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The flame propagations in the very first firing and subsequent cycles in an SI engine during cold start were studied to gain a better understanding of reaction fronts associated with liquid fuel (regular unleaded) in the cylinder. This work was performed using the Rutgers high-speed spectral infrared digital imaging system on a single-cylinder engine with optical access. The engine was mounted with a production engine head mated with a conventional port fuel injection (PFI) system.

In the study, four images in respective spectral bands were simultaneously obtained at successive instants of time, which was done for eight sequential cycles. This multiple-band successive-imaging was repeated in intervals of about two minutes over a period of more than twenty-five minutes after the engine start. During this experiment, the temperature changes at the intake port, the water jacket and the exhaust gas were monitored. In addition, pressure-time data was obtained from individual cycles in order to gain some insight into the overall in-cylinder reactions.

The first firing cycle exhibited almost invariably weak flame propagation, which was followed by very intense flame fronts in the next cycle. Note that the flame propagation in the first cycle seems to only indicate consumption of the fuel vapor available in the cycle. The flames in the third cycle were also intense in some cases, but mostly weaker than those in the second. Upon formation of the flame front in the beginning of combustion, some exceedingly strong local reactions started to grow, but no earlier than 15CA after TDC. The reactions appeared to be diffusion reaction fronts around liquid fuel layered over the chamber surfaces. The scale of these local reaction zones decreased with time and exhibited some significant transient changes. This variation continued to occur even though the engine was relatively well warmed.

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**Abstract**

The flame propagations in the very first firing and subsequent cycles in an SI engine during cold start were studied to gain a better understanding of reaction fronts associated with liquid fuel (regular unleaded) in the cylinder. This work was performed using the Rutgers high-speed spectral infrared digital imaging system on a single-cylinder engine with optical access. The engine was mounted with a production engine cylinder-head mated with a conventional port fuel injection (PFI) system.

In the study, four images in respective spectral bands were simultaneously obtained at successive instants of time during the combustion period, which was done for eight sequential cycles. This multiple-band successive-imaging was repeated in intervals of about two minutes over a period of more than twenty-five minutes after the engine start. During this experiment, the temperature changes at the intake port, the water jacket and the exhaust gas were monitored. In addition, pressure-time data was obtained from individual cycles in order to gain some insight into the overall in-cylinder reactions. Note that the fuel rate by the PFI for the first set of successive images was about 3.5 times stoichiometric and that for others was near-stoichiometric.

The first firing cycle exhibited almost invariably weak flame propagation, which was followed by very intense flame fronts in the next cycle. Note that the flame propagation in the first cycle seems to only indicate consumption of the fuel vapor available in the cycle. The flames in the third cycle were also intense in some cases, but mostly weaker than those in the second. Upon formation of the flame front in the beginning of combustion, some exceedingly strong local reactions started to grow, but no earlier than 15CA after TDC. The reactions appeared to be diffusion reaction fronts around liquid fuel layered over the chamber surfaces. The scale of these local reaction zones decreased with time and exhibited some significant transient changes. This variation continued to occur even though the engine was relatively well warmed. Results from some parametric studies are also reported.

**Introduction**

The large amount of unburned hydrocarbon (UHC) emitted by spark ignition (SI) engines during cold start basically stems from the fact that the liquid fuel introduced into the engine is poorly vaporized. Because of the fuel's low vapor pressure at this time, extra fuel is injected into the engine in order to produce enough vapor to achieve successful development of the flame propagation (with the throttle valve closed). This extra fuel causes accordingly large amounts of liquid fuel layered at the intake port and in the combustion chamber.

Let's consider what may occur during cold start in a typical modern SI engine with a conventional port injection fuel system (PIF). The present discussion concerns reactions during two different time periods from the start: They are: (1) the first period of several seconds, and (2) the early period before attaining a well warmed engine condition. The former is of interest because, in a typical modern SI engine, the over-rich fuel injection ceases immediately after the start. The latter is separately discussed because, during the warm up period, the in-cylinder formation of UHC continues to be high even with the mixture near stoichiometric.

**Engine Operation with Extra Fuel.** The very first fuel injected, although in an amount sufficient to produce a rich mixture of several times the stoichiometric, will probably not be connected to an immediate flame propagation, but will mostly wet the intake port and the combustion chamber surface. With no ignition occurring in this cycle, both a great amount of fuel vapor and probably even some liquid fuel would be wasted "raw" to the exhaust. In the next cycle, the fuel at the intake port will be added by the next fuel delivery to form a thicker liquid layer of fuel and an increased amount of vapor. When the intake valve opens, more fuel from this accumulation will be combined with the trapped fuel (in the cylinder from the previous cycle), which will also produce thicker layers of liquid fuel over the chamber surface and, of course, an increased amount of vapor. In spite of this, the cycle may not achieve a flame propagation either, and then the same will be repeated. The process involving wasting and accumulation of the fuel will continue until a sufficiently rich vapor-air mixture is produced near the spark plug for a successful fire ball formation. Even the first firing cycle may not be followed by the same, and then the above process will be repeated as before. The number and mode of such unsuccessful cycles during the start will depend on various factors, e.g. the amount of fuel injection per cycle; fuel distillation characteristics; temperature of the cold start; amount of the residual fuel trapped in the cylinder and the intake port after the previous engine operation. Note that the last is affected by the piston locations, the time period after the previous engine operation, and more.

The combustion, then, will produce the first hot (rushing) back-flow of combustion products, which will alter the thermal condition and fluid flows at the intake port to increase the atomization and vaporization of the liquid fuel deposit. The combustion will also change the transport process over the liquid fuel layers in the cylinder, which increases vapor formation and decreases the amount of liquid fuel loaded over the surface. The waste gas at this time is expected to contain a greater portion of incomplete combustion products for several reasons. For example, there will be over-rich diffusion flame fronts off the liquid layer, and fuel vapor leaving the layer (after the reaction fronts disappear) will not be well oxidized. Note that since the combustion chamber surface is at low temperatures, the wall quenching effects will be highly significant. In addition, the UHC diffused out of the quenched layer will be poorly consumed by the bulk combustion products. Such strong quenching effects and poor post-flame oxidation, plus the raw fuel mentioned above, will become main sources of the engine-out UHC during the cold start. The high complexity of the formation processes may be further realized as considered in the following.

In order to minimize the amount of UHC during this period, several possible injection strategies may be implemented in the very early cycles. As one such strategy, a minimum amount of fuel may be injected to produce a lean vapor-air mixture for a marginal ignition followed by a completing flame propagation, or a large amount of fuel could be injected to produce a near-stoichiometric vapor-air mixture. The first flame propagation by the former strategy is expected to be weak but leave a small amount of unconsumed liquid fuel over the chamber surface. Such a weak (lean-mixture) flame would be subjected to strong quenching effects to cause more incomplete products, but the small amount of liquid fuel is expected to produce less over-rich diffusion reactions and a smaller amount of wasteful fuel vapor before the exhaust-valve-open (EVO). The first flame by the latter method, if properly achieved in a well controlled manner, which depends on the cold start temperature, fuel characteristics and others, will be strong to help the engine to attain a high temperature sooner. This strategy will need fewer cycles of operation than the former before attaining a high temperature, which will additionally bring beneficial aspects such as an active post flame oxidation, but leaves a larger amount of liquid fuel over the surface, a negative factor in achieving low UHC emissions. Regardless of strategies, there will be a significant amount of liquid fuel deposit over the surfaces causing UHC, which would exhibit severe transient and cyclic variations.

The variations would be dependent on the amount of extra fuel, the temperature of the cold start, the engine speed (and change) and more. The massive amount of liquid fuel layers formed over the surface during the cold start may be disposed of in several routes, including: (1) consumed in the following cycles; (2) washed down to the crankcase; (3) vaporized (in the absence of reaction fronts) and wasted during EVO; and (4) carbonized over or within the deposit formation. It is desirable to obtain a better understanding of such in-cylinder events during this over-rich combustion period, particularly the flames (of consuming fuel vapor) and (diffusion) reactions over the liquid layers. In order to minimize negative consequences on not only the UHC but also on others as considered above, a delicate compromise will have to be made among various factors for the PFI control strategy in a prompt manner during the transient period.

The present discussion also is concerned with the number of cycles from the start when the over-rich fuel injection is taken off and a near-stoichiometric mixture is provided. It's importance can be seen from the fact that if the fuel is fully vaporized (upon the over rich injection of several times an amount of fuel in a near stoichiometric mixture) the mixture will be simply too rich to ignite. As the combustion cycle continues, the engine temperature rises to promote the vaporization of the fuel at both the intake port and in the combustion chamber. With the mixture preparation shifted to near stoichiometric, sooner or later, the catalytic converter becomes lit up.

**Liquid Layers during the Warm-up Period.** When the engine attains a warm condition, the fuel introduced for producing a near stoichiometric mixture may be well vaporized achieving predictable flame propagations. However, only recently, some new evidence came to light suggesting that the regular unleaded gasoline at ignition may not be well vaporized in the combustion chamber even after the engine is relatively well warmed. This poor vaporization may be a significant source of UHC emissions [1]*. This study reports a new discovery of locally reacting centers in the combustion chamber, in which successive images were captured by using our high-speed multispectral IR imaging system. Note that when the engine was warm, these local reactions were mainly found around the intake valve and that they were not found when the same engine was operated by gaseous fuels (namely propane and natural gas). In addition, when the engine was started at room temperature, reaction centers were found at multiple locations, even including the exhaust valve and spark plug. Also, there is some observation suggesting that the formation of local reaction centers may be affected by the distillation characteristics of fuel.

The above observation of local reaction centers, which were considered to occur due to liquid layers formed

*Numbers in parentheses designate references at end of paper.

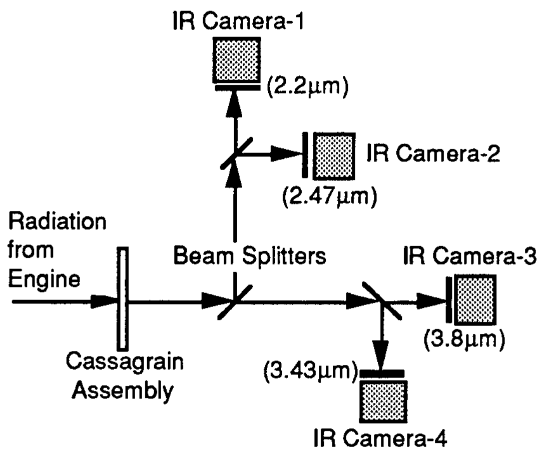



Fig. 1. Schematic Presentation of Rutgers SIS.

over the cylinder head during the intake period, may not be surprising in view that many research individuals report liquid fuel layers or puddles observed at the intake port (in warm SI engines). In addition, the local reaction centers, according to the above study, remain initially a surface phenomenon, which later become a volume phenomenon, i.e., around 70 after top-dead-center (ATDC). The radiation from the local centers was similar to that expected in diffusion flames. Note that an SI engine operated by a gaseous fuel, which did not exhibit any sign of local reactions, produces much lower engine-out UHC than the same engine fueled by regular gasoline. As to the phase of fuel in the mixture when it rushes through the intake port, it is actually desirable to have it only partially vaporized in order to achieve a high brake mean effective pressure (bmep). If, instead, an SI engine is designed to achieve a nearly full vaporization of the fuel at this time, at the expense of bmep, (for example, by excessively heating the port) the liquid fuel layer in a cylinder may not be formed. After finding this liquid burning, a strong need for obtaining better understanding of the phenomenon associated with many issues was pronounced, such as its transient variation and effects of engine-fuel factors.

If the formation of liquid layers is significantly responsible for UHC even in a warm SI engine, it should be reasonable to infer that the same would be a main process of the engine-out UHC during the remaining warm-up period after the over-rich fuel injection ceases at the intake port. It is desirable to investigate the behaviors of flames and diffusion reactions over the liquid layers during this transient period, while the engine is run by a near stoichiometric mixture.

## Experiment

Since the present investigation was performed based on findings from the earlier work [1], the same apparatus were used. They include (1) high-speed multispectral IR imaging system and (2) SI engine with optical access, which will be only briefly described here. More details of these apparatus may be found elsewhere [1-3].

**Table-I. Engine Dimensions**

| | |
|---|---|
| Bore x Stroke (mm), | 101.6 x 101.6 |
| Compression Ratio, | 9:1 |
| Spark Ignition, | 6 BTDC |
| Valve Timing: | |
| EVO | 135 ATDC |
| EVC | 10 ATDC |
| IVO | 10 BTDC |
| IVC | 135 BTDC |
| Fuel Rail Pressure | 200 kPa |

**Multispectral IR Imaging System.** This is a one-of-a-kind system designed and fabricated at Rutgers University, which is referred to as the Rutgers System or Super Imaging System (SIS). As shown in Fig. 1, this SIS has four high-speed IR digital camera units connected to a single optical train. The radiation passing through the optical access of the engine is collected by a cassegrain assembly consisting of two reflective mirrors, and is then relayed through three different spectral beam splitters. This arrangement produces four geometrically identical (pixel-to-pixel matching) images in respective spectral domains. A narrow-band filter installed in front of each camera further specifies, within the corresponding domain, the spectral nature of the image for the camera.

Some of the performance features of the SIS having Pt-Si imagers (64x128 pixels each) are: imaging rate over 1,800frames/sec per camera; independently variable exposure period as short as 20μsec; spectral range of 1.5-5.5μm; and total 256 images to be captured (in each experiment) per camera. The cameras in the SIS are simultaneously operated according to the predetermined setting, including: the exposure period; the total number of images to be obtained per cycle; the start of imaging (in crank angle, CA) with respect to a reference marker (here top-dead-center, TDC); the interval between successive images in CA.

Four spectrally distinct images simultaneously obtained by the SIS at successive instants of time implies that, ideally, distributions of four different pieces of information may be obtained at the CA of imaging, such as temperature, and concentrations of water vapor and soot. While new data processing methods for achieving such quantitative imaging are being developed at Rutgers, it was found that raw images produced by the SIS permit us to collect new pieces of in-cylinder information, which are difficult to obtain using conventional diagnostic devices. Some of them are reported here.

**Engine Apparatus.** The apparatus was built on a single-cylinder engine base by mounting a new Ford 302 cylinder head and a matching port-injection fuel system (PIF). Construction of the set-up was performed in an attempt to preserve the representative characteristics of the real-world SI engines. Figure 2 shows the arrangement of the optical access in the engine. Since an in-depth description was made in previous papers, some relevant engine information is summarized in Table-I.

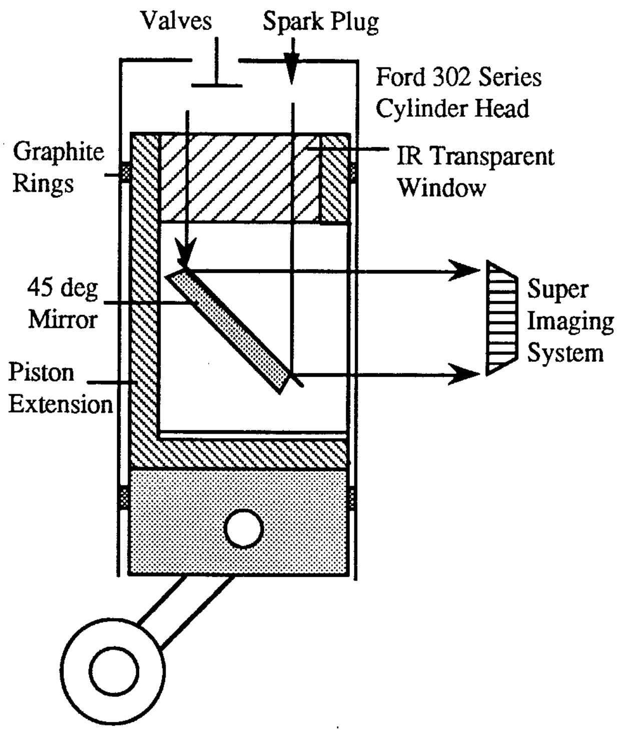



Fig. 2. Spark-Ignition Engine with Optical Access.

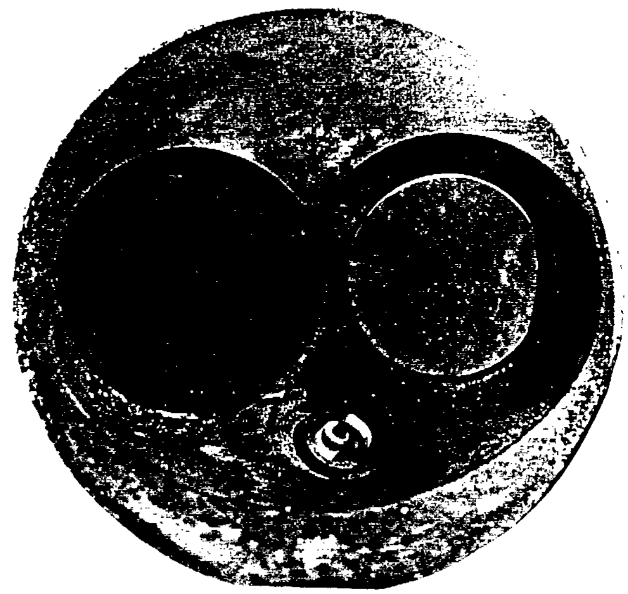


Fig. 3. A Visible-Ray Photograph of the Cylinder Head Exhibiting the Imaging View.

The engine apparatus was sufficiently instrumented in order to obtain consistent results from the experiment. Particularly to monitor the thermal condition of the intake port, thermocouples were installed where deemed appropriate. In addition, cylinder pressure-time (p-t) history was recorded for the corresponding sets of instantaneous images. This was achieved by synchronizing both pressure-time data acquisition and imaging to the same engine encoder.

Figure 3 is included here in order to indicate the imaging view, which shows the intake valve on the left, the exhaust valve on the right and the spark plug in between. This figure will be referred to when the instantaneous spectral images are presented later.

**Results and Discussion**

The main results from the study are a set of four separate spectral IR digital images simultaneously taken at successive instants of time during the combustion period. This high-speed imaging from a cold engine was done by starting from the very first cycle until the engine was fully warmed up with the intake manifold vacuum maintained at 24kPa. While the imaging was performed, the corresponding pressure-time data was obtained to gain some idea of the overall combustion condition. Temperature changes at the intake-port, the water-jacket (the cylinder heat) and the exhaust gas were recorded. The experiment was performed by using regular unleaded gasoline with ignition time at 6BTDC.

In each imaging, four sets (in spectral bands of 2.2, 2.47, 3.43 and 3.8μm) of thirty-two digital images per cycle, were simultaneously obtained from eight successive cycles, which filled up the memory in the SIS (over four megabytes in 12 bit dynamic resolution). Note that, in a separate run, the imaging was also carried out by obtaining (in each spectral band) eight images per cycle from 32 sequential cycles. In yet another experiment, the same was made to obtain a single image per cycle at 35 ATDC from 256 consecutive cycles. These data were transferred to hard drive to free the SIS memory for the next imaging, a process which typically took about two minutes. That is, in this experiment, such a batch of images was repeatedly obtained in about two-mimute intervals during the warm-up period.

The imaging of combustion events during the cold start was done in two steps in sequence: (1) over-rich mixture imaging; and (2) stoichiometric mixture imaging. In the first step, after the engine was motored to attain a speed of 350rpm. The injection started in an amount of about 3.5times that of a stoichiometric mixture, which seemed to produce a satisfactory start. Note that when a smaller amount of fuel was injected, the first successful firing cycle was not always followed by the same. The SIS was synchronized to capture images from the very first firing and subsequent cycles, which took only a few seconds and were immediately followed by a fuel-injection-rate change to provide a stoichiometric mixture. At this time, the external load was engaged on the engine in such a way that the speed did not exceed 500rpm. As soon as the SIS was ready again for imaging after transferring the first batch of images, the second batch was obtained in the same way using a stoichiometric mixture at constant engine speed of 500rpm.

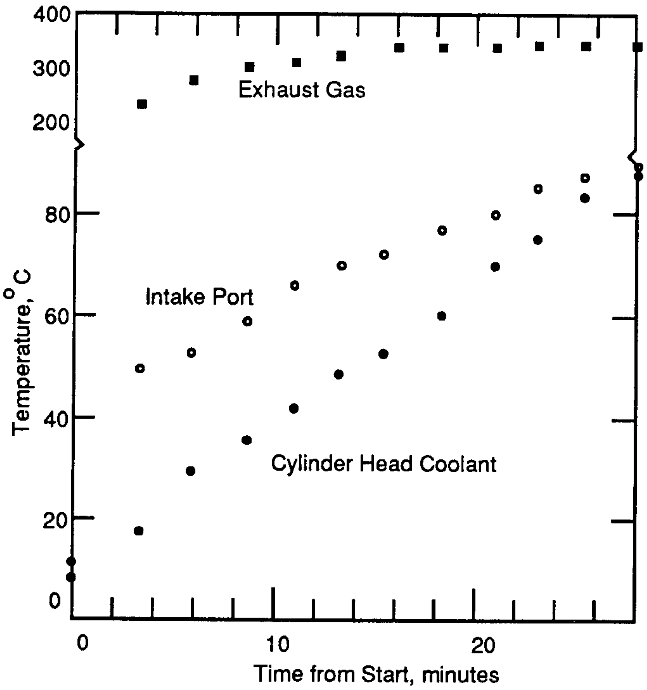



Fig. 4. Temperature-time Data at each Imaging.

Figure 4 summarizes the typical sequence of imaging and temperature measurements in the engine, which, although self-explanatory, still deserves some attention. During the warming period, the temperature at the intake port is consistently higher than at the cylinder head coolant, which is caused by the back-flow of the combustion products. As soon as the imaging from the over-rich starting was done, the heater in the coolant loop was turned on for a while in order to shorten the warm-up period. In this experiment, when the measured temperature at the coolant outlet was near 90°C, the coolant was almost boiling, which may be a condition a bit more over-heated than in a typical engine operation.

It should be added that the engine running for such a long period of time produced a layer of deposit over the optical window, which would have been impossible for visible ray to pass through. But the quality of spectral IR images in the present experiment did not appear to be significantly degraded by the deposit.

A large number of imaging trials were performed. Typical sets of spectral IR images obtained from the very first firing and the following seven cycles are presented in Fig. 5 (A) 3.43µm and (B) 3.8µm. The results obtained thereafter in about two-minute intervals are shown in Fig. 6 by indicating the start time of imaging. They are displayed in pseudo-color in order to enhance the presentation of more local variations. Those images in the former band were expected to indicate radiation from mainly water vapor (and soot if formed), exhibiting the consumption of fuel vapor. Note that this band was also observed to capture radiation from some intermediate species in the preignition zone [1,2]. Since the latter band is transparent to radiation from main combustion products including water vapor and carbon dioxide, it was considered to mostly exhibit those from the cylinder head surface, and since the soot formation was

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | -5 | TDC | 5 | 10 | 15 | 20 | 25 | 30 |
| 2 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 |
| 3 | 75 | 80 | 85 | 90 | 95 | 100 | 105 | 110 |
| | a | b | c | d | e | f | g | h |

Fig. 7. Look-up-table indicating the Time of Imaging.

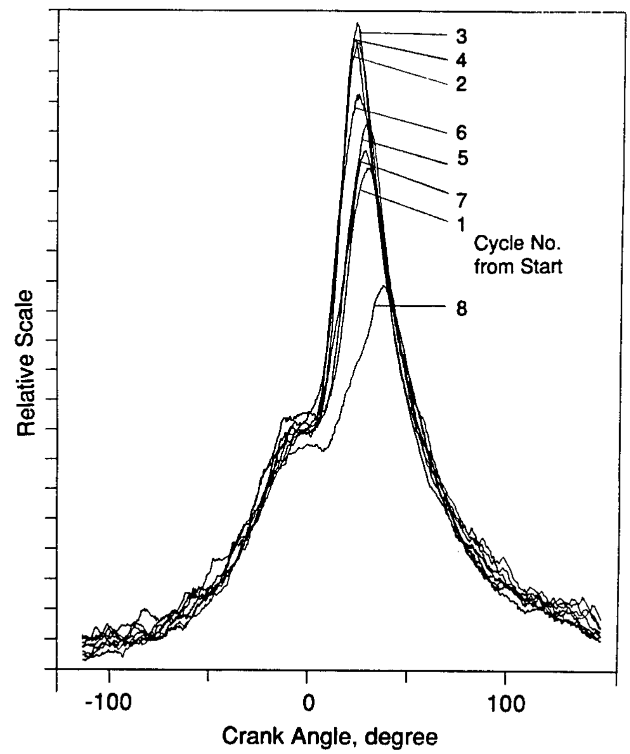



Fig. 8. Pressure-time Recorded in Early Cycles.

expected in very rich or diffusion reactions, it would be also reflected by the results in this band. The sequence of images captured in a 5CA intervals is from the left to the right and goes downward, like in a calendar. In order to indicate the individual times of imaging in CA, a look-up table (LUT) for the images is included in Fig. 7. In addition, Fig. 8 displays the pressure-time (p-t) histories to match with respective imaging cycles.

While in-cylinder events with the over-rich fuel injection (Fig. 5) were meaningful even after 110CA ATDC, as indicated by 3-h of Fig. 7, those with a near-stoichiometric mixture (Fig. 6) did not show such after 70ATDC, as included in the results. Because of the difference in strength of the radiation, imaging was made with the exposure period set to 170µsec for those with the over-rich fuel, and 310µsec for the near-stoichiometric mixture.

**Over-Rich Mixture for Start.** Discussing the results from the over-rich starting, the images of flame propagation (via 3.43µm) in the very first firing cycle are

Cycle-1

Cycle-2

Cycle-3

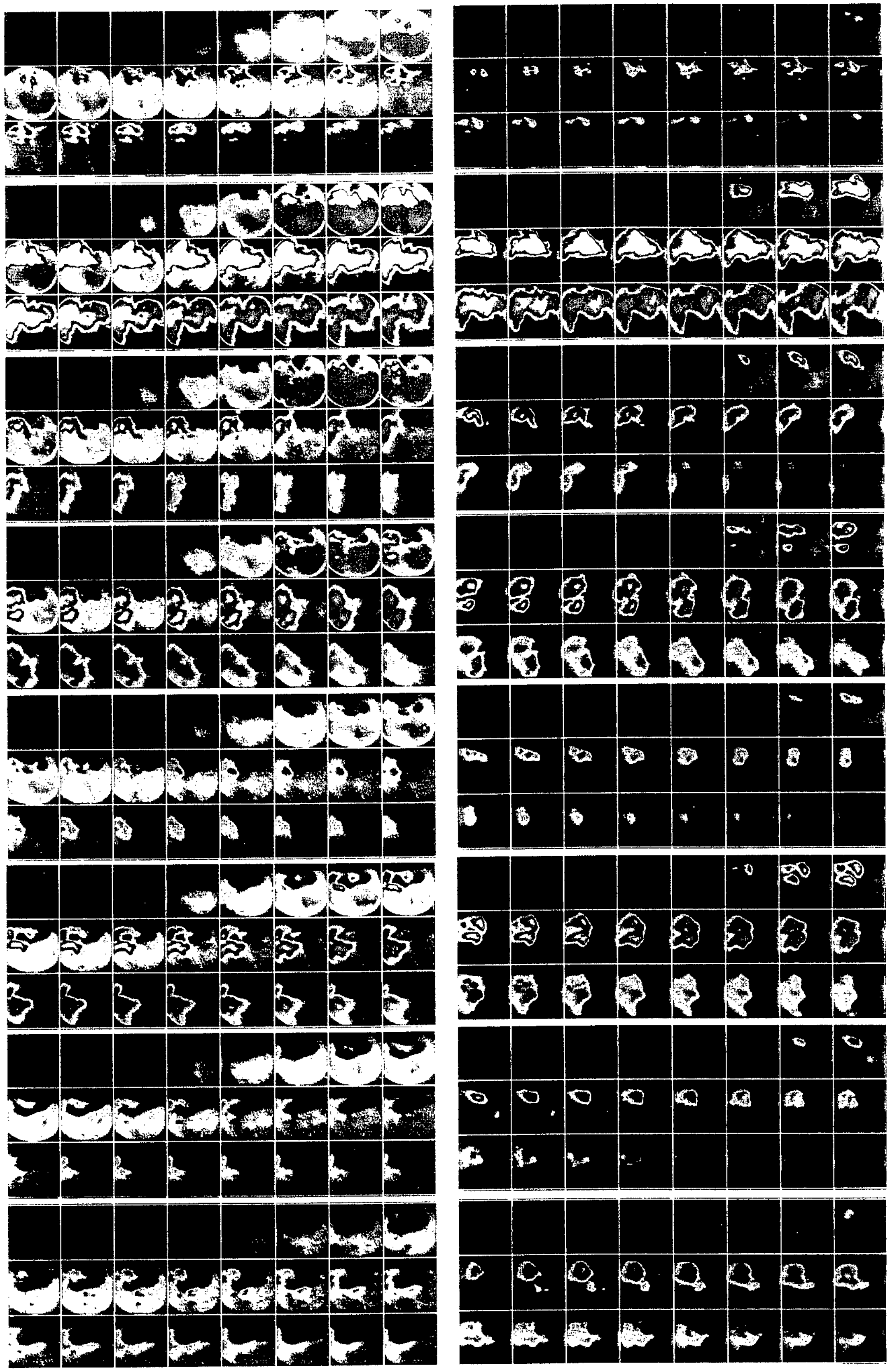
Cycle-4

Cycle-5

Cycle-6

Cyclle-7

Cycle-8



(A) (B)

Fig. 5. High-speed Spectral IR Images Obtained at First Eight Sequential Cycles from Start via Bands of: (A) 3.43mm; and (B) 3.8mm.

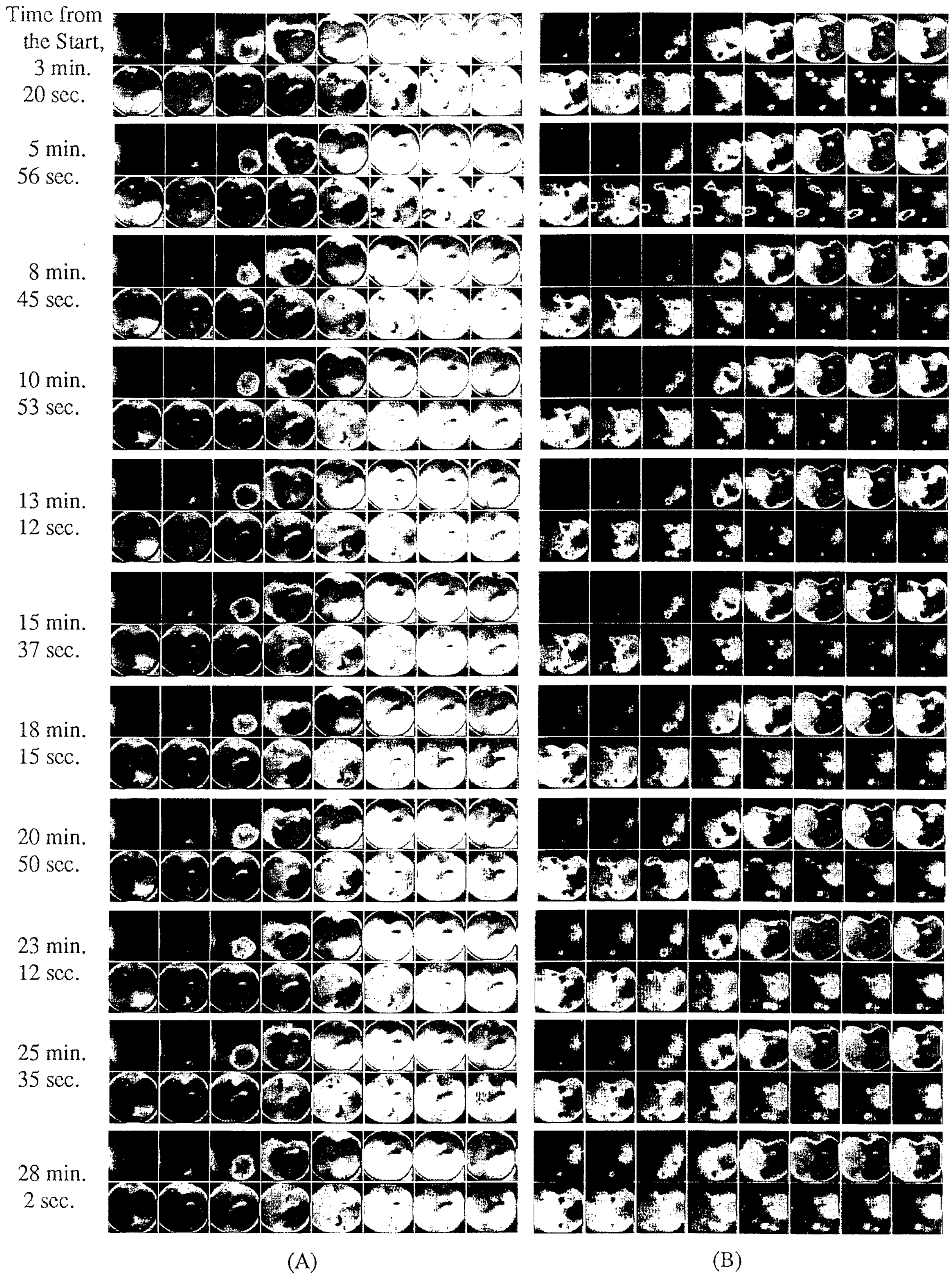



Fig. 6. High-speed Spectral IR Images Obtained during the Warm-up Period via Bands of: (A) 3.43mm; and (B) 3.8mm.

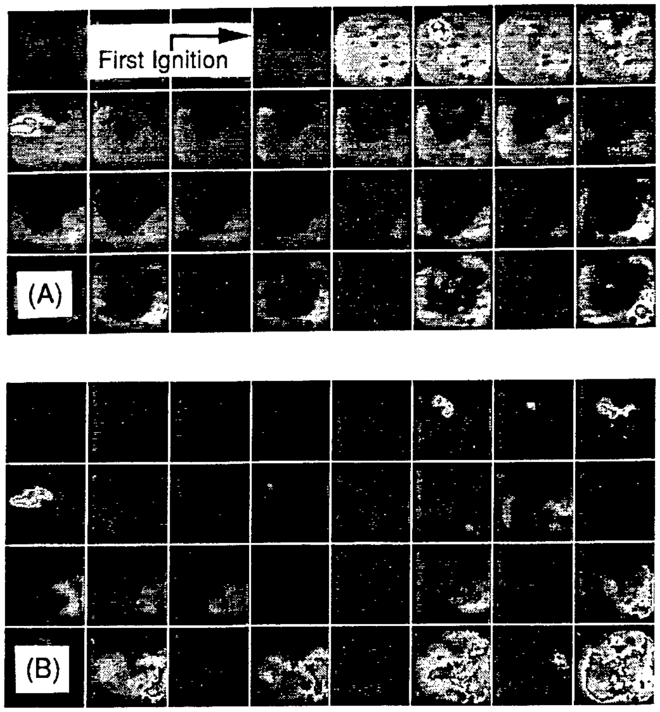



Fig. 9. Images obtained from Successive Cycles: One per cycle at 35CA ATDC: (A) 3.43μm and (B) 3.8μm.

relatively weak (Fig. 5-(A)). This fact seems to suggest that a relatively small amount of vapor was produced prior to ignition in the cycle. This weak flame front, however, became somewhat intense at the later stage of combustion in the cycle, exhibiting a sluggish consumption of fuel, which can be also seen from the p-t history (Fig. 8). Although the actual amount of accumulated fuel in the cylinder prior to the ignition is expected to be large, the energy release in the first cycle is small, which suggests that the unused fuel was either layered over the surface or partially lost (e.g. via wash-down). It is noted that, in the first ignition cycle, the flame fronts are observed over the entire imaging view of the chamber, which suggests that the fuel vapor was accumulated in the zone during the previous (no-ignition) cycles. This is in contrast with the following cycles having zones without emitting any significant mount of radiation by combustion products, particularly near the squish area. The radiation in 3.8μm (Fig.5-(B)), which is expected to reveal radiation from soot indicating diffusion reactions, is also rather insignificant, which indicates possibilities either that the amount of liquid fuel layered over the surface was small or that the flame was too weak (due to low temperatures) to produce a strong diffusion reaction.

The flame propagations in the 2nd, 3rd and 4th cycles are more intense and exhibit a remarkable difference in strength, i.e., it is extremely intense in 2nd and comparably weak in 3rd and 4th cycles. (In some trials, the difference of intensity between these cycles was small.) The radiation intensity, however, does not seem to properly represent the heat release according to the corresponding p-t data. That is, in spite of the remarkable difference in radiation among these cycles, which is most notably strong in the 2nd cycle, their p-t data look about the same. While the intensities of the flame propagations (via 3.43μm band) are somewhat weak but yet continue to be similar to each other, the radiation via 3.8μm (from a high soot formation to reflect rich diffusion reactions) became strong in 4th cycle, which was followed by weak radiation in 5th cycle. Such a cyclically varying mode of diffusion reactions repeated in the remaining cycles in the over-rich operation. It is noted that in some cases, two consecutive cycles exhibited strong radiation, followed by weak radiation and so forth, and vice versa. During these early cycles, the local diffusion reactions started to grow after 15-20ATDC, which is at least a period of 20CA after the flame fronts started. This time interval appears to represent the heating period required for the liquid fuel layered over the surface to commence/support the local diffusion reactions, which continues in an increasing intensity even long after the flame fronts disappeared. The continuing local (diffusion) reactions in the absence of flame fronts is further discussed later.

The p-t data indicates that the combustion started to deteriorate after the 5th cycle, which also seems to be reflected by the imaging results. The p-t data from the 8th cycle is particularly suggestive of what has been mentioned earlier, i.e., the vapor formation becomes sufficient enough within several cycles, and thereafter the vapor-air mixture becomes too rich to burn. In order to confirm this observation, an additional experiment was performed: One image per cycle was obtained in each band at the same CA (i.e., 35ATDC) from 256 successive cycles, but those from the first 32 cycles are displayed here (Fig. 9). It is clear that beyond several cycles after the start, the over-rich operation was no longer useful in achieving satisfactory flame propagation. This supports a fuel injection strategy of switching off the over-rich mixture within a few or several cycles from the start. The results also suggest that it would be meaningless to obtain images from over-rich cycles other than those already included in Fig. 5. Also, there was a considerable amount of liquid fuel flowing down along the cylinder surface as the engine was operated by the extended over-rich fuel injection. This observation plus the weak radiation of both flame propagation and diffusion reactions seen from images of the very first firing cycle (Fig. 5) lead us to expect that some of fuel washes down along the cylinder liner.

Continuously changing diffusion reactions (Fig. 5-(B)) strongly suggest a possibility of accordingly varying amount of fuel layers over the chamber surface. Such a variation in the cylinder may be dictated by the amount of fuel accumulated in the intake port during this early period. That is, the amount of liquid fuel layered at the port would affect the activities in the cylinder in a similar way. On the other hand, changes in fuel vaporization may be another possible factor affecting the variation, which would be related to the thermal condition of the cylinder entity, including temperatures of back-flow and the residual gas. Reviewing the images, however, particularly when comparing those in the 5th through 8th cycles with each other, a strong diffusion flame is not necessarily found with correspondingly intense flame propagation. The observations suggest that the variation in vaporization could of local diffusion reactions. That is, the varied amount of liquid fuel present in the cylinder seems to be the most probable factor in determining the subsequent in-cylinder reactions.

It is further noted that the activities exhibiting the local (diffusion) reactions started no earlier than 15ATDC (1-e in Fig. 7), which coincides with the time after the entire imaging view is covered by the flame fronts indicating near depletion of vapor-air mixtures (seen via 3.43μm band). This indicates that the liquid fuel layered over the (low-temperature) surface begins an active consumption only after the chamber temperature is elevated. Since the piston location becomes relatively far from the TDC thereafter, the reaction around the layers would be increasingly sluggish.

A few last observations to be mentioned about the images from the over-rich start are after the fuel vapor-air is consumed, some regions previously with no reaction front began to exhibit a new center of flame as observable in cycles 4, and 6, particularly in the squish area. The only possible explanation for this finding seems to be the slowly evaporating liquid fuel landed in those regions, which was not consumed by the flame fronts in the beginning, and the liquid layer upon receiving heat transfer produced enough vapor to support diffusion flames around. It is also noted that it is not unusual to find a cycle having flames similar to those in cycle-5, which has only small amounts of (diffusion) flames around the liquid layers. It seems most probable that such severe variations during those early cycles can be attributed to the intake-port condition dictating the fuel-air preparation in the cylinder. It is not conceivable that the in-cylinder thermal condition, which would affect the fuel vapor formation, changes so swiftly to cause such cyclic variations.

**Images with Stoichiometric Mixture.** Recall that immediately after the first batch of imaging was done with an over-rich fuel injection, the engine was fed with a near stoichiometric mixture for the next imaging (see Fig. 4). Since each batch of imaging contains results from eight consecutive cycles, it was attempted to choose a representative set of images in preparing Fig. 6.

In general, the radiation by gaseous mixture (as seen via 3.43μm band) gradually decreases with time particularly at the later stage of combustion, which may be seen by comparing those taken at 70ATDC with each other. This observation may be explained by the possibility of reducing postflame oxidation as the engine warms up. Since the early flame growths appear to be similar to each other (by looking at those obtained at 5ATDC, for example), the accelerating flame propagation before the piston goes away too far from the TDC may also explain the phenomena. As expected, the images captured in 3.8μm band show an increasing strength of radiation by the surface until the coolant temperature attained about 60°C (at about 20minutes under the present coolant system) and thereafter they seem not to vary considerably. Unlike the images taken right after the start, which show some parts of the chamber having almost no reaction (Fig. 5), those included in Fig. 6 indicate the flames propagating through out the entire reaction volume. According to the present experiment, once the engine ran for a few minutes from the start, the in-cylinder reactions become relatively predictable to expect a reasonable power output, except for a new finding as discussed below.

Although the difference in exposure period of imaging is taken into consideration, it was quite obvious that the amount of liquid fuel dramatically decreased within the period of about two minutes after the start. During the interval, there was a change in intake-port temperature from about 10 to 50°C. In general, the scale of the diffusion flame decreased with time. In turn, the temperature increase in the engine, most notably at the intake port (Fig. 4) and presumably over the chamber surface.

Let us review the sequential images in Fig. 6-(A) in reference to the imaging view (Fig. 3). For example examine those taken at 3.3 minutes after the start. There are intense local centers at the upper portion of the intake valve clearly visible starting from 35ATDC. (Note that in typical SI engines the flame fronts become no longer visible after about 30ATDC.) According to imaging results from the first eight cycles, the local reaction center started as early as 15ATDC, which was observable late in a warm engine. The reason for the difference was due to the radiation from combustion product masking that from the local centers over the surface. The dynamic nature of the local reaction is clearly observable when they are reviewed in a video animation display: It is restated that the centers stay as a stationary surface phenomena in the beginning, which become a moving volume reaction around.

The local centers continued to react even far after the flame propagation disappeared but in gradually decreasing intensity as the piston moves away from the TDC. According to observation by a video display, the diminishing image of the local centers seemed most likely due to the depletion of liquid fuel off the surface. Note also that imaging results obtained by a longer exposure period indicate that the local radiation continue to be remarkable even after the EVO. The weakening radiation may be also due to the lower piston location, which will cause the cylinder temperature to be low, resulting in both a low oxidation and low radiation. The above consideration brings up an expectation that the chamber surface is considerably cooled down during the non-combustion period before the next liquid fuel is delivered.

Without displaying a bulky volume of results, it is noted that the liquid layers producing such diffusion reaction centers showed remarkable cyclic variations. In some cycles, the local center was hardly observable, even when the engine was not at a high temperature, which can be seen in the sample results obtained at different times after the start (Fig. 6). For example, there were cycles exhibiting almost no local burning such as those captured at 8.25 minutes after the start, while the same obtained at 20.8 minutes (and also 25.6 minutes) indicated some remarkable local reactions. Again, it remains to be further studied that these reactions centers were often found in a rather remarkable strength even after the engine was relatively warmed, which observation was reported earlier [1].

**Significance of Diffusion Reactions after Flames Disappeared.** Regardless of the engine temperature, it is reasonable to expect that the continuing local reaction centers would be a significant source of UHC emissions. As mentioned earlier, the local diffusion reactions started to grow after around 15ATDC and continued far after the flame fronts disappeared (e.g. after EVO). It is again noted that the flames here mean the reaction fronts of consuming fuel-vapor and air mixtures.

Since the slowly reacting local centers are considered to occur over the liquid layers, it is quite appropriate to analyze the nature of the reaction environment. Many issues come into consideration. They are: (1) the location of liquid layers; (2) the flow of the layer over the surface; (3) the reaction anchored over the layers, (4) the stability of reactions; and (4) deposit effects on the reaction centers. The formation of layers is dictated by various factors such as the geometric configurations, and thermal and fluid flow characteristics of the engine. In this experiment, the most significant layers are found over the surface which perpendicularly divides between the chamber cavity and the squish area, and the upper part of the intake valve (refer to images in Figs. 5 & 6 and photo in Fig. 3). The liquid layers formed over the surfaces would be mobile according to gas motions, gravitational force and other effects. Referring to images indicated by 2-a through 2-h in Fig. 5 such as those obtained in 3rd cycle, the layer appear to move downward. In order to gain some insight into what is happening there, let us picture a flame spreading over a flowing fuel on an inclined surface. Since the gas motions are not small and insignificant in the chamber, the reaction front many be blown off if the reactions are improperly anchored where the vapor is formed. Such a stability issue may partially explain the cyclic variations of local reaction centers during the over-rich operation (Fig. 5) as well as some in the stoichiometric combustion (Fig. 6).

Regarding the relationship of deposit layers to the local diffusion reaction centers, although it is difficult to state a conclusive remark at present, some tangible effects have been realized during the course of the present work: The deposit layer formed over the cylinder head surface was inadvertently cleaned in the middle of experiment, and the clean head surface seems to reveal a lower frequency of having local reaction centers than before. A permeable deposit layer holding a liquid fuel would produce different modes and reaction periods of diffusion reaction from those formed over a clean smooth surface covered with the same fuel.

## Summary

An optical SI engine equipped with a conventional port injection fuel system was investigated during the cold start period as operated by unleaded regular gasoline. The results obtained in the study include high-speed multiple spectral infrared images from: (1) the very first firing cycle and next seven consecutive cycles; and (2) successive sets of the same images as the former as repeated during the warm-up period in an about two-minute interval. In the former imaging, the engine was operated with a over-rich fuel injection rate (equivalent to 3.5 the stoichiometric), and for the latter, it was run by a near stoichiometric fuel injection. The matching cylinder pressure-time data and temperatures at the intake port and others were obtained at the same time. The spark time was 6CA BTDC. Some of more significant findings are listed in the following.

(1) The very first firing cycle exhibited weak and low-rate flame propagations and insignificant reactions around the liquid fuel layers.

(2) The second, third and fourth cycles exhibited similar p-t results although their radiation intensities vastly varied both in times and locations with some remarkable cyclic variations.

(3) The flame propagations do not appear to be benefited by the over-rich fuel injection after a few or several cycles from the start.

(4) The reaction centers produce radiation after about 15ATDC, indicating the need of a time period for liquid fuel to be heated to support the local diffusion reactions.

(5) Some considerable amount of liquid fuel was flowing down along the cylinder during the over-rich start.

(6) The flame propagations and local diffusion reaction centers change quite dramatically within a few minutes from the start, producing more predictable flame and smaller amount of liquid fuel reactions over the surface.

(7) The reaction centers around the liquid fuel layer continued even (long) after the flame fronts disappeared.

(8) The liquid layers causing the local reactions did not appear in every cycle, and likewise the opposite was found after the engine was well warmed. Some cyclic variations in liquid layer formation is pronounced to exist in the engine cylinder.

(9) The deposit formation over the chamber surface appears to affect the formation-occurrence of local reaction centers around the liquid layers, which needs further study.

(10) The liquid fuel formed over the combustion chamber surface is considered to cause unburned hydrocarbon emissions from both cold and warm engines.

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