dietrich, J.B. Haggard Jr., F.L. Dryer, V. Nayagam, B.D. Shaw, F.A. Williams, Droplet combustion experiments in spacelab, In: 26th Symp. (Int.) on Combust., The Combustion Institute, Pittsburgh, 1996, pp. 1201–1207.

[14] V. Nayagam, N. Hicks, N. Kaib, M. Ackerman, J.B. Haggard Jr., F.A. Williams, 6th International Microgravity Combust. Workshop, NASA, Glenn Research Center, 2001, pp. 237–240.

[15] O. Fujita, Y. Inoue, M. Sudou, K. Ito, Combustion of a fuel particle in micro-external air flow, In: 39th Symp. (Japanese) on Combust., The Combustion Society of Japan, Tokyo, 2001, pp. 223–224.

[16] I. Gokalp, C. Chauveau, J.R. Richard, M. Kramer, W. Leuckel, Observations on the low temperature vaporization and envelope or wake flame burning of *n*-heptane droplets at reduced gravity during parabolic flights, In: 22nd Symp. (Int.) on Combust., Combustion Institute, Pittsburgh, 1988, pp. 2027–2035.

[17] Japan Space Utilization Promotion Center (JSUP), Research and development of combustion technologies in response to fuel diversification, Annual Report for 2001, 2001, pp. 51–66.

[18] S.L. Manzello, M.Y. Choi, A. Kazakov, F.L. Dryer, R. Dobash, T. Hirano, The burning of large *n*-heptane droplets in microgravity, In: 28th Symp. (Int.) on Combust., The Combustion Institute, Pittsburgh, 2000, pp. 1079–1086.

[19] A.J. Marchese, F.L. Dryer, V. Nayagam, Numerical modeling of isolated *n*-alkane droplet flames: initial comparisons with ground and space-bases microgravity experiments, Combust. Flame 116 (1999) 432–459.

[20] K. Nakanishi, T. Kadota, H. Hiroyasu, Effect of air velocity and temperature on the soot formation by combustion of a fuel droplet, Combust. Flame 40 (1981) 247–262.

[21] A.L. Randolph, C.K. Law, Influence of physical mechanism on soot formation and destruction in droplet burning, Combust. Flame 64 (1986) 267–284.