Progress in small-scale combustion

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Abstract
This article briefly reviews the recent works related to small-scale combustion and its potential impact into combustion science and engineering is presented. Followed by a simple description of the scale effect on combustion to highlight its “unique” feature, past related works are then summarized. The impact of heat recirculation appearing in combustion systems, which is the most prominent feature of a micro- or small-scale combustion system, is focused upon and is understood that exactly the same strategy promising better combustion performance is confirmed irrespective of flame type (either premixed or non-premixed). With respect to this, paying attention to the entire combustor design, to optimize within the target working range is a crucial matter when micro-scale combustion is adopted. Potential subjects to be covered to further promote these aspects in this field are then presented.

Key words: Microflame, Scale effect, Combustion, Heat recirculation, Excess-enthalpy

1. Introduction

Micro- or small-scale combustion is now a widely known terminology and has become one of established categories within the combustion community. It has been developed for not only engineering purposes but also as an effective approach or as a tool to understand the fundamentals of combustion. Numerous researches have been performed thus far, accordingly, a sufficient number of review articles were already available (e.g., Fernandez-Pello; 2002; Ju and Maruta, 2011; Maruta, 2011; Shirsat and Gupta, 2011; Kaisare and Vlachos, 2012). Key articles were published in the early 1990s from a group of U. Kentucky (e.g., Ban, et al., 1994), however, little attention was paid at that time because it was a purely fundamental study on the scale effect for a conventional laminar jet diffusion flame. Later, the small-scale effect on combustion stability suddenly became the center of interest in late 90s, at which time Defense Advanced Research Projects Agency (DARPA) started to support the development of micro-power devices as a promising power source for microelectromechanical system (MEMS). Without a doubt this was the trigger that boosted the research into, and technology of, micro- or small-scale combustion. Followed by this, a variety of research groups, mainly from the US and Japan and already involved in this field, rapidly contributed to its build up in order for it to become a recognized/established category within the combustion community. Consequently, in 2002, “micro-combustion” was nominated as a part of a “new concept” at The Combustion Symposium (e.g., Raimondeau, et al., 2002; Matta, et al., 2002; Maruta, et al., 2002), implying that there was expectation that there would be some type of “new” feature delivered by this series of researches. Although financial support from DARPA has ceased for the present, several interesting outcomes have occurred which have led to successful contributions that have established the micro-combustion community. Unlike others, research and development into micro- or small-scale combustion has grown very rapidly within a short period and at present is progressing at a more conventional speed but, despite this, many issues still remain unknown and undiscovered. In this article, a number of researches and developments related to micro- and small-scale combustion are briefly reviewed and their recent achievements are presented. In addition, apart from most of the available review articles, we will touch more on the non-premixed combustion system because it has not been paid much attention thus far. Finally, the impact of heat recirculation, which is the most prominent feature of micro- or small-scale combustion, is summarized and potential future works are presented.
2. Scale effect

2.1 \(Pe\) and \(Da\) controlling system

Firstly, let us begin with confirming the scale effect in combustion. Fig. 1 (left) shows the non-premixed flames in a variety of scales. As seen in the figure, when the interest scale is large, flames are presented in a turbulent field and buoyancy dominates its dynamics. The flame color becomes yellow suggesting that a substantial amount of soot is produced making it hard to identify the blue flame in the system (although it appears near the flame base). As the scale becomes smaller, the flame becomes less luminous (approaches to a blue flame) and seems that it does not feel the effect of buoyancy. This feature is confirmed by applying various orientations as shown in Fig. 1 (right). This is what we call a microflame (Ban, et al., 1994).

**Fig. 1.** Non-premixed flames at various scales (left) and micro diffusion flames (right).

The above observed feature, depending on the scale, can be clearly understood through a dimensional analysis approach. For gas-phase combustion, three important non-dimensional parameters (pi-numbers) appear in equations to be solved under \(Le = 1\) and low-Mach number flow assumption (Nakamura and Saito, 2001), such as Froude number \((Fr)\), Peclet number \((Pe)\), Damkohler number \((Da)\) shown in Fig. 2. The Peclet number becomes identical to the Reynolds number under the unity of Lewis number assumption so that they are no longer independent each other.

\[
\rho^* \frac{Du^*}{Dt^*} = \frac{1}{Fr^2} \rho^* g^* \nabla p + \frac{1}{Re} \left[ \rho^* \left( 2 \dot{c} - \frac{3}{2} \nabla \cdot \mathbf{w}^* \right) \right] \quad (1)
\]

\[
\rho^* c_p \frac{DT^*}{Dt^*} = \frac{1}{Pe^*} \left[ \nabla \cdot \mathbf{Q} + Da \rho^* \omega^* \right] - \nabla \left( \rho^* \nabla T^* \right) - Ma^2 (y - 1) \beta^* T^* \frac{Dp^*}{Dt^*} + \frac{Ma^2 \Phi^*}{Re} \quad (2)
\]

\[
\rho^* \frac{DY_z^*}{Dt^*} = \frac{1}{PeLe} \left[ \left( \rho^* \nabla \cdot \mathbf{Q} \right) + Da \omega^* \right] \quad (3)
\]

**Fig. 2.** Non-dimensional governing equations and the low-Mach number flow assumptions related to Froude number \((Fr)\), Peclet number \((Pe)\), Damkohler number \((Da)\) (Nakamura and Saito, 2001).

When the target is far from the extinction condition, \(Da\) can be recognized as sufficiently large number so that \(Fr\) and \(Pe\) remain as the only potential controlling parameters in the system. Let us consider the jet flame hereafter as the most fundamental/conventional/simplest flame system. Because micro- or small-scale combustion is the center of interest here, its characteristic length (i.e. jet diameter) must be small. To sustain the flame over the jet, a certain
amount of fuel must be ejected through a very fine burner so that the corresponding jet velocity is high. Therefore, the following condition must be fulfilled;

\[ Pe \sim O(1), \quad Fr \gg 1 \]  

(1).

Because \( Fr \) is sufficiently large, the buoyancy force appearing in the momentum equation can be negligible. Therefore, flames in micro- or small-scale system is similar to the one under a microgravity and this provides the reason why the flame shape becomes near spherical over the jet (see Fig. 2). It is interesting to note that \( Fr \) is no longer an important controlling factor because it is large enough (namely, the cases with \( Fr = 100000 \) and \( Fr = 200000 \) are both \( Fr \gg 1 \) and little influence in the transport system); this is shown in Fig. 2. Thus, in general, \( Pe \) is a very important transport parameter in a micro- or small-scale system. However, we must clarify that a general assumption, widely adoptive to the flame system, such as \( Da \gg 1 \), might not be always applicable to micro- or small-scale combustion. Rather, it obviously comes to play under the scale of interest here. As indicated in Fig. 2 (right), the thickness of the heat release zone is no longer “thin enough”, rather, it is closer to the scale of interest (namely, burner diameter). Therefore, it is summarized that the feature of micro- or small-scale combustion can be characterized by two non-dimensional parameters (pi-numbers); \( Pe \) and \( Da \). This demands that researches on micro- or small-scale combustion need to apply the detail of the chemistry, except for cases where the overall transport (dynamics) process is the primary interest.

2.2 Promising features via miniaturization

Other interesting (engineering) features of the scale effect appears in the volume of heat release in the flame system, the so called “heat release density”. From a combustion engineering point of view, a large heat release in a compact volume, i.e., large “density” of heat release, is favorable. To achieve this, turbulent combustion has been introduced to have a larger flame surface in a certain volume. As shown in Fig. 3, the grey-zone describes the heat release volume, considering that the thickness of the flame gets increased. Interestingly, as the scale is reduced, such a “larger heat release density” can be naturally achieved without any assistance of a turbulent nature. Because the flame thickness is no longer “thin” in such small scale, the heat release zone becomes relatively “thicker” to mimic the highly-dense heat release zone likely from a turbulent flame (see Fig. 3).

Lastly, we should not forget to point out the most promising feature that the flame-surface (wall) interaction is pronounced. As seen in Fig. 3, when the flame size gets smaller, not only does the flame size approach flame thickness, but also the flame tends to “cover” the burner tip. Such importance can be easily understood by the increasing feature of the surface-to-volume ratio \((S/V)\) in a small-scale system (because \( S \sim d^2, \quad V \sim d^3 \) where \( d \) is characteristic length scale, \( S/V \) should be scaled by \( d^{-1} \) implying that \( S/V \) becomes large under small \( d \)). This feature highlights the importance in the role of the (burner) surface on the combustion characteristics of a micro- or
small-scale combustion system. In other words, the chemical process and physical transport (mass and heat) through the surface could modify the flame structure in an effective way and affect the stability limit accordingly. As shown later, most of the micro- or small-scale combustion devices and technologies utilize this feature. For instance, thermal interaction is heavily utilized to stabilize the Swiss-role combustor (e.g., Kim, et al., 2005), catalytic activity is utilized to stabilize the flame in a narrow space whose length scale is much smaller than the ordinal quenching distance (e.g., Norton, et al., 2004). So far, the management of the heat transfer and chemical process at the surface have been utilized to improve the performance in a miniaturized combustion system, however, that of mass transfer through the surface was not attempted. If there is any combustion system which is controlled by the surface mass transfer processes, miniaturization might be a simple yet effective solution to have better control and performance of the combustion system. In terms of a fluid motion point of view, a high-viscous force through the large surface area can also be a prominent feature of a microscale system. One example can be found in the works by Wu and Kuo (2012, 2013): they utilize this feature to initiate DDT (deflagration-detonation transition) in a narrow tube, which is an excellent idea to utilize the microscale feature as a “tool” towards the science. The unique and promising features of micro- or small-scale combustion systems are summarized in Table 1 for the convenience.

Table 1 Features of large and small-scale combustion systems.

|                  | Large scale | Small scale                  |
|------------------|-------------|------------------------------|
| Da               | infinity    | ~ unity                      |
| Surface-volume ratio (S/V) (importance of surface adjacent to the flame) | small | large |
| Dominant length scale | transport | Transport=flame thickness |
| Desired modeling | connect flame scale and flow scale | Surface-flame interaction |
| Futured task(s)  | Turbulent modeling | Molecular dynamics approach |
| Necessary item(s) | Sensing combustion status properly |

3. Brief review on micro scale combustion

3.1 Application

The development of combustion based micro scale power generation systems have accelerated in the past twenty years to meet the increasing demands for portable power sources, small scale unmanned aircraft and vehicles and micro satellites. This is because it is considered that the energy density of hydrocarbon fuel is about two orders higher than that of batteries (such as the Lithium ion battery) (e.g., Fernandez-Pello, 2002).

As new micro-power devices, many micro scale thrusters, turbines and internal engines have been developed. Both micro scale bi-propellant rocket thrusters and micro scale gas turbines were developed at MIT (Epstein, et al., 1997).
Silicon was selected as the material. The MIT thruster (London, et al., 2001a; London, et al., 2001b), which was 18 mm long, 13.5 mm wide, 2.9 mm thick and weighed 1.2 g, could generate 1.0 N of thrust or 750 W of power by using methane and oxygen as the propellants. Compared to the other thrusters such as the “digital propulsion micro-thrusters” developed at TRW (Lewis, et al., 2000), and the “Mega-pixel micro-thrusters array” developed at Honeywell Technology Center (Youngner, et al., 2000), the MIT thruster was designed for high pressure (12 atm) combustion to improve performance.

The earliest version of the MIT micro gas-turbine had a 66 mm$^3$ combustion chamber, producing 10 – 20 W power or 0.05 – 0.1 N of thrust while consuming 10 g/h of hydrogen. The later version (Mehra, et al., 2000; Spadaccini, et al., 2003) extended from three wafers to six wafers with a larger chamber of 195 mm$^3$, demonstrating the feasibility to burn not only hydrogen but also hydrocarbon fuels at higher power densities (e.g., about 500 MW/m$^3$ for ethylene-air mixture). Micro-scale gas turbines were also developed at Tohoku University and IHI corporation (Tanaka, et al., 2007). This micro gas turbine has a compressor of 16 mm in diameter, a turbine of 17.4 mm in diameter, an annular combustor and a dummy electromagnetic generator. Its performance was tested using hydrogen as fuel, showing that the Brayton cycle was established at a rotation speed of 360000 rpm, when the combustor temperature was about 800 – 900 °C.

A project aiming to develop a micro-scale (1.0 mm$^3$) rotary engine was started at the University of California Berkeley. For the preliminary tests (Fu, 2001a; Fu, et al., 2001b), 1000 m$^3$ to 1700 m$^3$ volume combustion chambers with displacements ranging from 78 mm$^3$ to 348 mm$^3$ were made in steel, producing a maximum power of 2.7 W at 9300 rpm fueled by hydrogen-air mixtures. However, fabrication, sealing, and heat loss issues were found to be quite challenging to achieve the final goal. Additionally, micro internal combustion swing engines (the cylinder is of 3.0 mm inner diameter and 25 – 57 mm length) were developed at the University of Michigan (Dahm, et al., 2001), and small scale free piston engines employing homogeneous charge compression ignition (HCCI) combustion (the cylinder is of 3.0 mm inner diameter and 25 – 57 mm length) were developed at the University of Minnesota (Aichlmayr, et al., 2002a, 2002b, 2003).

![Fig. 5. Representative micro engines. Left: the rotary engine developed at University of California Berkeley (Fu, 2001a; Fu, et al., 2001b); middle: the micro swing engine developed at University of Michigan (Dahm, et al., 2001); right: the small scale HCCI combustion engine at The University of Minnesota (Aichlmayr, et al., 2003).](image1)

Over the past twenty years, many types of micro-scale combustors have been considered, attempted and then developed. Through the development, several fundamental understandings on small-scale flame behavior were demanded and fundamental researches on this subject were further boosted (e.g., how to control the combustion in such small volume etc.). In the following, several selected works have been surveyed for both types of flame system (premixed and non-premixed).

### 3.2 Premixed combustion

#### 3.2.1 Heat recirculation-assisted (excess-enthalpy) combustion

As described, one of the most prominent features of micro scale combustion is the enlarged surface-to-volume ratio (S/V). Thus, when a small combustion device surrounded by cold air is considered, loss of the combustion heat generated shall be enhanced toward the ambient, resulting that the system could become unstable (e.g., combustion is difficult to continue). This kind of heat loss effect sounds negative for a flame stabilization purpose, however, such
enhancement of the heat transfer can be “recirculated” by adopting the heat exchanger surrounded by the combustor, as indicated by Leach and Cadou (2005). They have proven that axial heat transfer widens stability limits, increases the burning rate, and thus can enable the construction of smaller, higher power density combustors. Ronney (2003) revealed the impact of heat recirculation on flame stability theoretically and its scale effect in a systematic manner. Essentially this is the exactly same concept of excess-enthalpy combustion proposed by Weinburg (1971) and Lloyd and Weinburg (1979). Takeno and Sato (1979) successfully achieved excess-enthalpy combustion by using a porous medium, which is considered as an aggregation of micro channel(s). The thermal properties of the channel wall is therefore of vital importance in affecting the combustion performance of the combustor. Norton and Vlachos conducted two-dimensional CFD computations (Norton and Vlachos, 2003, 2004) to investigate heat recirculation supported combustion in narrow straight channels (micro combustor: see Fig. 6 (left)). Their works clearly indicate that wall conductivity and thickness are key parameters because they determine upstream heat transfer, which is necessary for flame ignition and stability. Typical results are depicted in Fig. 6 (right), showing how “tough” both the methane- and propane-air flame could be under various kinds of wall, which acts as heat recirculation medium. It is interesting to reveal that there is or are “peak(s)” in the critical heat loss parameter under the “optimum” thermal conductivity of the wall irrespective of fuel type. Namely, the flame could not be stabilized effectively when the thermal conductivity of the wall is either very low (due to blockage of the heat transfer to prohibit heat recirculation) or very high (to promote heat loss). Later, Ju and Xu (2005) investigated the heat recirculation effect on a freely propagating propane/air flame theoretically and experimentally, showing that heat recirculation could make a flame propagate faster than an adiabatic flame in a meso-scale channel. Indeed, heat recirculation can effectively increase flame propagation speed at the near extinction condition. Several other works have also studied the impact of heat recirculation in small-scale combustion devices (Chen and Ronney, 2011; Kim, et al., 2007; Kuo and Ronney, 2007; Lee, et al., 2010; Vijayan and Gupta, 2010a, 2010b; Li, et al., 2016). By using a 2-D analytical model, Veeraragavan and Cadou (2011) indicated that heat loss to the environment actually reduces “net” heat recirculation. Very recently, this problem was further studied numerically with a focus on the two-dimensional effect (Gauthier, et al., 2014; Gauthier and Berghorson, 2016). It is indicated that two-dimensional effects play a significant role at the meso-scale and the upper-range of the micro-scale. The changes in flame shape result in an increase in burning surface area, which could further promote flame stability.

![Fig. 6. The numerical model (left) and the critical external heat loss coefficient as a function of wall thermal conductivity (right), for methane and propane combustion in narrow straight channels (Norton and Vlachos, 2004).](image)

As summarized, it is understood that the performance of a premixed type micro-combustion device would strongly depend on the entire design of the combustor. In other words, combustion performance is not simply determined by the mixture, but also by the system. With respect to this, taking into account that the heat transfer through the body is a crucial issue when a small-scale combustor is developed, the material must be carefully selected to fulfill not only the mechanical but also the thermal demands.
3.2.2 Dynamic instability

In a small-scale combustion system, the flame often shows unstable dynamic behaviors especially at the near extinction condition due to the larger heat loss driven by the flame-wall interaction (in this case, the interaction works negatively to suppress the flame). Imagine that the mixture flowing in the tube is ignited at the other end, the flame forms and propagates to the upstream. However, the flame fails to travel all the way to the upstream because the substantial heat loss causes the extinction. After a certain delay, the next ignition occurs at the end. In this way, repetitive ignition-flame propagation-extinction behavior can be observed. Such dynamic flame behaviors were systematically studied by the group of Kyritsis and their cooperators (Richecoeur and Kyritsis, 2005; Jackson, et al., 2007; Evans and Kyritsis, 2009). Interesting flame behaviors found in their series of works is presented in Fig. 7. Fuel rich mixtures were used and a flame is stabilized at the exit serving to heat the channel, and the dynamic behavior of another premixed flame inside the “U-shaped” channel is observed and well controlled by adjusting velocity and the equivalence ratio. The acoustic signal (Fig. 7 (right)) shows the repetitive behavior of the ignition-propagation-extinction along the tube. This dynamic behavior can be well-characterized by the non-dimensional numbers such as $Bi$ and $Fo$.

Fig. 7. Study on flame stabilization in curved mesoscale ducts by Richecoeur and Kyritsis (2005). Left: the experimental set-up; middle: the direct flame picture; right: the dynamic flame behavior represented by sound signals.

Using an external heat source is another effective way to establish such repetitive flame behaviors (Maruta, et al., 2005; Minaev, et al., 2007; Nakamura, et al., 2012; Pizza, et al., 2008a, b). It is noteworthy that weak flames are also possible to be observed at the near extinction condition (Tsuboi, et al., 2009) and this technique is very effective to characterize the reactivity of the fuel. Multiple weak flames stabilized in a micro channel with a prescribed temperature profile have been employed to study staged-ignition kinetics (Oshibe, et al., 2010; Yamamoto, et al., 2011).

As summarized, those works utilize the most prominent feature of micro- or small-scale combustion (such as flame-surface interaction) to control the local reactivity. It is interesting to note that the interaction can result in both positive and negative ways to show a “unique” dynamic behavior of the flame.

3.2.3 Interactions with surface chemistry

In addition to the thermal interaction between the flame and burner wall as described, chemical interaction including surface catalytic reactions and radical quenching reactions are also relatively important as the scale of the combustion system decreases (Chen G-B., et al., 2007). In 2002, Maruta et al. (2002) simulated the catalytic combustion of a methane-air mixture in a microscale channel coated with platinum (Pt) and revealed that gas-phase reactions were neglected and only the catalytic surface reactions were considered. Followed by this work, catalytic combustion in micro channel has been extensively investigated by the group of Vlachos for various fuels, including $H_2$ (Norton, et al., 2004), syngas (Federici and Vlachos, 2011), propane (Norton and Vlachos, 2005; Kaisare, et al., 2008; Scarpa, et al., 2009), and hydrogen/propane mixtures (Norton and Vlachos, 2005) at which mostly platinum catalyst was considered. The coupling effect between heat recirculation and surface reaction, and the relationship between
characteristic times of gas-phase and catalytic reactions, play key roles in determining the performance of microcatalytic combustors. Besides wall surface coated catalytic burners, Ahn, et al. (2005) and Takahashi, et al. (2009, 2014) successfully developed micro scale catalytic combustors with a porous catalyst layer sintered on the inner wall, which significantly increases the surface area of the catalyst. Takahashi’s burner can endure more than 1000 hours of combustion, and the energy density is about 2.5 times that of lithium-ion batteries.

Triggered by the earliest mechanisms proposed by Raimondeau, et al., (2002), the radical quenching effects on combustion in narrow channels have been examined for different materials, such as quartz, alumina and metals, by looking at the radical distribution adjacent to the surface by laser diagnostics (Saiki, et al., 2015; Saiki and Suzuki, 2013; Yang, et al., 2013). It has been proven that radical quenching does exist even for quartz wall, which is generally believed to be chemically-inert, and that the radical quenching effect becomes more significant for a flame in a narrow channel with a gas distance of less than 1.0 mm (see Fig. 8). According to Saiki and Suzuki (2003), it has been suggested that the most inert material under their studies was alumina, rather than quartz. However, a very recent study by Kizaki, et al. (2015) claimed that the radical quenching effect for a methane flame in a micro scale quartz reactor should be negligible and becomes pronounced only at low pressures (< 0.5 atm). It is implied that ambiguities remain and further studies on radical quenching mechanism are required.

Fig. 8. Study on effect of wall surface reaction on a methane-air premixed flame in narrow channels with different wall materials by Saiki and Suzuki (2013). Left: the experimental set-up; middle: the PLIF measured OH contours in the vicinity of the quartz and the alumina surfaces (a) quartz at Tw = 1073 K, (b) quartz at Tw = 1273 K, (c) alumina at Tw = 1073 K, and (d) alumina at Tw = 1273 K; right: wall-normal distributions of OH near the quartz and the alumina surfaces at Tw = 873 K, 1073 K and 1273 K.

3.3 Non-premixed combustion

3.3.1 Lower-limiting flame behavior

One of the earliest micro- or small-scale non-premixed (diffusion) flame (so called microflame) studies was conducted by Ban et al. (Ban, et al., 1994). Flame structures of ethane, ethylene, and acetylene were investigated using circular-port stainless-steel burners with inner diameters of 0.15, 0.25 and 0.40 mm. It was shown that the effect of buoyancy is negligible in small-size. Their theoretical analysis indicated that including the axial diffusion effect is important for better prediction of the flame shape. However, the assumption for their analytical approach does not allow for discussion about near-limiting behavior since quenching near the burner port cannot be taken into account. Matta, et al. (2002) precisely examined the lower-limit of the small diffusion flames of propane, indicating that the fuel burns in a flat premixed combustion mode due to the mixing of fuel and air within the stand-off zone between the flame and the burner tip. The near-extinction flame structure was further investigated numerically by Nakamura, et al. (2006, 2008), where the lower-limit curve is strongly affected by the thermal boundary condition of the burner. The Damköhler number concept was used to explain the extinction criterion, suggesting that the limiting feature can be well-summarized by the diffusion flame mode. Later, Kuwana, et al. (2009) developed a theory to predict the extinction of such a small diffusion flame based on the extinction of a Burke-Schumann flame. It was concluded that such a theory works to predict the extinction of methane and butane flames with reasonable accuracy. Further studies on methane microflame experimentally as well as numerically came out to discuss about the detail
radical structure (Chen C.P., et al., 2007; Cheng, et al., 2006a; Cheng, et al., 2008). Unlike in case of the hydrocarbon microflame, a hydrogen microflame showed unique behavior at near extinction limit. Cheng, et al. investigated the characteristics of the small-jet diffusion flames of hydrogen (Cheng, et al., 2005; Cheng, et al., 2006b). Discussions were made based on a comparison between experimental results using a UV Raman/LIPF system and numerical simulation results. What was found was that almost no fuel molecules can be found even at the exit of the jet when the jet diameter is sufficiently small (< 0.5 mm) and the fuel is hydrogen (no such behavior was found for methane-air flame). In their analysis in 2005, such a trend failed to be captured because the analysis did not include the thermal conduction processes through the burner. Hossain and Nakamura (2015) conducted a new series of numerical experiments by adopting a conductive burner with detailed chemistry. Their results showed that excess heating at the flame tip with a lower conductivity burner could modify the structure inside the micro-burner substantially to successfully reveal a tremendous reduction of hydrogen molecules at the burner exit (see Fig. 10 (right)).

Interestingly, such excess heating at the tip is hardly observed in a normal methane-air microflame, however, it
appears when ambient oxidizer is preheated (Fujiwara and Nakamura, 2013). This is because the quenching distance could be shorter under a preheated oxidizer environment so that a large amount of heat can be transferred. Most recently, Gao, et al. (in press(a)) explored the reason for extra-ordinal promotion of excess heating at the tip for a hydrogen-air microflame in comparison with a methane-air microflame. It has been suggested that the difference in temperature dependency of the heat release reactions at the vicinity of the burner tip is because a hydrogen-air flame can form a large heat release zone even at the burner surface (within thermal boundary layer) to promote modification of the thermal and chemical structures inside the burner. Although the prediction sounds reasonable, so far, there is no concrete experimental evidence to support this opinion. Further study on this is highly desirable.

3.3.2 Instability and others

The micro- or small-scale jet diffusion flames mentioned above were actually established in open environments. Non-premixed flames in a confined polycrystalline channel with a gap height of 0.75 mm were studied by Miesse, et al. (2004, 2005), where the cellular diffusion instability is presented (see Fig. 11 (left)). It was found that such unstable behavior is sensitive to fuel, and appears for CH$_4$ and C$_3$H$_8$ but not for an H$_2$-O$_2$ mixture. Xu and Ju (2009) studied this phenomena precisely and named it “flame street” (see Fig. 11 (right)). As summarized in Sec. 3.2.2, such instability behavior is triggered by the excess heat loss to the wall. In this sense, the appearance of instability in small-scale combustion systems is explained by the same reason irrespective of the flame type (premixed or non-premixed).

Several other studies have been undertaken to burn liquid fuels at the micro scale. A group at Yamaguchi University successfully burned an electro-sprayed ethanol/n-heptane mixture in a 3.5 mm inner diameter quartz tube with a wire mesh without any external heating or catalyst (Yuliati, et al., 2012). The mesh acts not only as a “collector” (to collect charged droplets), but also as a “flame holder” through heat recirculation (Mikami, et al., 2013). Laminar jet diffusion flames of liquid ethanol were stabilized by submillimeter tubes, as shown in the studies by Chen, et al. (2009) and Xu, et al. (2013). Additionally, motivated by developing a multiple arrayed microflame burner, the interactions of microflames have been studied by Hirasawa, et al. (2012) and Kuwana, et al. (2016). Most recently, an extremely small flamelet was made by using a counterflow configuration to burn methane with pure oxygen by Kadowaki, et al. (2016).

4. Recent progress and future works
4.1 Study on impact of heat recirculation for non-premixed flame

As found by a review of the literature so far, wall-flame interaction is a key issue that appears as a unique feature of micro- or small-scale combustion. In particular, as we can see in Sec. 3.2.2 and 3.3.2, the instability behavior in micro-scale combustion, where the reactivity is weakened due to a large heat loss triggered by the flame-wall interaction, was the direct cause irrespective of flame type (either premixed or non-premixed system). Then it is
naturally expected that the promotion of reactivity via flame-wall interaction to derive the heat recirculation effect, as stated in Sec. 3.3.1, would be also presented in a non-premixed combustion system and be a feature irrespective of flame type. In this section, let us consider whether this could be true or not.

Fig. 12 depicts a hydrogen-air non-premixed microflame (Cheng, et al., 2005) and a methane-air (preheated) non-premixed microflame (Fujiwara and Nakamura, 2013), showing that both flames clearly substantially preheat the burner. Because the flame is formed over the burner, a part of the combustion heat can be transferred to the burner as illustrated in Fig. 12. The “stocked” enthalpy in the burner shall be transferred to incoming fuel to achieve an “excess-enthalpy” state. Furthermore, it is possible to “control” the fuel gas temperature inside the burner through the heat transfer process, meaning that the flame structure could be much different from the one formed away from the burner (Fig. 13), at which the flame-sheet model is generally applicable. In this regard, combustion features characterized by the flame structure (e.g., extinction) of a microflame cannot be predictable via an ordinal counterflow diffusion flame (CFDF). This is consistent with the feature of a microflame as shown in Sec. 2, where $Da$ cannot be assumed infinitely large. Notably a unique flame structure formed in the microflame can be manipulated (controlled) by the adopted burner, namely, such flame is not an eigenvalue of the fuel and oxidizer, rather, it is of system-dependent quantities. This is quite consistent with what we have learned from our literature review for micro- or small-scale premixed-type combustion stated in Sec. 3.2.1.

![Fig. 12 Microflame over “hot” jet-tip. The left hydrogen flame figure comes from the work by Cheng, et al. (2005), and the right methane flame comes from Fujiwara and Nakamura (2013).](image)

![Fig. 13 Potential flame structure formed over microflame. The computed hydrogen flame temperature contours is employ from Hossain and Nakamura (2015).](image)

Most recently, authors have systematically examined the effect of burner properties on the degree of heat recirculation through the burner and propose a way to evaluate via a numerical experiment (Gao, et al., 2015; Nakamura and Gao, 2016; Gao, et al., in press(a)(b)). Analyzed heat flow in the simulation and a definition of “effective excess enthalpy, $H$” are depicted in Fig. 14. In this work, effective excess enthalpy is defined as the ratio of the transferred heat effectively used for heat recirculation to the loading rate of the fuel. It becomes zero when lost heat is identical to recirculated heat, therefore, its sign directly shows that conducted heat was mainly transferred to the fuel (recirculation) or ambient (loss). Because it is evaluated as unit mass (of fuel) basis (likely, emission index), it enables us to compare heat recirculation performance by using various kinds of fuel.
Fig. 14. Heat flux analysis for a micro scale diffusion flame, and the definition of “effective excess enthalpy, $H$” (Gao, et al., 2015; Nakamura and Gao, 2016; Gao, et al., in press(b)).

$\begin{align*}
\text{Total heat flux received from the flame} & \quad Q_1 + Q_2 = Q_3 + (Q_4 + Q_5) \\
\text{heat recirculation} & \quad Q_{rec} = Q_3 \\
\text{heat flux that lost to the ambient air} & \quad Q_{loss} = (Q_4 + Q_5) \\
\text{The effective excess enthalpy} H (\text{J/kg}) & \quad H = \frac{(Q_{rec} - Q_{loss})}{M} \\
\end{align*}$

where $M$ is the mass flow rate.

$H = 0$: negligible thermal interaction
$H > 0$: heat recirculation dominates
$H < 0$: heat loss dominates

Fig. 15 Computed temperature and heat release rate contours at a fuel jet velocity of 0.4 m/s for different burner properties: (a) different burner wall thicknesses of $c_b = 0.8 \text{ mm}$, $0.4 \text{ mm}$, and $0.2 \text{ mm}$ with constant burner thermal conductivity of $k_b = 6 \text{ W/(m-K)}$; (b) different burner thermal conductivities of $k_b = 100 \text{ W/(m-K)}$, $16 \text{ W/(m-K)}$, and $1 \text{ W/(m-K)}$ with a constant burner wall thickness of $c_b = 0.2 \text{ mm}$ (Nakamura and Gao, 2016; Gao, et al., in press(b)).

Fig. 15 shows the 2-D heat release contours under various burner thicknesses (a) as well as various thermal conductivities of the burner (b). As expected, a thinner burner with lower conductivity could heat the burner tip substantially. It is interesting to note that the burner behaves in a “thermally-thin” manner showing little thermal gradient toward the radial direction through the burner wall. Hence, most of the heat received by the burner from the flame could be transferred through the burner only in an axial direction ($Q_5$ in Fig. 14), then utilized to heat up the gas adjacent to the burner surface ($Q_3$ and $Q_4$ in Fig. 14). In this respect, the heat flux analysis constructed in Fig. 14 should be considered as being reasonable.

The excess enthalpy analyses have been performed under various thicknesses and thermal conductivities of the micro burner. Typical results are shown in Fig. 16. This figure indicates two important facts. One is that there exists the condition to provide maximum heat recirculation, suggesting that this should be an “optimum” condition to utilize the feature of miniaturization of a non-premixed combustion system. As described, heat recirculation works positively to support reactivity when we have positive $H$ in the domain. According to Fig. 16, we have only selected a range in $Re$ under limited thermal burner materials (thickness and thermal conductivity) to have positive $H$. It is worthwhile to note that such a positive effect appears only at the first order of thermal conductivity ($< 10 \text{ W/(m-K)}$) for a methane-air combustion system and diminishes in both lower and higher thermal conductivities. Although not
shown in this figure, we have confirmed that the condition to show the positive $H$ can vary when different fuel is used. This is the exactly the same trend observed in the premixed type micro-combustion system (see Sec. 3.2.1).

![Diagram showing effective excess-enthalpies and flame temperatures over fuel jet velocities range from the extinction limits to 3.2 m/s for different burners: Burner-A with $c_b = 0.2$ mm and $k_b = 1$ W/(m·K), Burner-B with $c_b = 0.2$ mm and $k_b = 6$ W/(m·K), and Burner-C with $c_b = 0.8$ mm and $k_b = 6$ W/(m·K) (Nakamura and Gao, 2016; Gao, et al., in press (b)).](image)

The other fact is that the local maxima in positive $H$ appears at the lower $Re$ when the suitable material for the burner is selected, which is an essential condition for a microflame (eq. 1). This suggests that the microflame condition promises to have a positive heat recirculation effect supporting reactivity. Interestingly, $H$ is gently varied when $Re$ increases, whereas it drastically changes when $Re$ becomes lower than its optimum value, then eventually turns into negative $H$. In this sense, a flame that is too small cannot stably exist even when using heat recirculation probably because it cannot compete with the heat loss induced by natural convection. Considering the difference sensitivity of $H$ against $Re$, from an engineering point of view, a preferable working condition should be with a slightly higher $Re$ than the optimum one because slight disturbances of $Re$ do not greatly affect the performance of the combustion system. More importantly, $Re$ can be one of the user-controllable parameters to achieve higher $H$, which is not possible in a premixed-type combustion system. In this regard, an additional degree of freedom to control combustion characteristics is available to a non-premixed type combustion system, which is a distinguishing difference from a premixed-type combustion system.

4.2 Potential future tasks

It has been understood that there is a desirable feature of a micro- or small-scale combustion system, however, as noted, most of knowledges found here are “predicted” numerically without any precise validation. Although a detailed chemistry model was adopted, validation data by experiment would be highly preferable. Unfortunately precise visualization by experiment has not been undertaken to any great degree as it is very hard to access. For example, laser diagnostics by using a laser sheet is very powerful and enables us to access detailed information on the distribution of the radical species. However, when the scale of interest is the same order of the thickness of the laser sheet, the measured distribution is somewhat ambiguous. Considering that sensing is an essential task to verify/support predicted findings, further development in this field is very necessary.

Other progress should be made to introduce the concept of microscale reactive fluid dynamics. This is because the assumption of continuous fluid might fail when the scale of interest decreases further and close to the mean-free path. Under such conditions, a non-equilibrium state would be expected and it would be difficult to define the “flame” itself. Recently, a molecular dynamics (MD) approach was applied to combustion study (e.g., Yanagihara, et al., 2014) and further development would be expected to apply it to micro-scale combustion.
5 Concluding remarks

In this review, recent works related to small-scale combustion are surveyed and summarized. Although most of the available review articles focus on a premixed flame system, the non-premixed combustion system is also surveyed to find a common feature in scale, not related to flame type. Heat recirculation, which is one of the “unique” and “promised” features of such micro- or small-scale combustion, was investigated and confirmed that exactly the same strategy to promise better combustion performance irrespective of flame type. This fact suggests that paying attention to the entire combustor design to optimize within the target working range is a crucial matter when micro-scale combustion is adopted. Development of sensing technology and a molecular dynamics approach would help to further growth in this field.

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