

Experimental Investigation of the Combustion of Organic-Gellant-Based Gel Fuel Droplets

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ABSTRACT

The phenomena involved in the combustion of two organic-gellant-based gelled fuels, one non-metallized and one metallized, were investigated. The non-metal part consisted by 15% organic gellant and 85% JP-8. A high-speed (up to 2,000 frames/sec) digital video camera was employed in the present study. The combustion characteristics of the organic-gellant-based gel fuels were found to be different from those of inorganic-gellant-based gels. In both the metallized and the non-metallized gel cases, a non-permeable elastic film, consisted mainly by the gellant, was formed around the droplet and prevented fuel evaporation. This produced an expanding vapor bubble in the droplet interior that resulted in significant swelling of the droplet. At a certain stage, the film was ruptured, allowing the fuel vapors to escape and it collapsed on the droplet surface. This process repeated itself until all combustible material was consumed.

Key Words: Gel, fuel, droplet, combustion.

Title shortened version: Combustion of Organic-Gellant-Based Gel Fuel Droplets

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INTRODUCTION

The demand for high-performance and improved safety propellants for various rocket motor applications has been constantly increasing during the last decades and gels seem to be a promising answer to these requirements. In this particular solid-liquid state, these propellants combine the advantages of the solids with those of liquids. A review on gel propellants that discusses all various issues on the subject was conducted by Natan and Rahimi (2001).

Gels are liquids whose rheological properties have been altered by the addition of certain gelling agents (gellants) and as a result their behavior resembles that of solids. Gel is defined by Brinker and Scherer (1990) as "a substance that contains a continuous solid skeleton enclosing a continuous liquid phase. The continuity of the solid structure gives elasticity to the gel."

Very little is known about the combustion characteristics of gels and the phenomena involved are not yet fully understood. The addition of the gelling agents may affect combustion in various ways. For example, Eldridge and Ferry (1954) indicate that the melting temperature of gelatin gels increases with gelatin concentration and both Harrison et al. (1974) and Tar (1974) show that heat of gelation varies with concentration of the co-solved substances in the gelling system.

Consequently, the heat of vaporization, which in droplet combustion is a rather significant parameter, is also affected.

Since the 50's, extensive theoretical and experimental work has been done in the field of liquid droplet evaporation and combustion to determine the fundamental mechanisms. Tests validated the theoretical d^2 -law (Spalding (1979), Williams (1985), Glassman (1996)) and a $p^{1/3}$ dependence of the burning time resulting from diffusion controlled combustion (Koboyasi (1954), Rosner (1967)). The effect of the gelling agent on the burning time can be taken into account through the heat of vaporization.

Nachmoni and Natan (2000) conducted an experimental study on the ignition and combustion characteristics of inorganic gellant, non-metallized, JP-5 based, gel fuels. In addition, calorimetric tests were conducted to evaluate the heat of vaporization of gels. Nachmoni and Natan (2000)

indicated that in general, gels obey the d^2 -law of diffusion-controlled combustion. The heat of vaporization of gels was found to increase with increasing gellant content in the liquid fuel and gels burned at lower burning rates than the pure liquid. In gels as in liquids, burning rate was found to increase with increasing oxygen mass fraction. The qualitative effects of the gellant content and the ambient pressure on ignition and combustion characteristics of non-metallized, inorganic gellant-based gels are presented in Table 1.

Significant work has been done on the combustion of metallized slurry droplets since the early 80's. Szekeley and Faeth (1982, 1983) and Sakai and Saito (1983) in their experimental studies showed that solid agglomerates are formed and they remain after vaporization of the liquid. Wong and Turns (1987, 1989) and Turns et al. (1987) found that these agglomerates are hollow, with a porous shell structure. Antaki (1986) presented a first theoretical model for the transient processes in a rigid slurry droplet during liquid vaporization and combustion. The model assumes that after an initial period in which part of the liquid evaporates, a continuously thickening rigid porous shell is formed around the slurry droplet. The outside diameter of this porous shell stays constant during burning while the inner diameter decreases cubically with time (d^3 -law model). Lee and Law (1991) indicated that since the total volume of the droplet is fixed by the rigid shell, the continuous depletion of the liquid due to evaporation must create a continuously expanding, vapor saturated space (bubble) within the slurry core interior to the shell.

Experiments conducted by Lee and Law (1991) using JP-10/carbon slurry, were found to be in good agreement with the theoretical model. At the first stage, the droplet burns like a pure JP-10 droplet and from the point of distortion the droplet size attains a nearly constant value until fragmentation is reached. Increasing the carbon particle content results in a lower initial burning rate and droplet distortion occurs earlier. The authors indicated that during the constant-diameter period, burning is disruptive. Disruption and jetting through the porous shell were also observed by Wong and Turns (1989). In a detailed theoretical study, Bhatia and Sirignano (1992) indicate that depending on the shell characteristics, different modes of liquid vaporization from the droplet can occur.

Mueller and Turns (1993, 1996) observed that depending on the aluminum loading within the gel/slurry droplet and the initial droplet diameter, the rigid shell can be ruptured due to the development of high pressure within the shell and a micro-explosion can take place. This results in a secondary atomization, which can significantly reduce propellant burnout distances, aluminum oxide residual size and radiation heat losses

Clausen et al. (1988) suggested introducing volatile additives into the slurry in order to intensify the micro-explosion and secondary atomization. Their experimental results indicate that the addition of 5% volatile miscible fuels to carbon slurry can substantially reduce the mean fragment size. Wong et al. (1990) investigated the effect of high molecular weight surfactants, which are added to disperse the particles and stabilize the fuel, on the disruption mechanism. Disruption was found to increase with increasing surfactant concentration.

Inorganic gellants contain materials that cannot burn, reducing the heat of combustion of the fuel. On the contrary, the use of an organic gellant is quite favorable from the energetic performance point of view.

The purpose of the present experimental study was to characterize qualitatively the combustion behavior of organic-gellant-based gel fuel droplets. In the first stage, the investigation was limited to droplet combustion under atmospheric pressure conditions.

EXPERIMENTAL APPARATUS AND PROCEDURE

Two gel fuels, one non-metallized and one metallized, were examined. The non-metal part consisted by 15% organic gellant and 85% JP-8. JP-8 is a kerosene-based fuel with boiling point temperature range of roughly 160-270 °C. The metallized gel included 55% boron. The gellant (Thixatrol 289) consisted by two parts, 50% high viscosity liquid (Methyl Isoamyl Ketone with boiling point temperature of 144 °C) that served as a solvent, and 50% organic solid particles that are the actual gellant (AG). The melting point of the AG was found to be ~40 °C and both its boiling point temperature and heat of vaporization are significantly higher than those of JP-8.

The droplet diameter size varied between 1-3.5 mm. Although such droplets are not expected to appear in a realistic motor combustion chamber, since even much smaller droplets burn in a diffusion controlled regime and the phenomena involved in the combustion process are the same, working with relatively large droplets is more convenient.

A schematic diagram of the experimental system is presented in Fig. 1. The experimental apparatus enabled a wide scope of single droplet combustion experiments using a variety of liquid and gel fuels, different ambient gaseous compositions and pressure levels higher than 100 bars. Within a pressure chamber, the droplet was suspended on a thin Pyrex wire by its surface tension or colloid forces. The droplet was ignited and the combustion process was video-photographed by a high-speed (up to 2,000 frames/sec) digital video camera through an optical glass window located at the side of the pressure chamber. The high speed allowed observation of very fast phenomena such as micro-explosions or droplet collapse.

Ignition was achieved by heating a platinum wire located below the droplet holder. The heat required for the droplet ignition is regulated by a DC electric power supply. The igniter operation time and the power input (0.3-2 kW) required for ignition varied with pressure and gel fuel kind. Ignition timing was computer controlled.

The image analysis system consisted of a Redlake Imaging MotionScope e/Cam 2000 SC color digital camera with magnifying lenses, a Pentium III computer and image analyzing software that enabled the investigation of the combustion process. The image analyzing system capabilities include computation of the burning rate of the fuel in real time and displaying the motion of a particle moving inside a droplet. The latter is very important when trying to detect viscosity changes within the droplet.

Due to the character of the gel, the droplets were not always spherical. A mean droplet diameter was calculated from the computed surface area of the droplet image. For an average droplet diameter of 1.5 mm, the accuracy of the mean droplet diameter measurement was $\pm 1 \mu$.

RESULTS AND DISCUSSION

Combustion of non-metallized gel droplets

The gelling agent that is used for the gelation of the liquid affects the structural nature of the gel. In general, inorganic gellants produce a rigid, stiff solid skeleton that captures the liquid and does not permit any movement inside. On the contrary to that, organic gellants produce gels of a different structure and character. When heated adequately, the gel ceases to exist as before and behaves more like a liquid mixture. Therefore, slow movement of small dirt particles planted into the droplet can be observed during burning.

At the beginning of the burning process, the droplet consists of a homogeneous, highly viscous liquid droplet and its burning can be classified as "classic" liquid droplet combustion with a distinct flame envelope that surrounds the droplet. The liquid consists of three major parts: 85% JP-8, 7.5% MIAK and 7.5% AG. Edwards (2002) indicates that JP-8 consists of many different constituents (18% aromatics, 35% naphthenes, 45% paraffins, 2% olefins) that each one has a different boiling point between 160-270 °C.

As droplet temperature rises, the first to evaporate is MIAK since its boiling point temperature is the lowest. The JP-8 compounds and AG evaporate at higher temperatures. The temperature inside the droplet reaches MIAK boiling point and stays constant. Turbulence inside the droplet is observed and internal mixing takes place. However, in comparison to liquid droplets, the turbulence intensity is low due to the high viscosity, therefore the mixing is very slow. Since homogeneity of the mixture cannot be maintained, the concentration of MIAK at the outer part of the droplet decreases continuously. At some point, a film of a very high viscosity AG is formed around the droplet enclosing the gel and the result is that neither MIAK nor any JP-8 compound cannot pass through the gellant layer and evaporate towards the flame.

This is similar to gels produced by inorganic gellants, nevertheless, there are several differences:

a. While in inorganic-gellant-based gels, the outside envelope is solid and "dry," like a wrinkled crust, in the organic-gellant-based gels, the envelope is liquid and uniform;

b. although the initial content of gellant in organic-gellant-based gels is higher than in the inorganic-gellant-based gels, the surrounding layer formation is much slower, probably because of the internal mixing during burning.

In any case, heating-up of the droplet results in the formation of a vapor bubble (MIAK at first and JP-8 compound afterwards) inside the droplet (Fig. 2a). According to the well-known model of bubble formation in a slurry fuel droplet, a rigid shell is formed around the droplet and there is pressure built-up that leads to shell disruption and droplet explosion. Contrary to that, in the organic-gellant-based gels, since the liquid layer is far from being rigid, expansion of the bubble results in significant swelling of the droplet while the pressure inside the bubble can remain approximately constant (Fig. 2b-d). Figure 2d shows the droplet when it reaches its maximum size. The thickness of the viscous gellant layer reduces as droplet expands until the film is ruptured producing a jet of fuel vapor. The envelope collapses back to the droplet and a new gellant layer is formed. This process repeats itself several times until the almost all-gellant residue-droplet burns completely. In a few extreme cases the bubble "explosion" resulted in a "blow-off" of the flame. This characteristic "periodic" burning is described in Figs. 3, 4 and 5. The droplet volume change with time is shown in Fig. 3. At first, MIAK evaporates and burns resulting in a volume decrease. As the first bubbles are produced (Fig. 2a), the droplet volume increases slowly (Fig. 3) and after approximately 0.7 s the inner pressure causes rupture of the surrounding layer and a fuel vapor jet leaves the droplet, resulting in an immediate decrease of the droplet volume. An examination of the ratio between the change in the droplet volume prior to the bubble "explosion" and the initial droplet volume (Fig. 4) shows that the first bubbles occupy approximately 40% of the original volume. The process goes on and at the final stages the bubbles form and grow quite fast, reaching an almost 1.8 times the droplet volume before the last expansion. Figure 5 demonstrates the droplet surface area change with time and indicates that while the early stage bubbles stretch the elastic gellant layer area by 25% until it ruptures, the later stage ones stretch the envelope by 100% of its original size.

The probable reason is that at the beginning the layer thickness is small and ruptures easily by the MIAK / JP-8 vapors. The vaporization of the JP-8 compounds causes the layer thickness to increase, increasing also its resistance. However, during burning, as JP-8 evaporates, the AG/JP-8 proportion changes. The boiling point of the mixture increases and also AG evaporates. Therefore, near the end of burning, the percent of AG vapors is high and the thickness of the AG layer decreases rapidly. This process is described schematically in Fig. 6.

In general, the formation of the highly viscous gellant layer that slows down diffusion of the liquid fuel to the droplet surface results in a low burning rate. In order to increase the droplet burning-rate, gellants with boiling point temperature and heat of vaporization very close to those of the liquid fuel are required.

Combustion of metallized gel droplets

It has to be noted that in these experiments boron is not expected to burn. Shortly after the beginning of burning, JP-8 from the outer part of the droplet evaporates, leaving accumulated metal particles and unburned gellant that form a layer. While in non-metallized gels there is some turbulence inside the droplet during combustion, in metallized gel droplets the high metal particle content diminishes the possibility of any movement. This results in unmixedness between the outer gellant layer and the internal gel. Actually this layer is a kind of elastic shell made of metal particles bonded together by the highly viscous gellant.

As previously, a JP-8 vapor bubble is formed inside the droplet. As burning goes on, the bubble expands and since the outer layer is elastic, the droplet expands too, while the layer thickness decreases. At some point, the outer layer is ruptured and collapses back to the droplet. Since the metal particle content is high, the remaining layer collapsing is halted by the closer particles. The whole process is asymmetrical and the droplet growth can occur in many different directions.

Every time a bubble is formed, metal particles are pushed towards the weakest point increasing the thickness of the layer, thus the layer break-up, vapor jetting and layer collapsing can occur in another part of the droplet.

Finally, after all JP-8 is consumed, the droplet does not expand anymore and the gellant starts burning inside a "sponge" shape unburned metal lump. This lump consists of metal particle agglomerates, stuck together leaving passages that lead to the droplet center and remains until the end when all the gellant burned out.

The burning time of the metallized gels is significantly higher, approximately 7 times longer than non-metallized gels. The size of the remaining metal lump is 1.5-2 times larger than the original droplet size. The burning process of metallized droplets can be seen in Figs. 7 and 8. Figure 7 exhibits the growth of a droplet, while Fig. 8 shows the growth and collapse (see the arrows) of the metal shell in a different droplet.

CONCLUSIONS

In the present study, the phenomena involved in the combustion of organic-gellant-based gel droplets were investigated.

In general, the burning characteristics of organic-gellant-based gels are different from those of the inorganic-gellant-based gels. In both metallized and non-metallized gel cases, the experiments indicate that a non-permeable elastic layer, consisted mainly by the gellant, is formed around the droplet and it prevents fuel evaporation. As a result, fuel vapor bubbles are formed inside the droplet and cause significant swelling. At a certain stage the layer is ruptured, the fuel vapors escape and the layer collapses. The process repeats itself periodically until all combustible material is consumed. The reason for this phenomenon is the difference between the boiling point temperature and the heat of vaporization between the organic gellant and the liquid fuel.

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Table 1

Ignition and Combustion Characteristics of Non-Metallized, Inorganic Gellant-Based Gels
(Nachmoni and Natan (2000))

	Increasing gellant content	Increasing ambient pressure
Ignition delay time	Increases	Decreases
Required heat input for ignition	Increases	Decreases
Droplet temperature	Increases	Increases
Burning rate	Decreases	Increases
Heat of vaporization	Increases	Decreases

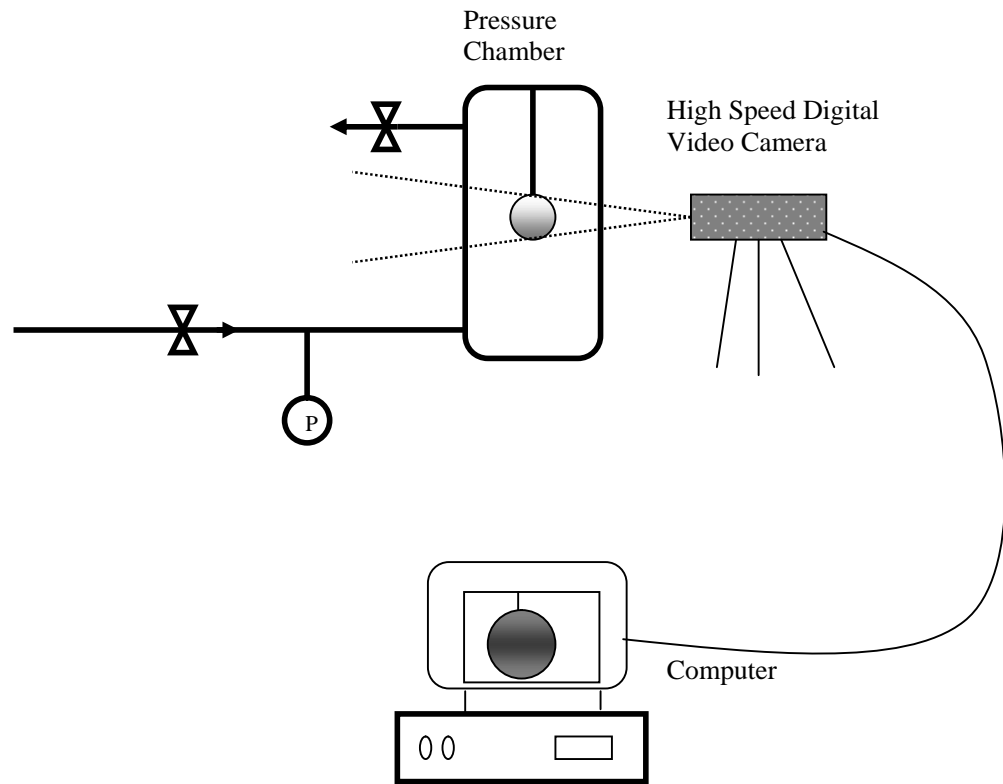
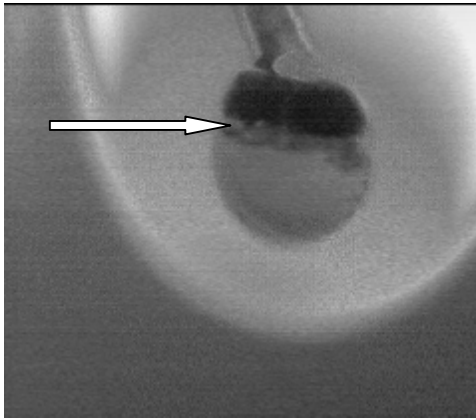
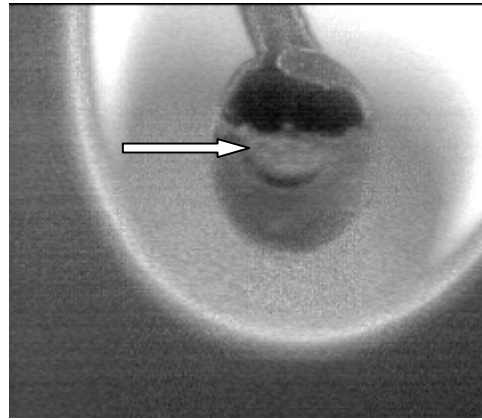


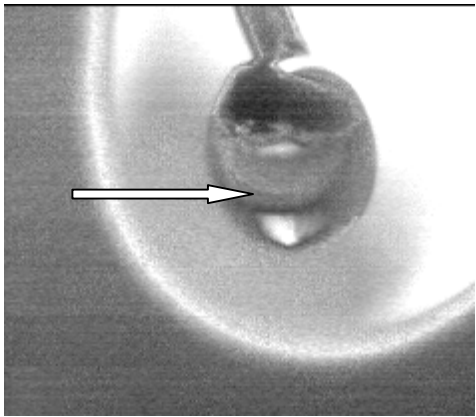
Figure 1. Experimental system.



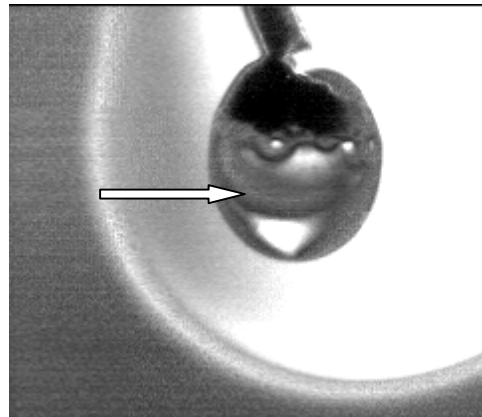
(a)



(b)



(c)



(d)

Figure 2. Combustion of a non-metallized droplet. Initial droplet diameter 1.5 mm. Scale: 1:16

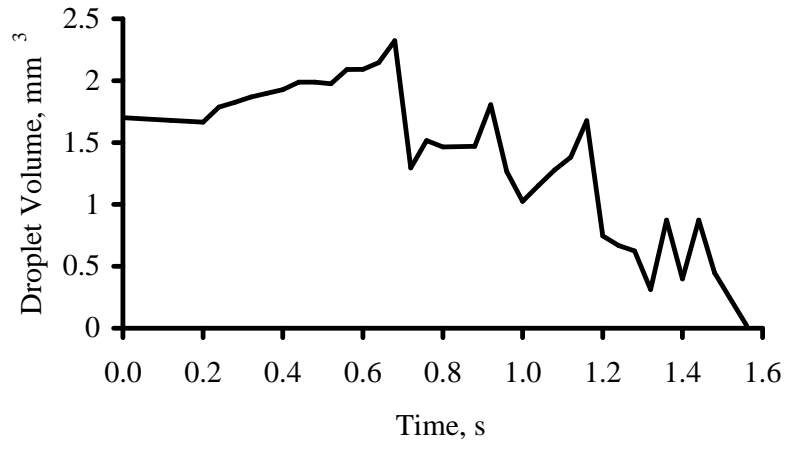


Figure 3. Droplet volume change with time.

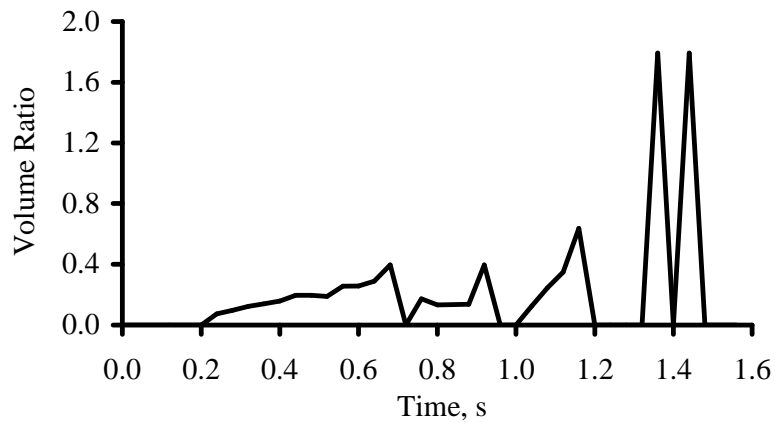


Figure 4. Ratio between the change of the droplet volume prior to the "explosion" and the initial droplet volume of each stage vs. time.

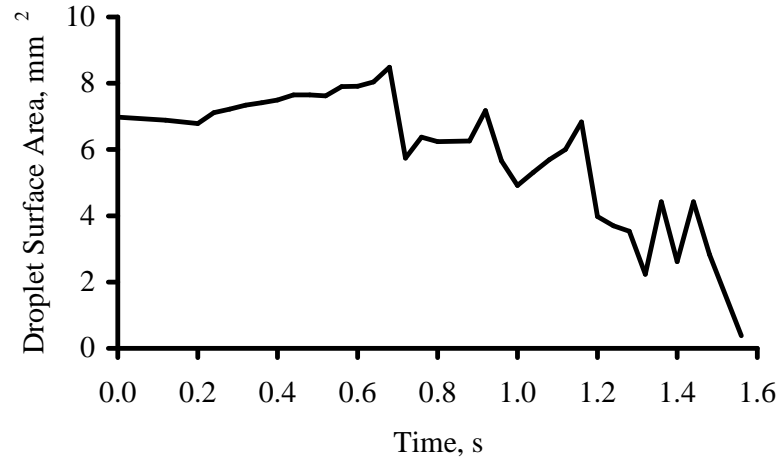


Figure 5. Droplet surface area change with time.

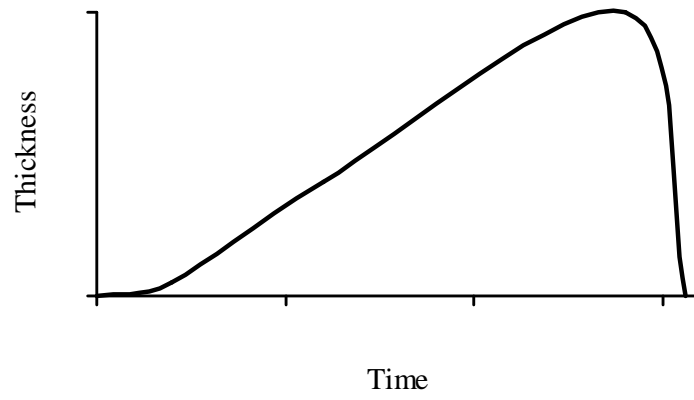
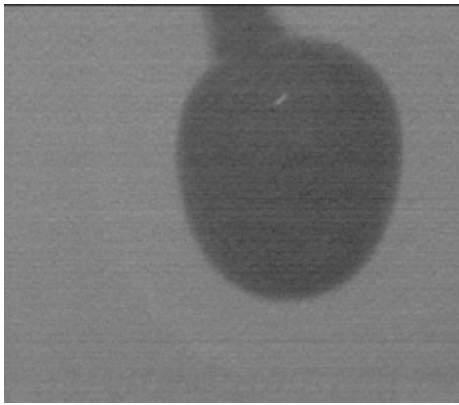
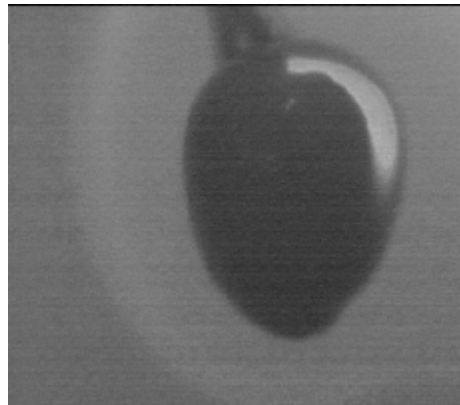


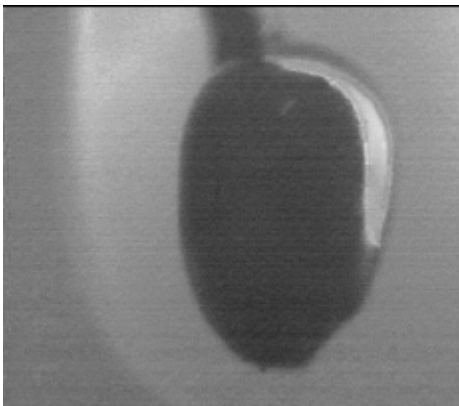
Figure 6. Schematic history of the gellant layer thickness.



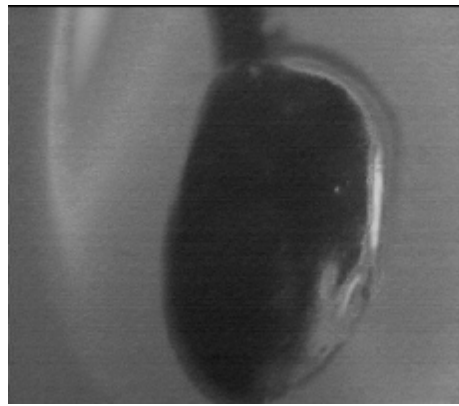
(a)



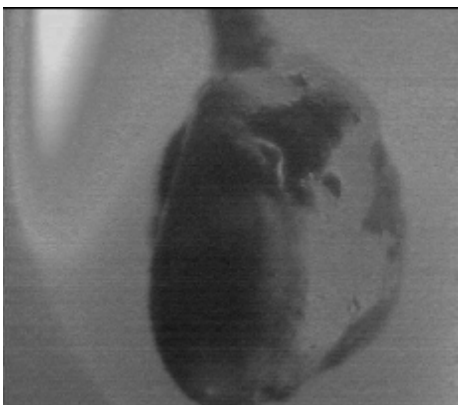
(b)



(c)



(d)



(e)



(f)

Figure 7. Metallized gel droplet burning.

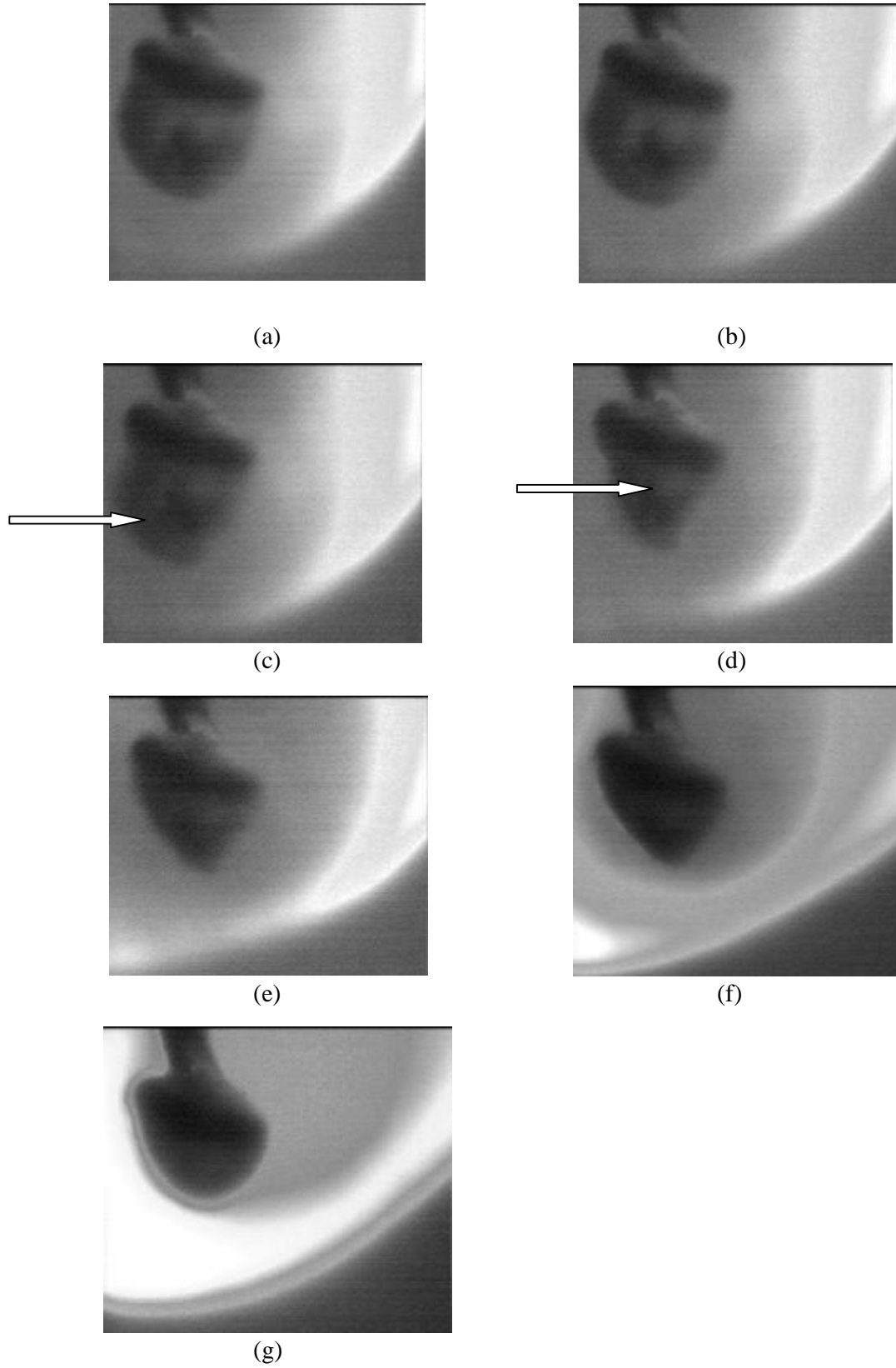


Figure 8. Metallized droplet combustion, swelling, jetting and collapse (speed: 250 frames/s).