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Combustion Characteristics of Mg Vapor Jet Flames in CO_2 Atmospheres

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Abstract

An experimental study was performed on the combustion characteristics of a jet diffusion flame of Mg vapor injected through a small nozzle into CO_2 atmospheres at low pressures from 8 to 48 kPa with a view to using Mg as fuel for a CO_2-breathing turbojet engine in the Mars atmosphere. The Mg vapor jet produced three types of the flame. At lower pressures and higher injection velocities, a red-heated jet flame formed, in which the injected Mg vapor was heated by spontaneous reactions, turning red. At medium pressures and injection velocities, a stable luminous lifted-like flame developed above the rim of the chimney, a tube-like combustion product for the Mg vapor passage that grew on the nozzle during combustion. The flame had similar flame length properties to laminar jet diffusion flames of gaseous fuels. At higher pressures and lower injection velocities, a stable luminous attached flame developed at the rim of the chimney. The same reactions, producing MgO(g), CO and MgO(c), proceeded preferentially for all flames and chimneys. Carbon was only subordinately generated. Burning behavior of Mg vapor jets in a CO_2 atmosphere has been represented, including the homogeneous reaction of Mg vapor with CO_2, the diffusion of CO_2, and the condensation and deposit of MgO. The injection velocity of Mg vapor at the rim of the chimney and the exothermic reactions with diffused CO_2 that occur there play a crucial role in the attachment and development of the flames. The flame structure may be explained in terms of the relatively low gas-phase reaction rate of Mg with CO_2.

Keywords: Mars jet engine, metal combustion, Mg vapor flame, CO_2 atmosphere, combustion characteristics

Introduction

We have proposed a CO_2-breathing turbojet engine using Mg as fuel for a Martine aircraft, and studied the ignition and combustion of Mg in CO_2 gas streams.[1-3] Our previous experiments showed that Mg-CO_2 flames produced CO, part of which could diffuse back onto the Mg surface, and also produce a somewhat protective condensed MgO-C film on the surface, due to the surface reactions.[2,3] The film inhibited further gas-phase oxidation, resulting in slow and incomplete combustion. To prevent such poor combustion, Mg surface must not exist in the combustion region of an Mg-CO_2 system. Two burning methods that satisfy this condition are available. One is to use ultra-fine Mg powder that completes evaporation before flowing into the flame front of Mg-CO_2. Several similar experimental studies on the combustion of metal powder, not including Mg, in hot gas streams have been performed.[4-6] The results may be useful in evaluating the possibility of realizing the combustor of the jet engine with metal powder.

The other method is to form a jet diffusion flame of Mg vapor. However, only limited studies have been made on the Mg flames in O_2-Ar mixture atmospheres. Markstein[7] and Deckker[8] developed Mg-O_2 dilute diffusion flames at pressures from 0.1 to 1 kPa. Both found that spherical shape flames were formed. However, their studies focused not on the combustion characteristics, but on the reaction mechanism of Mg vapor with O_2. Thus, as far as we know, no work has been reported on the development of a pure Mg vapor jet flame in a CO_2 atmosphere or on its combustion characteristics.

The atmospheric pressure on the surface of Mars is about 0.6 kPa. If the CO_2-breathing engine works at the same pressure ratios of ordinary jet engines used on the Earth, Mg vapor must be burned in the combustor at pressures from about 9 to 25 kPa. In this paper, therefore, we carried out an experimental study to investigate whether a stable Mg vapor jet flame could actually be developed at low pressures in CO_2 atmospheres, and to reveal some fundamental combustion characteristics of the flame.

Experimental Apparatus and Procedure

Figure 1 shows a schematic of the experimental apparatus. CO_2 at room temperature flowed into the chamber. The burner with an 11-mm inside diameter and a height of 18 mm was made of stainless steel and had a small nozzle of 1-mm in diameter. An Mg sample (mass: 0.6 g, purity: 99.9%) mounted in the burner was heated using a high-frequency induction heater.

The experiment was performed at the combustion chamber pressures P_{amb} from 8 to 48 kPa. The CO_2 flow rate was kept constant at 0.05 g/s, independent of P_{amb}, which was well above the mass flow rate of Mg (see later) for complete combustion. Before each test run, the Mg sample in the burner was heated in an Ar atmosphere at a predetermined pressure and flow rate. When the Mg vapor began to actively issue from the burner nozzle, the combustion test run was initiated by changing Ar to CO_2 of the same pressure. Throughout the present study, except for particular runs (see later: Flame length), the electric power of the heater was kept constant at 2.2 kW.

It is very difficult to pinpoint the mass flow rate of vaporizing Mg due to the progression from gaseous phase to condensed phase during issue. In this experiment, the flow rate was estimated from the weight decrease rate of the Mg sample in the burner mounted on a beam by using two non-magnetoresistive foil strain gages pasted on the beam.[9] The accuracy of the weight measurement was on the order of ±0.03 g. In the case of issuing Mg vapor into an Ar atmosphere, the vapor temperature T_v was measured using a chromel-alumel thermocouple (K-type) with a 0.15-mm diameter junction at 1-mm downstream from the nozzle exit. The Mg sample temperature T_m in the burner was measured using a K-type thermocouple. To investigate the flame structure, three photographs of the same flame were taken simultaneously on infrared film through filters corresponding to Mg, MgO and continuum emissions [Mg(g) emission=517nm; halfwidth=1.7nm, MgO(g) emission=498nm; halfwidth=15nm, the continuum emission>700nm]. Condensed combustion products gathered after the experiments were analyzed chemically as well as using an x-ray diffractometer.

Experimental Results

Flame Development

(i) Mg temperature history

Figure 2 shows a typical example of the time variation of T_m and T_v, when Mg vapor was injected into an Ar atmosphere. T_m was corrected by the melting point of Mg. Just after T_m reached the boiling point of Mg at P_{amb}, the nozzle began to eject Mg vapor actively, and there was a corresponding sharp increase in T_v. During vaporization, T_m remained almost constant at the boiling point of Mg at P_{amb}, but T_v reached a maximum lower than the boiling point by about 50 K and then decreased in spite of the injected Mg vapor. This value and tendency of T_v was due to the heat loss through the wires of the thermocouple and the decreased heat transfer rate achieved by the deposit of molten Mg on the junction of the thermocouple. This suggests that T_v would be almost equal to T_m, if the heat loss and heat transfer could be appropriately corrected. In this experiment, the tendency of T_m and T_v varied little over time with P_{amb}. On the other hand, when the Mg vapor burned in CO_2, it was confirmed that the value and tendency of T_m was the same as those without combustion.

(ii) Mg vapor injection velocity

The weight of Mg in the burner was measured to decrease linearly with time during vaporization. This showed that the Mg sample vaporized at a constant rate after reaching the boiling point. Therefore, the averaged mass burning rate of Mg m_{Mg} was roughly estimated using the vapor injection period and the initial mass of the Mg sample. m_{Mg} was almost constant within a range of scatter of ±15% at any variation of P_{amb}. The scatter was mainly due to a slight shift in the positions between the burner and the working coil at each point of assembly.

The averaged injection velocity of Mg vapor u_{jnz} at the burner nozzle exit was estimated from m_{Mg} by assuming that the Mg vapor temperature and pressure were equal to T_m and P_{amb}, respectively. Figure 3 shows u_{jnz} against P_{amb} with and without combustion. For both cases, u_{jnz} decreased with increasing P_{amb} due to increasing the density of Mg vapor. The Reynolds number of the Mg vapor jet was in the range of 100-200, which was estimated using u_{jnz}, the nozzle exit diameter and the dynamic viscosity of the Mg vapor calculated by molecular transport properties[10] at T_m and P_{amb}. These jets were in the laminar range.

(iii) Flame appearance

The Mg vapor jet ignited spontaneously when T_m reached the boiling point of Mg at ambient pressure. Three types of Mg vapor jet flames were observed. Amongst these, typical examples are shown in Fig.4. At less than P_{amb} =9 kPa, the injected Mg vapor was heated red after the CO_2 replacement, as shown in Fig. 4(a). The boundary between the vapor jet and the ambient was intensely heated and u_{jnz} was so high at 233 m/s that its height reached to about 80 mm. Here we call this flame red-heated jet flame. A small amount of combustion products accumulated on the rim of the nozzle exit during Mg vapor injection.

For P_{amb} between 10-30 kPa and u_{jnz} between 90-170 m/s, a luminous region appeared in the Mg vapor jet after the gas replacement. This was followed by a stable jet flame of Mg vapor as shown in Fig.4(b). The flame generated large quantities of white smoke. During the combustion, combustion products piled up on the rim of the burner nozzle exit, building a tube-like structure for the Mg vapor passage. Hereafter, the deposit structure, referred to as a chimney, continued to grow until the burning process was complete. As the figure shows, the rim of the chimney shone clearly while the chimney grew. In this type of flame, the diameter of the chimney was found to vary little with time. It should be noted that this flame seemed to be lifted above the rim of the chimney and there was a consistent presence of a rather dark region just downstream of the chimney, where the combustion reactions were weak. We called this type of flame lifted-like flame, and the average injection velocity of Mg vapor at the chimney exit was noted with $Ujch$, which was estimated by assuming that the vapor temperature was equal to Tm.

On the other hand, at higher $Pamb$ between 21-48 kPa and lower $Ujnz$ between 40-110 m/s, the very luminous region, which appeared initially well above the burner nozzle exit in the Mg vapor jet at the gas replacement, moved upstream and was attached to the rim of the burner nozzle, developing an attached flame, and building the chimney as shown in Fig. 4(c). The diameter of the chimney increased with time. We call this type of flame attached flame. The flame was characterized as extending from the rim of the chimney of the attached flame, shining much more intensely than that of the lifted-like flame, and there was no dark region downstream of the chimney. The heights of the bright region of the chimney were measured to be about 1 mm, independent of the time. In addition, a very bright thin layer existed in the flame boundary adjacent to the ambient. Figure 5 shows a magnification near the rim of the chimney of the attached flame. It was found that the bright thin layer appeared from the inside of the chimney rim and a luminous flame region expanded towards the inside even further.

Both the lifted-like and attached flames could develop in the medium pressure range near 21-30 kPa. When $Ujnz$ was high, the lifted-like flame was formed. However, if the chimney diameter increased during combustion, the lifted-like flame dropped back to the chimney rim, resulting in the attached flame. This suggests that $Ujnz$ and $Ujch$ were controlling factors in determining flame type.

Flame characteristics

(i) Filtered photographs

Figure 6 shows the filtered photographs of a lifted-like flame with binary code processing, the transformation of a gray-scale image to a black and white one, to clearly identify the reaction region of the active species. The emissions at the base of the flame were so weak that they were not visible in the filter photographs. All the emissions of the flame were found to appear approximately in the same region, except for the fact that the tip of the continuum emission was not closed. This indicates that for the lifted-like flame, the gas-phase reactions of Mg(g) and CO_2 and the condensation of MgO(g) occurred simultaneously and actively in the middle region of the lifted-like flame, but not actively, or not at all, at the base of the flame. This suggests further that the ratio of the chemical reaction characteristic time of Mg with CO_2 to the characteristic time of the Mg-CO_2 diffusion process was large in comparison to ordinal laminar fuel jet flames with air; that is, the flame was partially premixed.

Figure 7 shows the filtered photographs of an attached flame with binary coded processing. The MgO(g) emission was not visible at the base of the flame, but was strong near the center axis of the downstream. It was closed at the tip of the flame. Strong emission of the continuum was attached to the chimney. The emission extended toward the center axis along the downstream, and grew weaker again toward the outside after passing through the region corresponding with the strong MgO(g) emission region. The emission was not closed at the tip. Our spectroscopic analysis [3] showed that the emission intensity passing through the filter for the Mg lines included the emission intensity of the continuum. This implied that the emissions, which were like two horns appearing along the boundary with the atmosphere shown in Fig.7(a), were attributed to the continuum emission. The true emissions of the Mg lines were considered to be similar to that of MgO(g). The results obtained in Fig.7 indicated that the gas-phase reactions of Mg with CO_2 proceeded at the wide mixing region around the center axis in the flame. The condensation reactions started from the rim of the chimney and also occurred in the flame at the boundary between the flame and the ambient.

(ii) Combustion products

Table 1 shows typical concentrations of the combustion products of three flames, which adhered to the ceiling of the combustion chamber, and two chimneys. The combustion products of the red-heated jet flame were white powder composed of MgO, including C at less than about 4%, and no unburned Mg. This suggests that the red-heated jet flame was also one of the flames of the Mg vapor with CO_2. For both the lifted-like and the attached flame, the combustion products were comprised of MgO and about 2% of C, but no unburned Mg was identified. This composition result reveals that the Mg vapor in the flames preferentially reacted to produce MgO and CO. The chimney products were composed of MgO, unburned Mg and C. The concentration of C was less than 2%, and relatively large amounts of Mg were presented in the chimney. From the masses of the chimneys and the compositions of C, the masses of the Mg component in the chimneys were estimated to be about 4 and 12 % of the initial mass of the Mg sample for the lifted-like flame and the attached flame, respectively. This indicates that the accumulation of unburned Mg in the chimney reduces the volume flow rate of the Mg vapor injected through the burner nozzle. The substantially same compositions for the three flames and two chimneys, except for the unburned Mg, suggests that the gas-phase reactions and the reactions proceeding inside of the chimney have the same reaction kinetics to produce mainly MgO and CO, and C subordinately.

(iii) Flame length

The flame length Lf, defined as the distance between the chimney rim and the flame tip, and the rim diameter of the chimney Dch for the lifted-like flame varied little over time. Dch for the attached flame, larger than that of the lifted-like flame, increased over time. However, its Lf, which was less than the half of the lifted-like flame, decreased over time.

Figure 8 shows the variation of Lf of the lifted-like flame with m_{Mg} divided by $Tm^{0.5}$, considering the diffusion coefficient on temperature and pressure. Although the data of Lf were scattered, as a whole, Lf had a tendency to increase with $m_{Mg} / Tm^{0.5}$. (Limited to this experiment, the electrical input power was slightly changed to vary m_{Mg}.) The reasons for the scatter were due to the slight varying in the mass flow rate of Mg and the different rim diameter of the chimney at every test run by the indeterminacy of the chimney developing process. This dependency of Lf is essentially the same as that of the ordinary laminar diffusion flames.[11] The Reynolds numbers of the Mg vapor jets of the lifted-like flames at the rim of the chimneys in Fig.8 ranged from 52 to 155. This supports the assumption that the lifted-like flames were in the laminar range.

If the attached flame was one of the simple laminar jet diffusion flames, its length should only be proportional to m_{Mg}, independent of the rim diameter[11]. However, this correlation was not established for the flame. Considering these results, it may be concluded that for the attached flame, a part of m_{Mg} injected from the Mg burner nozzle reacted actively inside the chimney. Judging from the chimney weight after burning, most of the burning products that had formed on or near the chimney surface were carried downstream, and a portion of them piled up on the surface of the chimney before passing through the chimney rim, causing growth of the chimney.

Discussion

Reaction kinetics

Our previous studies [2,3] show that when the temperature of the Mg/CO_2 system was much higher than the melting point of Mg and there was no condensed phase of Mg, the following overall reactions were predominant: (1) Mg+CO_2→MgO(g)+CO and (2) MgO(g)→MgO(s). When the flame temperature was lower or a condensed Mg surface existed, the overall reactions (3) Mg+1/2CO_2→MgO(s)+1/2C and (4) Mg+CO→ MgO(s)+C were possible. The compositions of C obtained in the present experiment were almost the same as that obtained in the Mg-CO_2 counterflow diffusion flames of our previous study at low pressures.[3] The adiabatic flame temperatures of Mg/CO_2 system[12] are very high. These results indicate that reactions (1) and (2) can take place preferentially in all of the flames and at the chimneys, and reactions (3) and (4) are only subordinate.

On the other hand, a critical stagnation velocity gradient with a blow-off of gaseous fuel flames may represent a measure of the overall reaction rate.[13] A comparison of the critical blow-off limits of the Mg/CO_2 counter diffusion flames and the gaseous fuels/air flames shows that the former critical velocity gradient was about 1/5 -1/30 lower than the latter ones.[3,12] This suggests that the overall reaction rate of Mg/CO_2 flames may be much slower than those of ordinary fuel flames. Although the diffusion coefficient of Mg vapor is unknown, the value may be the same magnitude as those of ordinary gases such as O_2 and N_2, if it is evaluated by the bifurcation approximation.[10] The wide reaction regions observed in the *lifted-like* and the attached flame are consistent with those considerations.

Red-heated jet flame

The high velocities of the red-heated jet flames increases entrainment of the ambient CO_2 into the Mg vapor jet, which causes a decrease in temperature and Mg vapor concentration in the jet before the combustion reactions of Mg with CO_2 proceed actively. Previously, we found that Mg ultra-fine particles could allow active reactions with air and burn even in room temperature as long as they were not covered with oxide. This is known as the pyrophoric property. This fact implies that the Mg vapor diluted with the CO_2 atmosphere may react with CO_2 and release heat to the degree of heated-red in accordance with the reactions (1) and (2). However, the flame temperature at low pressures is not as high due to low fuel concentration, in which case the reactions (3) and (4) simultaneously proceeded to form C.

Attached flame

Figure 9 shows a schematic representation of the attached and the lifted-like flame as to how the Mg vapor jets burn in CO_2. The exit velocity of the Mg vapor at the rim of the chimney with a wide diameter is so slow at about 3-10 m/s that the ambient CO_2 may quite easily diffuse inside the chimney. The CO_2 reacts with the sufficiently high temperature Mg vapor in the gas phase near the chimney surface to produce MgO(g) and CO, according to the reaction (1). A part of the MgO(g) easily diffuses forward to the inside surface of the chimney and condenses on it, causing the chimney temperature to increase due to the heat release of MgO condensation. Simultaneously, the reaction (4) occurs with the Mg vapor to form additional MgO(s) and C on the inside surface. These exothermic processes sustain the active reaction near the rim of the chimney, which acts as if a pilot flame exists there. This is a decisive difference from the ordinary diffusion flames stabilized on the burner rim.

A decrease in the flame length with time can easily be explained by an increase of the mass flow rate of Mg vapor which was consumed and accumulated in the chimney because the height of the reacting region of the chimney varied little over time, remaining consistently at a level of about 1 mm, and the diameter increased. A part of the MgO(g) produced at the rim condenses in the downstream region of the chimney. The rest is convected by the bulk flow to the outside of the chimney while it is condensed. In the main part of the flame, the Mg vapor forms a diffusion flame with a wide reaction zone in the ambient CO2. MgO(g) generated there diffuses toward the outside to be condensed, and gathers MgO(c) coming from the rim of the chimney, developing a thin layer shown in Figures 4(c),5 and 7(c). C is generated by the reactions (3) and (4) in the low temperature region near the outer reaction zone of the flame.

Lifted-like flame

The initially formed luminous region of the Mg vapor jet in the CO_2 atmosphere could not propagate upstream due to high injection velocity of the lifted-like flame.

However, as Mg vapor is highly reactive, it reacts with CO_2 to form a chimney on the nozzle exit with a somewhat slow velocity region. Diffusion of the ambient CO_2 toward the inside of the chimney should be prevented because of the high injection velocity of the Mg vapor, resulting in an active reaction limited to the narrow region of the chimney rim. Thus, although the flame is initiated from the rim, the main part of the flame develops in the region far downstream from the rim due to the low reaction rate of Mg vapor with CO_2. This allows a sufficient amount of the ambient CO2 to enter the Mg vapor jet before the main flame reaction begins, leading to the lifted-like flame development. MgO(g) generated inside the flame condenses not only in the flame, but also at the boundary with the ambient, as shown in Fig.6(c). That the C composition of the lifted-like flame nearly coincided with that of the attached flame supports the assertion that C was generated by the same mechanism. The comparison between the lifted-like flame and the attached flame suggests that an essential factor which controls the combustion processes of the two types of the flames is the Mg vapor exit velocity through the chimney rim. In fact, the lifted-like flame was sometimes observed shifting to the attached flame when the chimney diameter increased.

Application to practical combustor

Our findings suggest that the Mg vapor burning technique has two significant problems. Firstly, there is the issue of how to effectively heat Mg and secondly, working fluid losses due to the accumulation of combustion products and unburned Mg on the chimney. To solve the former problem, a large amount of energy is required to heat Mg because Mg has a high vaporization heat (128 kJ/mol) in comparison to that of water (40.6 kJ/mol). The heat for cooling the Mg-CO2 combustor will only be available by using a regenerative cooling combustor with liquid Mg. To solve the latter problem, the chimney should always be removed and injected into the combustor to reuse as fuel and working fluid. If methods for the effective heating of Mg and the removing of the chimney can be developed, this flame technique will be useful in burning Mg completely and rapidly.

Conclusions

1. At low ambient pressures and high injection velocities of Mg vapor, a red-heated jet flame developed. It was characterized by spontaneous heating of active Mg vapor. Both the two other flames types, the lifted-like flame, which developed at middle

pressures and injection velocities, and the attached flame, which developed at higher pressures and lower injection velocities, had a chimney composed of combustion products that accumulated with time on the Mg vapor nozzle exit. At the rim of the chimney, exothermic reactions occurred. The lifted-like flame had a flame length property similar to laminar jet diffusion flames of gaseous fuels, but the attached flame did not.

2. The same reactions producing MgO(g) and CO, as well as the condensation of MgO(c), proceeded preferentially in all the flames and on the chimneys. Carbon was produced as a by-product.
3. The flame appearance and properties are determined by the injection velocity at the chimney rim and the activity of exothermic reactions of Mg vapor with diffused CO_2.

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TABLE CAPTIONS

Table 1. Combustion products of Mg vapor jet flames in CO_2 atmospheres.

FIGURE CAPTIONS

Fig.1. Schematic of experimental apparatus.

Fig.2. Time variation of Mg sample and burner nozzle exit temperatures. Without combustion at P_{amb} = 21 kPa.

Fig.3. Variation of Mg vapor injection velocity at burner nozzle exit with ambient pressure.

Fig.4. Flame appearances: (a) Red-heated jet flame at P_{amb} = 8 kPa, u_{jnz}=233 m/s, (b) Lifted-like flame at P_{amb}= 21 kPa, u_{jnz}=141 m/s and u_{jch}=35 m/s, (c) Attached flame at P_{amb} = 35 kPa, u_{jnz}=62 m/s and u_{jch}=4.1 m/s.

Fig.5. Base of an attached flame. P_{amb}=21 kPa, u_{jnz}=85 m/s and u_{jch}=3.7 m/s.

Fig.6. Filtered photographs of a lifted-like flame with binary coded processing: P_{amb}=21 kPa, u_{jnz}=130 m/s and u_{jch}=32 m/s.

Fig.7. Filtered photographs of an attached flame with binary coded processing: P_{amb} =35 kPa, u_{jnz}=103 m/s and u_{jch}=14 m/s.

Fig.8. Variation of flame length with corrected mass flow rate.

Lifted-like flame: P_{amb} =21 kPa, u_{jnz}=98-145 m/s, u_{jch}=18-49 m/s, and Re=124-182.

Fig.9. Schematic representation of Mg vapor jet flames revealed in this study.

Table 1. Combustion products of Mg vapor jet flames in CO_2 atmospheres.

Flame Type	Sample	Compositions (wt%)		
		MgO	Mg	C
Red-heated Jet Flame	Combustion Product	96.2	0	3.8
Lifted-like Flame	Thin Chimney	82.7	15.7	1.6
	Combustion Product	98.0	0	2.0
Attached Flame	Wide Chimney	85.9	12.9	1.2
	Combustion Product	97.9	0	2.1

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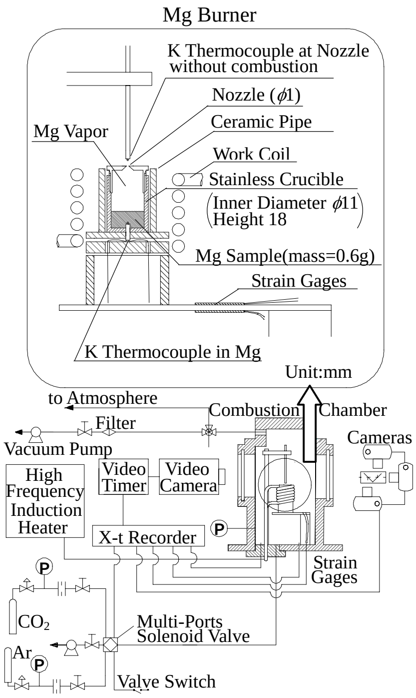

Fig.1. Schematic of experimental apparatus.

(90 + 10) x 2.2 + 5 = 225 words

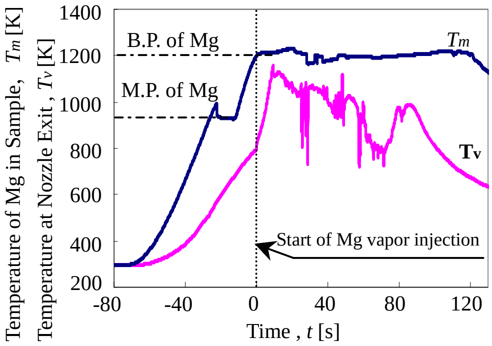

Fig.2. Time variation of Mg sample and burner nozzle exit temperatures. Without combustion at *Pamb*=21 kPa.

Color figure in electronic version only

(45 + 10) x 2.2 + 17 = 138 words

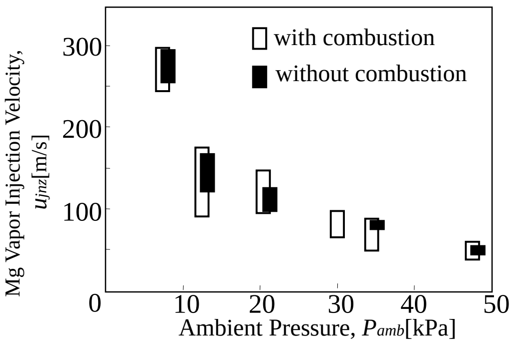

Fig.3. Variation of Mg vapor injection velocity

at burner nozzle exit with ambient pressure.

(45 + 10) x 2.2 + 14 = 135 words

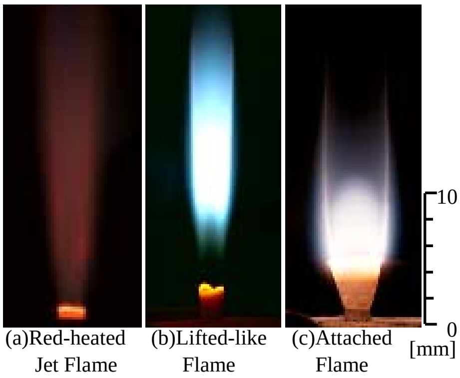

Fig.4. Flame appearances:
(a)*Red-heated Jet Flame* (P_{amb}= 8 kPa, u_{jnz}=233 m/s)
(b)*Lifted-like Flame* (P_{amb}=21 kPa, u_{jnz}=141 m/s, u_{jch} =35 m/s)
(c)*Attached Flame* (P_{amb}=35 kPa, u_{jnz}= 62 m/s, u_{jch} =4.1m/s)

Color figure in electronic version only

(49 + 10) x 2.2 + 39 = 168 words

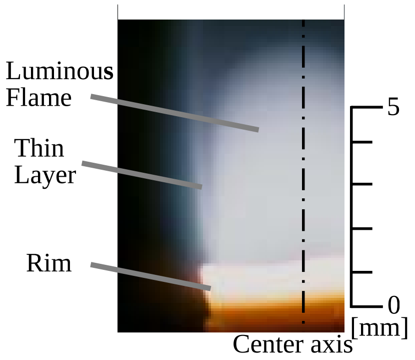

Fig.5. Base of an attached flame.
(P_{amb}=21 kPa, u_{jnz}=85 m/s, u_{jch}=3.7 m/s)

Color figure in electronic version only

(44 + 10) x 2.2 + 15 = 134 words

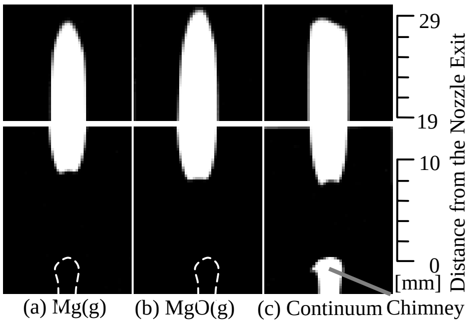

Fig.6. Filtered photographs of a *lifted-like* flame with binary coded processing. (P_{amb}=21 kPa, u_{jnz}=130 m/s, u_{jch}=32 m/s)

(42 + 10) x 2.2 + 21 = 135 words

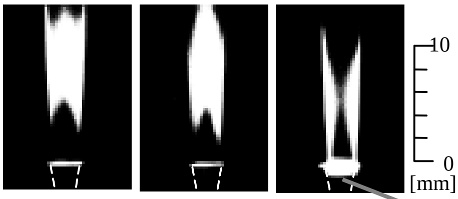

Fig.7. Filtered photographs of an *attached flame* with binary coded processing.
(P_{amb}=35 kPa, u_{jnz}=103 m/s, u_{jch}=14 m/s)

(28 + 10) x 2.2 + 20 = 104 words

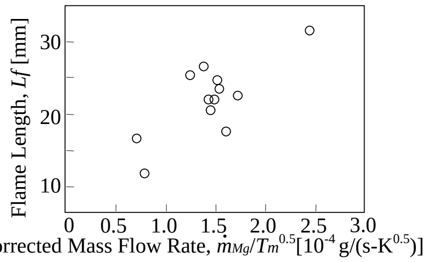

Fig.8. Variation of flame length with corrected mass flow rate: *Lifted-like Flame* (P_{amb}= 21 kPa, u_{jnz}=98-145 m/s, u_{jch}=18-49 m/s, Re=124-182)

(33 + 10) x 2.2 + 27 = 121 words

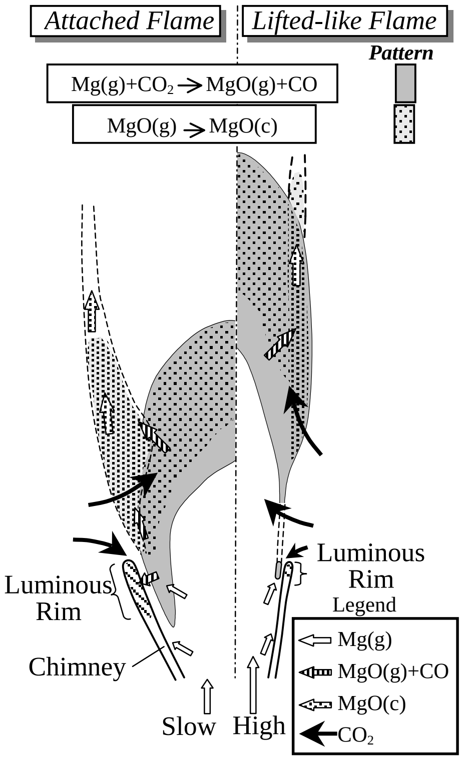

Fig.9. Schematic representation of Mg vapor jet flames revealed in this study.

(100 + 10) x 2.2 + 12 = 254 words