PERGAMON

Progress in Energy and Combustion Science 25 (1999) 253–273

PROGRESS IN ENERGY AND COMBUSTION SCIENCE

www.elsevier.com/locate/pecs

Combustion-chamber crevices: the major source of engine-out hydrocarbon emissions under fully warmed conditions

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Received 1 July 1998; received in revised form 23 November 1998

Abstract

This article presents a critical review of the studies performed to investigate combustion-chamber crevices as sources of hydrocarbon (HC) emissions, and an evaluation of potential technologies for reducing these emissions. Of the combustion-chamber crevices, the piston upper crevice volume is the main contributor to engine-out HC emissions. Chamfering the piston crown or reducing the top-land height and/or the volume behind the top compression ring may result in significant reductions in HC emissions. Modest reductions may also be achieved by reducing the central-electrode crevice of the spark-plug. However, reducing the head gasket crevice of current production engines appears to have little effect on engine-out HC emissions. In general, the sensitivity of the HC emissions to the combustion-chamber crevices is influenced strongly by the in-cylinder flow field and combustion, which influence the concentration of burned gases in the crevice gases.

Keywords: Hydrocarbon emissions; Combustion-chamber crevices flame quenching; Spark-ignition engines

Contents

1. Introduction

Any serious approach to meet the upcoming, stringent, federal standards for vehicle tailpipe hydrocarbon (HC) emissions should include the reduction of engine-out HC emissions. In some instances, the HC emissions standards may not be achievable without the reduction of engine-out HC emissions. Of the several sources of HC emissions,

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0360-1285/99/$ - see front matter
PII: S0360-1285(98)00026-4

Table 1
HC sources and their relative magnitude

Source	% HC
Combustion-chamber crevices	38
Single-wall flame quenching	5
Oil film layers	16
Combustion-chamber deposits	16
Exhaust-valve leakage	5
Liquid fuel	20

combustion-chamber crevices appear to be the largest contributors to engine-out HC emissions under fully warmed engine conditions [1–4].[1,2] However, under cold-start or generally under cold conditions, some of the other HC sources such as fuel preparation, lubricating oil films, and single-wall flame quenching are believed to become equally important with combustion-chamber crevices [3,6–8].

For a fully warmed engine, Cheng and coworkers [3] estimated the relative importance of each of the sources of HC emissions. These estimates are presented in Table 1. Combustion-chamber crevices represent 38% of the HC emissions. However, Wentworth [1] reported reductions in engine-out HC as high as 74% when piston crevices were virtually eliminated, and Alkidas et al. [4] found that combustion-chamber crevices represent more than 50% of the HC emissions. Irrespective of the percent contribution, the importance of combustion-chamber crevices to engine-out HC emissions is well established and resulted in numerous investigations, the vast majority of which were focused on the piston crevices, which are the largest crevices in the combustion-chambers of engines.

The present study is a critical review of the investigations in the open literature that have examined combustion-chamber crevices as a major source of engine-out HC emissions.

2. Definition of combustion-chamber crevices

The crevices in the combustion-chamber of the engine which may result in unburned HCs are shown in Fig. 1. They are: the piston-ring-pack crevices; the head gasket crevice; the spark-plug crevices, which consist of the thread crevice and the central-electrode crevice (gap between central-electrode and the plug body); and the valve-seat crevice. The piston-ring-pack crevices (see Fig. 2), which may conveniently be called the piston crevices, consist of the piston upper crevices and the piston lower crevices. The piston upper crevices consist of the top-land volume and the volume behind the top compression ring (volume within the top groove not occupied by the ring). The piston lower crevices consist of the volume between the first and second compression rings and the volume behind the second compression ring. The upper crevices, which effectively are in pressure equilibrium with the combustion-chamber, are the primary crevices of the piston-ring-pack crevices. The lower crevices, which are in communication with the upper crevices and the oil ring crevices through the ring gaps, contain much less trapped combustion-chamber gas because of their much lower pressure level. Thus, the piston lower crevices may not be considered a combustion-chamber crevice, however, the geometry and size of the piston lower crevices affect the mass transfer between the two crevices and consequently affect the crevice HC.

Table 2 lists sizes of the combustion-chamber crevices for a typical four-cylinder DOHC engine. At TDC (top dead center) the combustion-chamber crevices represent about 3.5% of the total combustion-chamber volume. However, the corresponding mass fraction of the combustion-chamber gases stored in the crevices is much higher because of the relatively lower temperature of the trapped gases in the crevices in comparison to that of the combustion-chamber gases. For a part load engine condition, the mass ratio of crevice gas to total combustion-chamber gas may be of the order of 7%. Moreover, the crevice gas consists not only of unburned gases but of residual gases and of burned gases. The relative magnitude of these components varies during the combustion process with the unburned gases representing the largest component.

In the combustion field, a crevice is defined as any small space surrounded by walls and connected to the main combustion-chamber by a narrow passageway whose characteristic dimension, such as the diameter of the hole or the thickness of the channel, is such that a flame cannot propagate into it. A simple measure of the ability of a flame to propagate into a narrow passageway is the two-wall quench distance, which is a combustion parameter that is experimentally defined as the minimum plate separation for which flame propagation can be achieved in a combustible mixture confined by two parallel flat plates [9]. If the characteristic dimension of the passageway is smaller than the two-wall quench distance, then the flame cannot penetrate into the crevice to consume the HC. Moreover, if the characteristic dimension is bigger than the two-wall quench distance, then the flame can penetrate into the crevice and consume the HC.

Figs. 3 and 4 show, respectively, the variations of the

[1] Numbers in brackets indicate references found at the end of the text.

[2] In contrast to most studies, a recent analytical study by Saika et al. [5] showed that, for steady-state fully warmed stoichiometric conditions, the piston crevices contribute only about 11% to engine-out HC emissions. This percent contribution increases to a maximum of 43% for an equivalence ratio of 0.65 (lean conditions). Based on these results, they concluded that the lubricating oil film is a larger contributor to engine-out HC emissions for near-stoichiometric conditions. However, there is no experimental evidence to support this finding which is suspected to have resulted from uncertainties in the mixing and HC oxidation modeling.

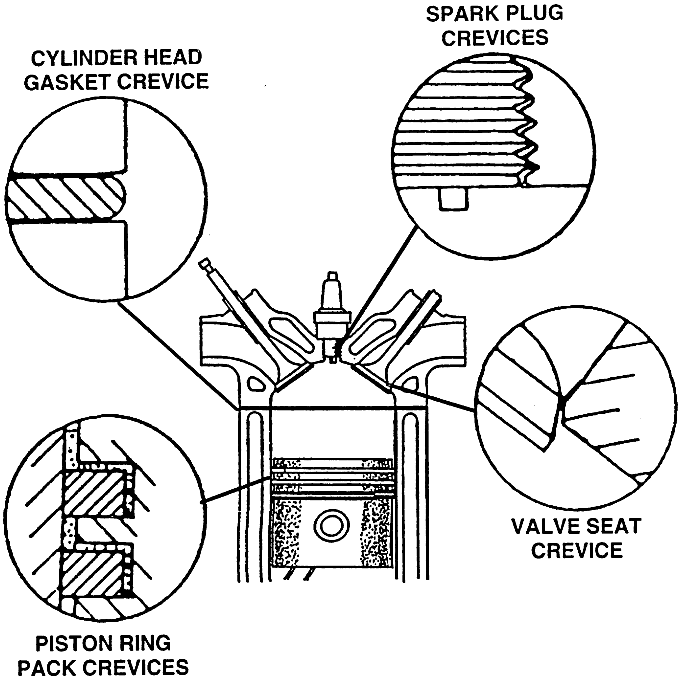

Fig. 1. Combustion-chamber crevices.

two-wall quench distance with the equivalence ratio of a combustible mixture and with charge dilution for various levels of gas pressure. The reactants were propane and air. The computations were performed using a comprehensive two-wall quench-distance correlation developed by Lavoie [10]. Lavoie's correlation assumes that the ratio of heat release by the chemical reaction to the heat loss to the walls (= Peclet number) is constant for a given configuration.

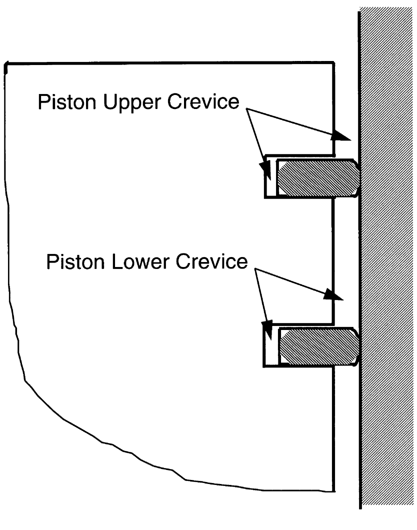

Fig. 2. Schematic of piston showing the crevices.

The two-wall quench distance is given in terms of the Peclet number, the laminar flame speed and the adiabatic flame temperature. Very recently Ishizawa [11] developed the following empirical equation for two-wall quench distance based on experimental measurements in the combustion-chamber of an engine:

$$d_q = 14.8 \times (P_{max})^{-0.9}(T_w)^{-0.5},$$

where d_q is the quench distance in mm, P_{max} is the maximum cylinder pressure in MPa, and T_w is the quenching wall temperature in K. This equation, which is only valid for stoichiometric combustion without charge dilution, is of the same form as much earlier correlations of Friedman and Johnston [12] in a propane burner, and of Goolsby and Haskel [13] in a CFR engine with isooctane fuel.

Table 2
Combustion-chamber crevices

	Volume (mm^3)	
Piston upper crevices		980
Head gasket crevice		335
Spark-plug crevices:		600
Central-electrode crevice	525	
Thread crevice	75	
Valve seat crevice		—
Clearance volume, $V_{CL} = 55\,920$ mm^3		
Total crevice volume = 1915 mm^3		

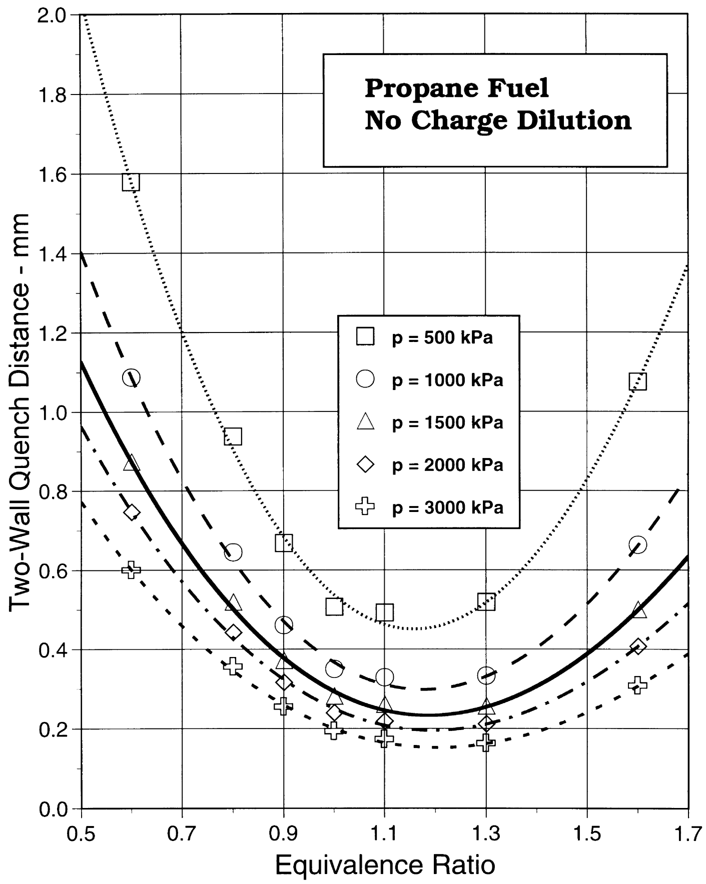

Fig. 3. Computed two-wall quench distance vs. equivalence ratio at various pressure levels for a stoichiometric propane–air mixture at 0% charge dilution (residual mole fraction $X_r = 0.0$).

Fig. 3 shows that the variations of the two-wall quench distance with equivalence ratio exhibit minima in the rich region near stoichiometric composition ($\phi = 1.1$–1.2). As the mixture becomes richer or becomes leaner than stoichiometric composition, the two-wall quench distance rapidly increases. This suggests an advantage of stoichiometric engine combustion over lean engine combustion with regard to the crevice HC as the main source of engine-out HC emissions.

Increasing charge dilution dramatically increases the quench distance. This increase is attributed to the resultant reduction in the laminar flame speed. The large increase in the two-wall quench distance with charge dilution has serious consequences for high exhaust gas recirculation (EGR) conditions and for idle conditions, where residual gas fraction is relatively high.

Considering the pertinent experimental investigations, Saika and Korematsu [14] found that the earlier mentioned simple criterion for flame propagation in crevices was valid for the piston crevice of an engine; that is, they observed a sudden reduction in engine-out HC emissions when the piston top-land clearance became larger than the two-wall quench distance. However, important details of the empirical quench thickness correlation used (evaluation of the experimentally determined exponents for pressure and temperature) were omitted from their article. In contrast, Yoshida [15] found that the percent reduction in exhaust HC emissions correlated by the ratio of top-land radial clearance to top-land height. The higher this ratio, the higher the percent reduction. The range of ratios examined was from about 0.035 to 0.20 (this ratio for a typical production engine with 6 mm top-land pistons is about 0.06). Additionally, a recent study by Alkidas et al. [4] showed that the simple two-wall quench distance criterion may not be valid, universally. In this study [4], the observed trends of the variations of exhaust HC emissions with top-land radial clearance for pistons having different top-land heights suggested a more complex relation between crevice geometry, flame propagation, and exhaust HC emissions. Evidence on the complex character of flame propagation in crevices were provided also by several non-engine combustion studies [16–18]. These studies showed that the flame propagation in crevices is

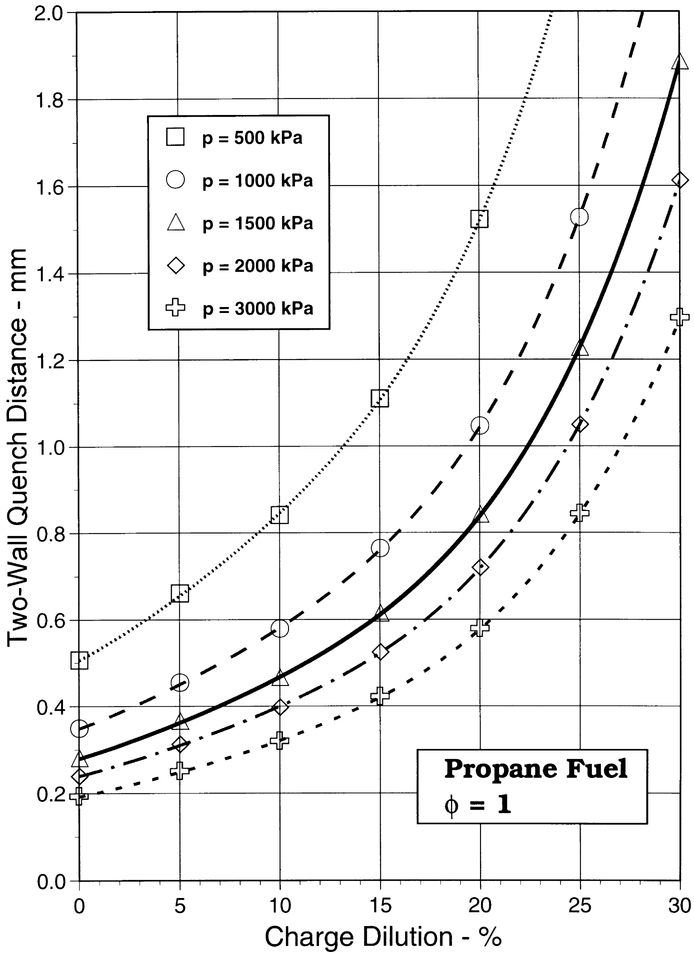

Fig. 4. Computed two-wall quench distance vs. charge dilution at various pressure levels for a stoichiometric propane–air mixture (equivalence ratio $\phi = 1$).

dependent, in a complex fashion, on both passageway thickness (or diameter) and length of crevice.

3. Crevice hydrocarbons

3.1. Piston crevices

As stated earlier, the piston crevices consist of the top-land volume, the volume between the first and second compression rings and the volumes within the top and second ring grooves not occupied by the two compression rings (top and second ring crevices). Of these, the most important is the piston top-land crevice and top-ring crevice (the volume behind the top ring).

The vast majority of the studies dealing with the effect of combustion crevices on engine-out HC emissions focused on the piston crevices, which are the largest crevices in the combustion-chamber of engines. The geometric parameters examined were mainly the top-land height and, to a much lesser degree, the top-land radial clearance.

Table 3 summarizes key studies on the influence of piston crevices on engine-out HC emissions. Wentworth [1] and Boam et al. [7] used experimental piston-top ring designs that practically eliminated the piston crevices. Wentworth's sealed ring orifice (SR-O) design is shown on the top of Fig. 5. The achieved reductions in exhaust HC concentration averaged about 170 ppm C_3 which corresponded to about 60% reduction in engine-out HC emissions. Boam et al. [7], using an experimental PTFE sealed piston, the design of which is shown schematically on the bottom of Fig. 5, achieved a 30% reduction in HC emissions on a simulated cold start condition (100 s after a 20 C start). The corresponding reduction in exhaust HC concentration was about 400 ppm C_3, a very large reduction indeed. However, all testing with the PTFE sealed piston was limited to 2 min only.

A reduction of top-land height of the piston was found to

Table 3
Selected past studies on the effects of piston crevices on engine-out HC (l_{tpl} = top-land height, D_{rcl} = radial clearance)

Study	Engine	Test conditions	Crevice modifications l_{tpl} (mm) D_{rcl} (mm)	Results/comments
Wentworth [1]	Single-cylinder CR = 8.5 : 1	800–2000 rpm 3 part loads, WOT	$l_{tpl} = 6.35$, $D_{rcl} = 0.483$ SR-O ring	47–74% reduction in exhaust HC
Haskell and Legate [32]	Single-cylinder CFR engine CR = 4.5–9 : 1	885 rpm $A/F = 13$ WOT	$D_{rcl} = 0.050$–0.356	Increasing clearance up to 0.178 mm increased HC. At this point a sharp decrease in HC occurred. Further increases in top-land clearance did not change HC
Yoshida [15]	Single-cylinder air-cooled engine	2000 rpm, 780 kPa and 4400 rpm, 920 kPa	$l_{tpl} = 9.5^*$, 6.5, 3.0, $D_{rcl} = 0.3^*$ and 0.5 45° chamfer (*baseline dimensions)	Reducing l_{tpl} and/or increasing D_{rcl} reduced HC. In comparison to the baseline geometry, a 45° chamfer ($l_{tpl} = 6$ mm) reduced HC by 26%; 3 mm top-land height and 0.5 mm radial clearance reduced HC by 23%
Boam et al. [7]	Single-cylinder Hydra engine	2000 rpm 48 kPa MAP warm-up testing	PTFE sealed piston	The PTFE seals reduced the piston crevice volume by 97% and resulted in about 30% reduction in exhaust HC. Runs with PTFE sealed pistons were limited to 2 min (few data)
Sterlepper et al. [33]	Single-cylinder engine CR = 10.1 : 1	2000 rpm 200 kPa BMEP	$l_{tpl} = 6^*$–6.5, $D_{rcl} = 0.39^*$–1.0 3 mm—45° chamfer (*baseline geometry)	Increasing clearance from 0.39 to 0.7 and then to 1.0 mm decreased HC by 5.2% and 11.9%. The 3 mm-45° chamfer resulted in 22% reduction. Results correlated to the frequency of flame detection in crevice. Very few data
Min et al. [20]	Single-cylinder Hydra MK III CR = 8.29 : 1	900–2500 rpm 40–100 kPa MAP	$l_{tpl} = 7.87$ and 2.80 increase crevice volume by means of grooves	The reduction in top-land height resulted in 7% reduction in HC. In general, a 100% change in crevice volume resulted in 20% reduction in HC
Alkidas et al. [4]	Four-cylinder production engine CR = 9.5 : 1	Idle and 3 part loads (1300 and 2200 rpm)	$l_{tpl} = 6$ and 3, $D_{rcl} = 0.191$–1.267	Piston crevices contribute about 50% of HC emissions. For part loads, the variation of exhaust HC with radial clearance had a maximum at a radial clearance of about 0.4 mm. For idle, increasing the radial clearance increased HC, monotonically

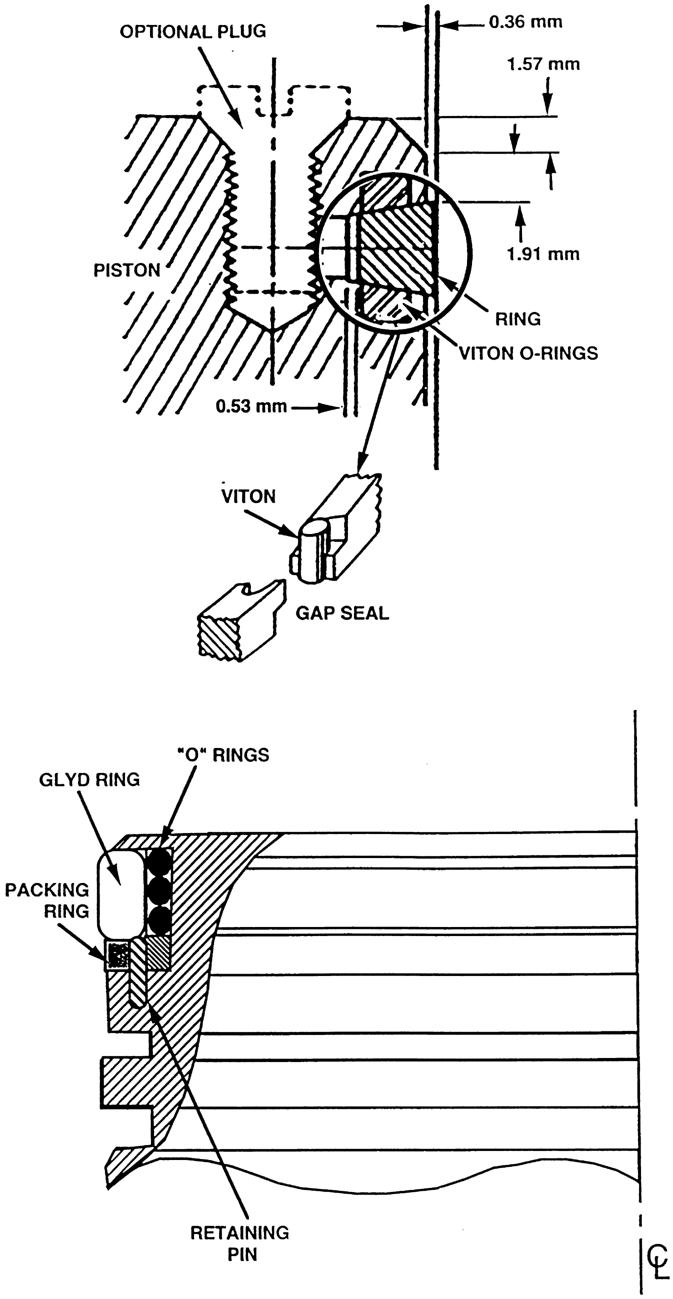

Fig. 5. Upper figure: Wentworth's sealed-ring orifice (SR-O) design [1]; lower figure: PFEM sealed piston design [7].

reduce engine-out HC emissions. Yoshida [15] found that decreasing the top-land height from 9.5 to 3.0 mm, which corresponds to a reduction in the piston crevice volume of about 52%, reduced the HC emissions by about 16%, for a top-land radial clearance of 0.3 mm. However, for a 0.5 mm radial clearance, the corresponding reduction in crevice volume was 57% and the resulting HC reduction was 23%. Min et al. [19–21] found that decreasing the piston crevice volume from 1737 to 650 mm^3, a decrease of about 63%, decreased the engine-out HC emissions by about 13%, a modest decrease. The top-land radial clearance was 0.30 mm and propane was used as the fuel to reduce the effects of liquid fuel and fuel absorption and desorption by the lubricating oil. However, Alkidas et al. [4], using a production 1.9 L four-cylinder engine, found that decreasing the top-land height from 6 to 3 mm, which resulted in a

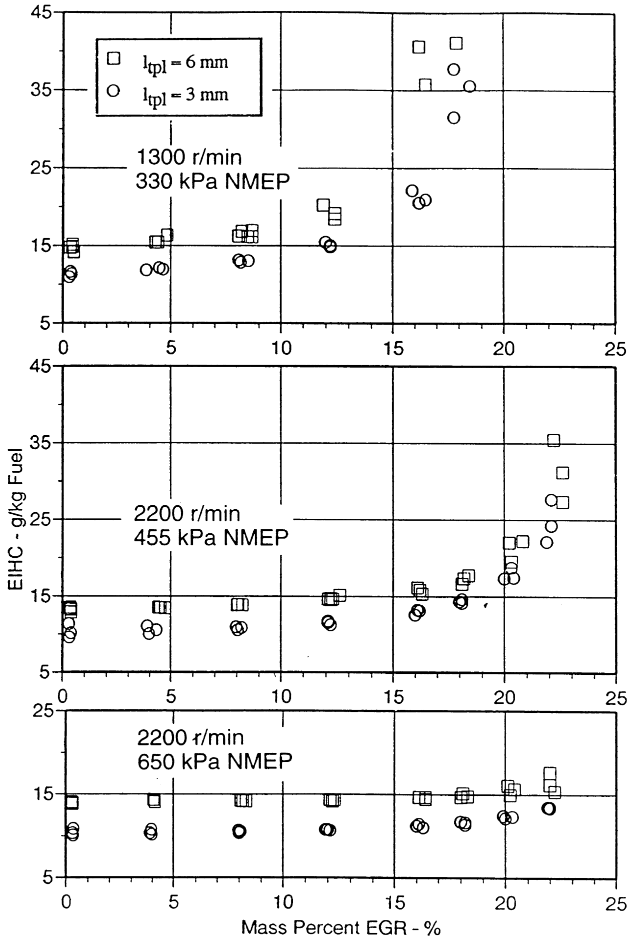

Fig. 6. HC emissions index vs. EGR for three part loads. Comparisons of STD pistons with 6 mm top-land height with LCV pistons with 3 mm top-land height [4].

reduction in piston crevice volume of about 47%, resulted in an overall decrease in engine-out HC emissions of 22%. Fig. 6 presents results from that investigation. It shows plots of the emission index of HC (EIHC)[3] versus mass percent of EGR for three part-load conditions. For these data, the radial clearances of the pistons used ranged from 0.45 to 0.37 mm. The results show that, with the exception of the highest levels of EGR, where the combustion stability of the engine may be significantly deteriorated, the use of pistons with 3 mm top-land height instead of the normal production value of 6 mm resulted in significant reductions in HC emissions.

Significant reductions in engine-out HC emissions resulting from corresponding reductions in piston top-land height were observed also by Adams and Kerley [22], Stefanides [23], Prasse et al. [24], Willock and coworkers [25,26], Lee et al. [27], Haag and coworkers [28], and Takahashi and coworkers [29].

[3] EIHC is defined as g of HC per kg of fuel.

In contrast to the top-land height, top-land radial clearance affects engine-out HC emissions in a complex manner via its influence on the flame propagation into the crevice volume. Fig. 7 shows variations of engine-out HC emissions with the radial clearance of the piston measured by Alkidas et al. [4] and Huang et al. [30,31] respectively. Alkidas et al. [4] measurements were in a four-cylinder engine at three part load conditions and Huang et al. [30] in a single-cylinder engine at WOT conditions and for several engine speeds ranging from 1200 to 2000 rpm. In general, the observed behavior of the HC emissions with radial clearance is what one may expect. Ideally, as the radial clearance of the piston increases from the theoretical value of zero, the HC emissions are expected to increase because of the resulting increase in the crevice volume. However, as the radial clearance is increased, a critical value will be reached beyond which the flame in the combustion-chamber will begin to penetrate into the crevice volume and to consume the unburned HCs. Thus, at the critical radial clearance the HC emissions should reach a maximum, and beyond this

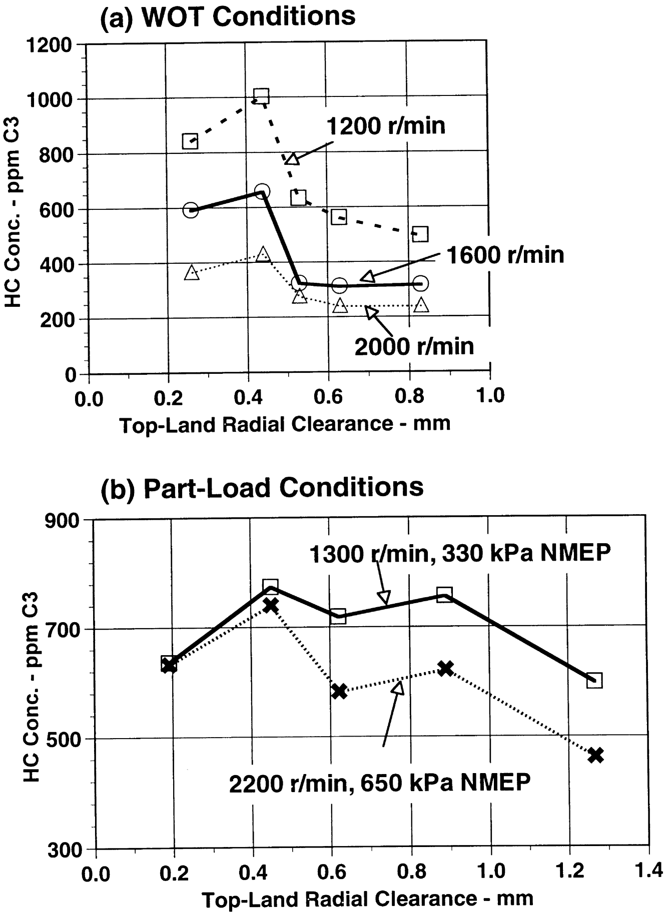

Fig. 7. Exhaust HC concentration vs. top-land radial clearance for: (a) WOT conditions [30,31]; and (b) part-load conditions [4].

point the HC emissions should decrease with increasing radial clearance to an asymptotic value that corresponds to the case of the flame consuming all the unburned HC present in the piston crevice volume. The critical radial clearance, which may be equal to the two-wall quench distance for pistons with relatively large top-land heights, is a function of the properties of the combustion gases in the crevice and the wall temperatures.

The critical top-land radial clearance in the Haskel and Legate [32] study, which was performed in a CFR engine, was 0.18 mm for the WOT condition examined.[4] Yoshida [15] observed a significant reduction in engine-out HC emissions when the top-land radial clearance was increased from 0.3 to 0.5 mm. Alkidas et al. [4] found that decreasing the radial clearance of the production pistons (6 mm top-land height) from 0.45 to 0.19 mm resulted in a modest decrease of HC emissions of 4%. However, increasing the radial clearance of the standard piston from 0.45 to 1.27 mm, which increased the corresponding room-temperature top-land crevice volume by 111%, resulted in about 25% decrease of engine-out HC. For the part load conditions examined, the critical radial clearance was around 0.45 mm, which corresponded to the production radial clearance. Similarly, for WOT conditions Huang et al. [30,31] found that the critical radial clearance was around 0.4 mm. Above a radial clearance of about 0.5 mm, the exhaust HC concentration was found to be independent of radial clearance. Sterlepper et al. [33,34] found that increasing the top-land radial clearance from the production value of 0.39 to 0.7 mm, and then to 1.0 mm, while keeping the top-land height roughly constant (6–6.5 mm), reduced HC emissions by roughly 5% and 12%, respectively. As shown in Fig. 8, these HC reductions were correlated to the increase in the frequency of detection of the flame propagating in the top-land crevice. At a top-land radial clearance of 0.39 mm the flame seldom entered the piston crevice.

Significant decreases in engine-out HC emissions from a four-cylinder, four-valve engine were observed by Haag and

[4] For present production engines, radial clearances below 0.18 mm are impractical because of the differential expansion between piston and bore at high loads and speeds.

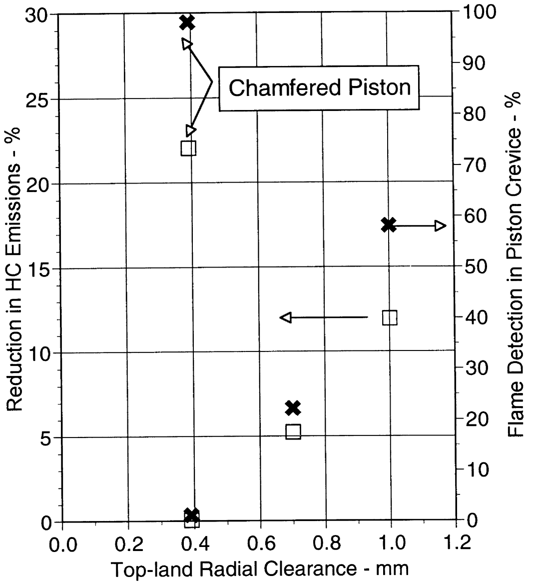

Fig. 8. Percent reduction in HC emissions and frequency of flame detection in piston crevice as functions of top-land radial clearance.

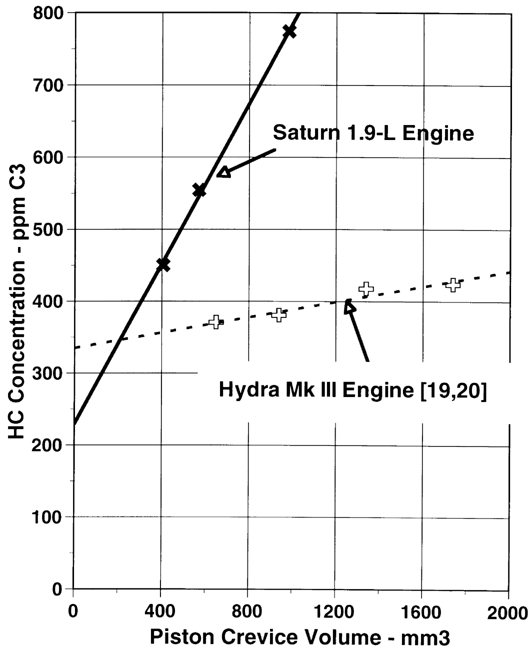

Fig. 9. Linear variation of the exhaust HC (concentration) with piston crevice volume.

coworkers [28], who by employing carbon pistons were able to reduce the top-land radial clearance to 0.135 mm from the typical production value of 0.39 mm for aluminum alloy pistons. For two part-load conditions (BMEP = 200 and 400 kPa) at an engine speed of 2000 rpm, the percent reduction in HC emissions using carbon pistons instead of the production pistons was 17% and 12%, respectively.

For top-land radial clearances which do not allow penetration of the flame into the piston crevices, the engine-out HC emissions vary linearly with the piston crevice volume. Fig. 9 shows measured linear variations of exhaust HC concentration with piston crevice volume for two engines at comparable part-load conditions The study performed by the author was on a Saturn 1.9-L four-cylinder engine. The study performed by Min et al. [19,20] was on a single-cylinder Hydra MK III engine. It is very clear that the engine-out HC emissions from the two engines have significantly different sensitivity to changes in the piston crevice volume.

The sensitivity of engine-out HC emissions to piston crevice volume (defined as percent change in HC emissions per unit percent change in piston crevice volume [20]) was 0.31 and 0.40 for Yoshida [15] for top-land radial clearances of 0.3 and 0.5, respectively; 0.20 for Min et al. [19,20]; and 0.47 for Alkidas et al. [4]. In a much earlier study, Wentworth [1] observed a sensitivity of engine-out HC emissions to piston crevice volume of about 0.6. These wide range of sensitivities of the HC emissions to changes in crevice volume (0.2–0.6) found in the literature is believed to be as a result of differences in fuel type, engine conditions and engine combustion-chamber geometry, which affect post-combustion oxidation rates and crevice gas composition (unburned gas fraction). In addition, the sensitivity of the HC emissions to crevice volume, as defined earlier, depends strongly on the size of the crevice. Considering the linear relation of the HC with the piston crevice volume shown in Fig. 9, the HC sensitivity to the piston crevice volume may be given by an equation of the form:

$$\lambda = \frac{1}{(1 + c/V_{\mathrm{pcr}})}$$

where λ is the sensitivity, V_{pcr} is the piston crevice volume and c is a function of engine conditions, but it is independent of crevice volume. Thus, the larger the piston crevice volume the higher is the sensitivity of HC emissions to it.

An alternative way to reduce the piston crevice is to chamfer the top corner of the piston (piston crown). The effects of chamfered pistons on engine-out HC emissions were examined by Yoshida [15], Sterlepper et al. [33,34], Thompson and Wallace [35] and Alkidas et al. [4]. Yoshida [15] found that chamfering of a piston to reduce the top-land height from 9.5 to 3.5 mm reduced engine-out HC emissions by about 23%. In contrast, for the same test condition (2000 rpm, BMEP = 780 kPa, ϕ = 1.11) and the same top-land radial clearance of 0.3 mm, reducing the top-land height from 9.5 to 3 mm resulted in only about 15% reduction in engine HC emissions. Also, he found that chamfering of the piston caused a small increase in cylinder wall temperature of about 2–3%, but it had no effect on blow-by or fuel economy. Sterlepper et al. [33,34] achieved a 22% reduction in HC emissions by employing a chamfered piston of top-land height of 3.5 mm instead of the standard piston of top-land height of about 6 mm. Most importantly, they found that chamfering of the piston caused the flame to enter the piston crevice practically always, whereas for the standard piston, with the same top-land radial clearance of 0.39 mm, the flame seldom entered the crevice. Finally, Alkidas and coworkers [4] found that chamfered pistons with 3 mm top-land height, resulted in decreases in HC emissions of about 11% for idle conditions and 5% for part load conditions, in comparison to the standard pistons with top-land height of 6 mm and the same top-land radial clearance of 0.89 mm.

It is apparent from the earlier studies that chamfering the piston crown is a most effective way to reduce engine-out emissions. The achieved reduction in HC emissions appear to be much larger than one would expect from the corresponding reduction in piston crevice volume This may be because of two possible effects. One, chamfering allows the flame to propagate easier into the crevice volume as a result of a smooth entrance transition section. Two, the outflow of gases from the crevice into the combustion-chamber is directed away from the cylinder wall towards the hot bulk gases, thus promoting their mixing and subsequent oxidation.

In the earlier discussion, the influence of crevices on engine-out HC emissions was examined primarily based on flame propagation into the crevice but without consideration of the gas flow interchanges.

The effectiveness of reducing crevice volume in the reduction of engine-out HC emissions depends strongly on the crevice-gas composition, and more precisely on the amount of unburned gases that reside in the crevice. The higher the unburned gas fraction in the crevices the stronger is its effect on HC emissions. The crevice composition, in turn, is largely dependent on the location of the spark-plug in the combustion-chamber. A centrally located spark-plug, which is the general practice for four-valve engines, results in the highest amount of unburned gas fraction in the crevices. As the location of the spark-plug moves away from the axis of symmetry of the bore, more burned gas flows into the crevices resulting in the reduction in the unburned fraction of the crevice gases with the consequence that the influence of crevices on engine-out HC emissions is reduced.[5]

In addition to the location of spark-plug relative to the axis of symmetry of the bore, it appears that the location of the spark-plug relative to the location of the end-gap of the top compression ring affects the crevice-gas composition. Wentworth [37] was the first to examine the effects of the location of the top-ring end-gap on engine-out HC emissions. His results are presented in Fig. 10. The angular location of the top-ring end-gap resulted in maximum variation in HC emissions of the order of 27% of the average value. For the two-ring case, the angular location of the top-ring end-gap for the lowest HC emissions was 60° from the spark-plug location, which is near the exhaust valve (see upper diagram of Fig. 10). However, computations by Namazian and Heywood [33] and very recently by Roberts and Matthews [39], who modeled the flows through the piston-cylinder-ring crevices, found that the HC emissions should be minimum when the top-ring end-gap is closest to the spark-plug and maximum when this gap was farthest from the spark-plug.

Blow-by, which is the gas that flows from the combustion-chamber past the piston to the crankcase, affects engine-out HC emissions. This gas, which is predominantly unburned air–fuel mixture [40], is removed from the piston crevices thus preventing a portion of the crevice gas from returning to the combustion-chamber. Wentworth [37] found that the smallest end-gap of the two compression rings controlled the blow-by flow rate. This alone was found to correlate with the engine-out HC emissions. Increasing the blow-by flow rate decreased the HC emissions. The average change in HC emissions per unit change in the blow-by flow rate was about -20 ppm C_3/(l/min). Typically, the blow-by rate for the part load condition of 1300 rpm and 275 kPa BMEP is about 6 l/min.

In contrast to the experimental findings of Wentworth [37], Namazian and Heywood [38] computations showed that the blow-by flow rate increased by increasing the ring end gap of either ring and the effect is compounded if both end gaps increased. However, Kuo et al. [41], employing a modified version of the Namazian and Heywood model, found that the effect of end gap size is relatively small; a 20% increase in ring end-gap area increased the predicted blow-by by less than 5%.

It is intuitively obvious (see also [35]) that for minimum[6] amount of unburned HC returning to the combustion-chamber the top-ring end-gap should be minimum and the second-ring end-gap should be maximum. Conversely for maximum amount of unburned HC returning to the combustion-chamber the top-ring end-gap should be maximum and the second-ring end-gap should be minimum.

Experiments performed by the present author on a six-cylinder spark-ignition engine showed that a two-fold decrease in the end-gap of the top ring had little effect on the engine-out HC emissions. A similar finding was also obtained by Thompson and Wallace [35], who measured HC by a fast-response FID (FRFID) instrument. However, their results also suggested that top-land height did not influence engine-out HC emissions, a result which contradicts the findings of a great number of studies. The FRFID measurement is a point measurement and possibly the location of their measurement, because of the great stratification of the HC species in the exhaust stream, may not have represented a spatial average measurement.

[5] Adamczyk [36], in a cylindrical combustion bomb, found a complex relation between the spark location and the crevice location and geometry.

[6] Namazian and Heywood [38] concluded that the amount of unburned HC is minimum when the top ring end-gap size is in mid range and the second ring end-gap is large.

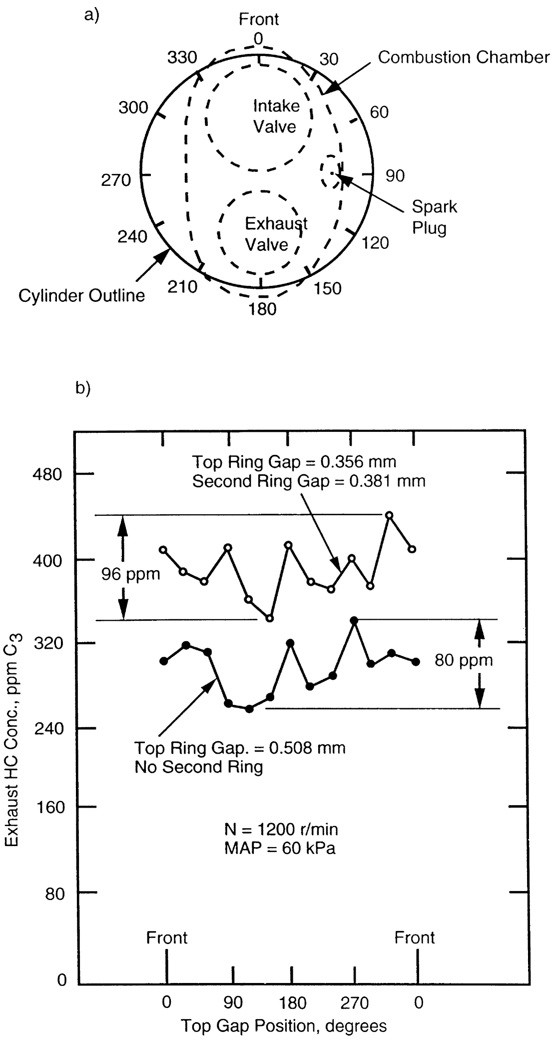

Fig. 10. Top view of top-ring gap position, and the effect of gap position on engine-out HC emissions for one- and two-piston ring systems [37].

Reitz and Kuo [42] performed multi-dimensional computations to assess the effect of crevice flow on combustion and engine-out HC emissions. They found that HC emissions are more sensitive to top-land radial clearance than to top-land height. A small top-land radial clearance resulted in a stronger annular wall jet,[7] which enhanced mixing and oxidation of the unburned HC.

Simple computations performed roughly 24 years ago by Furuhama and Tateishi [44] showed that reducing the crevice volume behind the top ring is a very effective way to reduce crevice HC. Namazian and Heywood [38] showed that a 75% reduction of this volume resulted in about 20% decrease in the HC which returned to the combustion-chamber from the piston crevices.

Kuo and coworkers [41] found that increasing the second-land volume or increasing the volume behind the second ring increased the calculated blow-by,[8] and that this effect was compounded when both volumes increased. However, earlier computations by Namazian and Heywood [38] showed that the volume of the second land had little effect on engine-out HC emissions. Also, measurements by Willcock et al. [26] showed that increasing the second-land volume by about 160% resulted in only modest reductions in engine-out HC emissions, despite the fact that it affected the HC species distribution. Finally, it is important to mention here that a very recent study by Yoshida et al. [45] found that increasing the second-land volume may increase the blow-by and may significantly reduce oil consumption. The magnitudes of these effects depend strongly on the shape of the second land. A V-shaped groove in the second land was found to be a very effective geometry. Reducing oil consumption or increasing blow-by are expected to have beneficial results on engine-out HC emissions.

3.2. Head gasket crevice

The second largest crevice in the combustion-chamber is the head gasket crevice. However, because for most production engines under normal combustion conditions the head gasket compressed thickness is relatively large (1–1.5 mm) in comparison to the two-wall quench distance, the head gasket crevice does not behave like a combustion crevice. Thus the flame is allowed to propagate into its volume to consume most of the unburned HC.[9]

Very few studies examined the effect of head gasket crevice on engine-out HC. Adamczyk et al. [46], using a combustion bomb manufactured from a 1.6-L Ford Escort production engine and replacing the head gasket with an indium wire seal, found that the head gasket contributed about 12.5% of the HC emissions exiting the reactor. In comparison, the piston crevice contribution was 80.5%. Boam et al. [7] concluded that this crevice is of equal importance as the piston crevice. However, these tests were performed in an experimental single-cylinder engine, the head gasket of which was set well back from the cylinder bore, unlike production engines. Similar results were

[7] Driscoll and coworkers [43], based on a simple flow model of filling and emptying of a simple crevice, showed that the important geometric parameter is the ratio of the orifice area to the crevice volume. For a given volume the higher the area the faster the crevice fills and the faster it empties. Thus a critical value of the parameter exists where the analysis shows maximum amount of crevice hydrocarbons.

[8] In contrast, the top-land volume and the volume behind the first compression ring were found to have no effect on the calculated blow-by [41].

[9] Even with the flame propagating into the head gasket crevice, not all unburned HC will be consumed because a quench layer always exists between a wall and a flame.

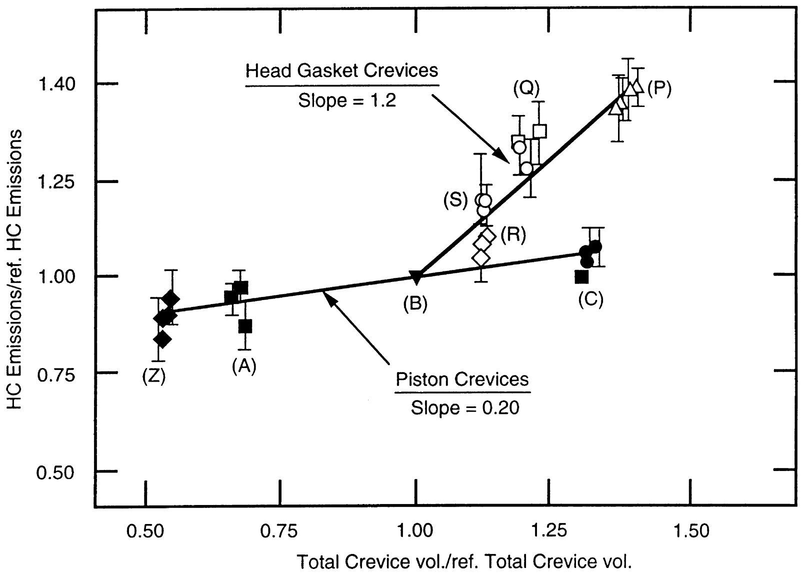

Fig. 11. Sensitivity (slope of linear variation) of HC emissions to the piston crevice and the head gasket crevice [19,20].

obtained recently by an MIT study [19,20] that found the cylinder-head gasket crevice to be very important; in fact, the sensitivity of engine-out HC to the cylinder-head gasket crevice was 6 times larger than its sensitivity to piston top-land crevice (compare slopes in Fig. 11). The sensitivity coefficient, defined as percent change in HC emissions per unit percent change in crevice volume, was about 1.2 for the head gasket crevice. Thus, a decrease of 50% in head gasket crevice is expected to reduce engine-out HC emissions by 60%. Moreover, a 50% reduction in piston crevice is expected to reduce engine-out emissions by only 10%. However, the tests in the MIT study were performed in an experimental engine that had a compressed gasket thickness of about 0.3 mm, which is at least 3 times smaller than present-production engine head gaskets.

Recent experiments at the GM R&D Center on a 4-cylinder spark-ignition engine showed that head gasket crevice had little or no effect on engine-out HC emissions, for a production head gasket thickness of 1.3 mm. Fig. 12 shows comparisons of the exhaust HC concentrations from the test engine for various values of EGR at the two part load conditions, using a standard production (STD gasket) and prototype (PRO gasket) head gaskets of the same compressed thickness of 1.3 mm. Using the prototype head gasket, which was a flush mounted head gasket with minimal crevice volume, instead of the 2 mm recessed production head gasket with a crevice volume of 340 mm^3, resulted in no changes in engine-out HC emissions at the light load condition and for EGR levels below 12%. For higher EGR levels and for the high-load test condition the low-crevice head gasket resulted in very small decreases in engine-out HC emissions (based on 95% confidence analysis).

Under normal engine combustion conditions and low charge dilution, the compressed thickness of 1.3 mm of the head gasket is relatively large in comparison to the two-wall quenching thickness (see Fig. 3); therefore, the flame is expected to enter the head gasket crevice and consume most of the unburned HC. However, under high dilution the head gasket thickness may be of the same order or smaller than the two-wall quenching thickness, and therefore the flame may not penetrate totally through the head gasket crevice with the result of an increase in HC emissions.

3.3. Spark-plug crevices

A spark-plug has two crevices that may cause an increase in the engine-out HC emissions. One is associated with the threads of the plug and the other is the cavity between the central-electrode and the plug body. Adamczyk and coworkers [46] measured a 5% contribution from the spark-plug threads but a 0% contribution from the central cavity of the spark-plug in a combustion bomb experiment. However, Boam and coworkers [7], in a single-cylinder Hydra engine, found that both spark-plug crevices had no detectable effects on engine-out HC emissions.

Recent experiments at the GM R&D Center showed that a four-fold reduction in the central-electrode crevice of the spark-plug (scavenge volume between the central-electrode and the plug body) resulted in a 5–11% reduction in engine-out HC emissions. However, the spark-plug thread crevice was found to have no detectable effect on engine-out HC emissions.[10]

[10] The thread crevice was eliminated by using multilayer Teflon® tape on the threads.

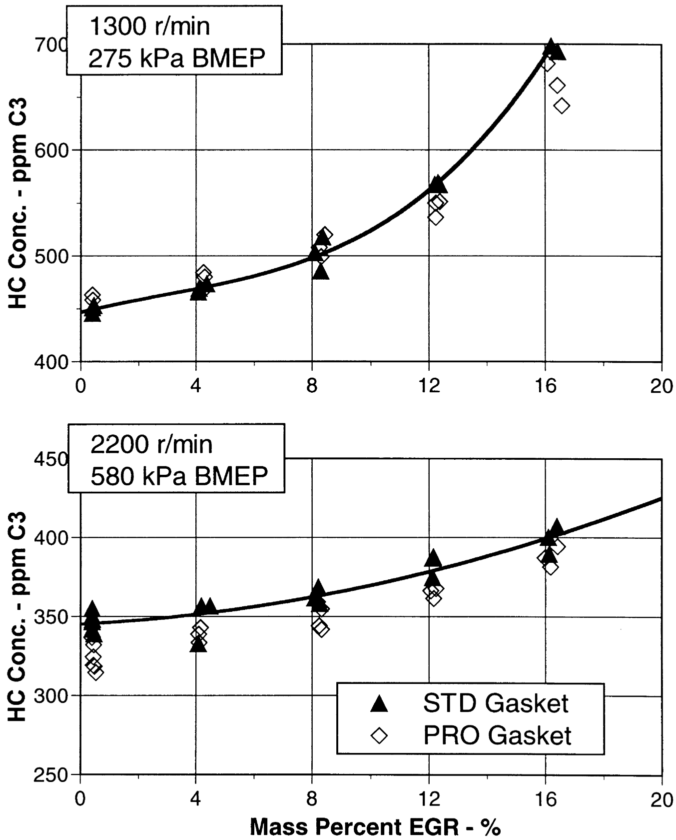

Fig. 12. Comparisons of the engine-out HC concentrations using an STD head gasket and a prototype (PRO) head gasket of the same compressed thickness but with greatly reduced crevice volume.

In Fig. 13, the upper graph shows the corresponding comparison of the variation of the exhaust HC concentration with EGR, and the lower graph shows comparison of the HC–NO trade-off curves. On the average, substituting the spark-plugs with a scavenge volume of 127 mm^3, for the production spark-plugs, which have a scavenge volume of 524 mm^3, resulted in a 42 ppm C_3 decrease in exhaust HC concentration.

4. Transport mechanisms of crevice HC

During the expansion stroke as the piston moves downwards, the outflow of HC from the piston crevices to the combustion-chamber begins shortly after the occurrence of peak cylinder pressure, and by the end of the expansion stroke most of the crevice outflow is completed. This is clearly demonstrated in Fig. 14 which shows computations of the history of the trapped mass in the piston crevices and the history of the mass outflow expressed as percent of the maximum mass trapped in the piston crevices.

In general the outflow of crevice gases into the combustion-chamber is slower than the speed of the piston moving downwards, which suggests that the outflow of the HC from the piston crevices forms a thin layer which is laid down along the liner during the expansion stroke [21,47]. Namazian and Heywood [38], using a phenomenological flow model analysis and Schlieren photography, found that the crevice outflow consists of two types of flow: a low-velocity flow around the circumference of the piston which begins shortly after peak pressure, and a jet-type of flow through the top piston-ring gap, which occurs later in the expansion stroke when the pressure above the ring falls below the pressure beneath the gap. Namazian and Heywood [38] observations of the crevice outflow were during the early and mid-stroke stages of the expansion stroke which as shown from Fig. 14 comprise most of the crevice gas outflow.

An apparently different view of the piston crevice outflow during the *post-flame period* (later stages of the expansion stroke and during the exhaust stroke) was observed very recently by Green and Cloutman [48] using planar laser induced fluorescence (PLIF). Fig. 15 shows the temporal outflow of crevice gas at a location away from the ring gap, and Fig. 16 shows the corresponding outflow from

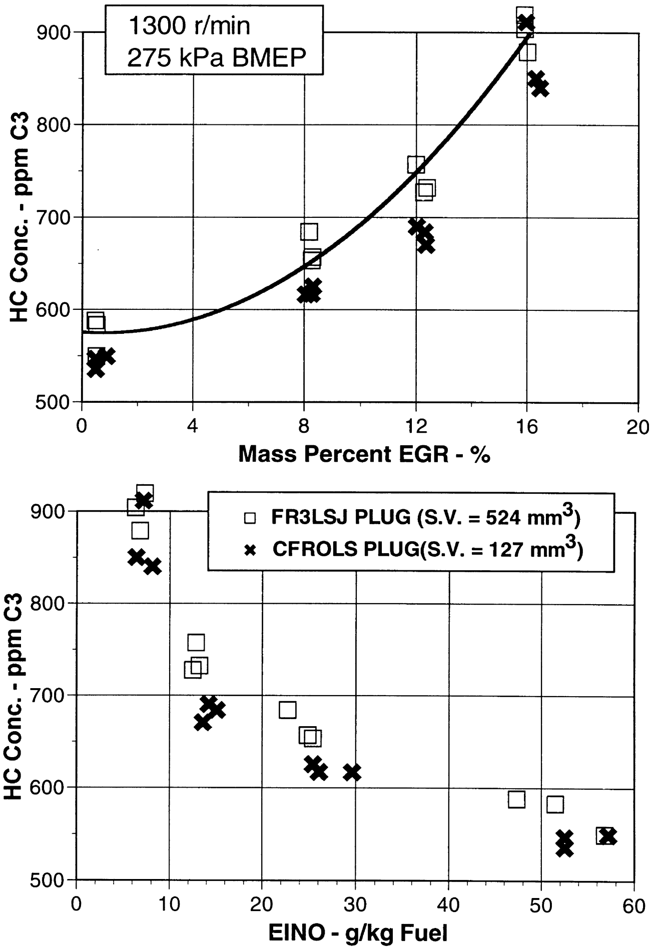

Fig. 13. Comparisons of the engine-out HC emissions using production spark-plugs and spark-plugs with reduced central-electrode cavity upper graph: exhaust HC concentration vs. EGR lower graph: exhaust HC concentration vs. emission index of NO.

the ring gap. For the location away from the ring gap, no crevice-gas outflow is evident prior to bottom dead center (BDC = 540°). At BDC a wall jet comprised of unburned charge is visible exiting the piston crevice and subsequently expanding into the combustion-chamber. As this outflow began at the start of the exhaust stroke, Green and Cloutman concluded that unburned high-pressure charge trapped between the two compression rings escapes, as a wall jet, during ring reversal at BDC. Moreover, for the ring gap location (Fig. 16), the crevice gas outflow begins at about 90° before bottom dead center (460°), which was interpreted [48] as being a low-velocity plume that deposits unburned fuel along the cylinder wall during the later stages of the expansion stroke. The sequence of pictures covering the exhaust interval from 570° to 610° clearly demonstrates the wall layer being scraped into a "roll-up" vortex by the ascending piston.

The HC from the thin layer and those that have diffuse outwards in a region in the neighborhood of the wall are transported out of the cylinder by means of two mechanisms [49] (see also [50]): (i) entrainment in the bulk gases as they exit the cylinder during the exhaust blowdown process, and (ii) vortex motion, which is generated in a region near the piston crown and the cylinder wall.

The transport of crevice HC out of the cylinder is presented schematically in Fig. 17, taken from the work of Lavoie and coworkers [49]. During the exhaust blowdown process, the crevice HC which were laid down along the cylinder wall expand into the bulk gases as the cylinder pressure falls. Some of this HC are being entrained by the rapid motion of the bulk gases, which is generated by the exhaust blowdown. This entrainment process continues during the whole exhaust stroke. Additionally, during the exhaust stroke a roll-up vortex begins to form in the neighborhood of the piston crown and cylinder wall. This vortex sweeps away HC near the cylinder wall. The recirculation flow, which is formed in the upper corner of the cylinder away from the exhaust valve, forces the vortex to detach

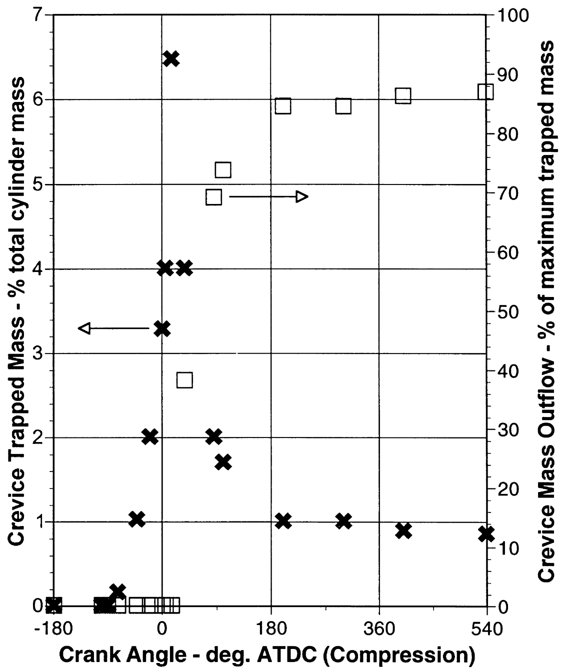

Fig. 14. Computations of the histories of the mass of gas trapped in the piston crevice and of the crevice mass outflow to the combustion-chamber.

itself from the wall and be swept by the bulk gases exiting the cylinder.

Most of the crevice HC[11] which are entrained or diffused into the cylinder's bulk gases are oxidized. The overall rate of HC oxidation depends on the type of fuel as well as on the chamber conditions [52]. For the time scales associated with the transport mechanisms, Weiss and Keck [53], who employed a fast sampling valve in the cylinder of a CFR engine, deduced that complete oxidation of HC occurs for gas temperatures above 1250 K. However, Medina, Green and Smith [54] based on Shadowgraph photography and spontaneous Raman spectroscopy determined that HC exiting a small tube in the combustion-chamber (simulated crevice) did not undergo rapid oxidation at temperatures up to 1400 K. Also, very recently, Eng and coworkers [55,56] deduced from engine experiments that the critical cutoff temperature for post-flame HC consumption was near 1500 K. Also, a numerical simulation study of the post-flame oxidation of HC by Wu and Hochgreg [57] found the critical temperature to be around 1400 K. In contrast, the HC in the layer in contact with the cylinder wall undergo slow oxidation because of the relatively low gas temperatures.[12]

A number of studies, mostly analytical, showed that a large fraction of crevice HC undergo in-cylinder oxidation [21,47,60–65]. Additionally, after leaving the cylinder a significant fraction of the HC oxidized in the exhaust port of the engine [53,66–71].[13] Schramm and Sorenson [59], using a simple, one-step kinetic mechanism of the oxidation of gasoline, found that about 35% of the HC from the piston crevices and from the lubricating oil oxidize in the cylinder, and an additional 35% oxidize in the exhaust port of the engine. Hamrin and Heywood [65] computed that 68% of the HC originated in the combustion-chamber crevices and quench layers undergo in-cylinder oxidation, and 35% of all HC exiting the cylinder undergo exhaust-port oxidation. Min and Cheng [47] specifically studied the oxidation of the piston crevice HC during the expansion process. The oxidation of propane fuel was modeled by one-step kinetic mechanism. They found that the crevice HC which come out in the combustion-chamber during the early part (roughly the first quarter) of the expansion process were almost completely oxidized.[14] This is demonstrated in Fig. 18, which shows the fraction of crevice gas remaining at EVO (exhaust valve opening) as a function of position along the liner. It is clear that there is a "transition" point in the expansion process after which oxidation was not effective and much of the crevice HC survive. This transition point depends on the local temperature which, in turn, depends on the heat generated from the exothermicity of the HC oxidation process. Thus, increasing the piston crevice volume results in an increase in crevice HC outflow, which leads to a higher heat release and, consequently, the "transition" point occurs later in the expansion stroke, as shown in Fig. 18. Conversely, as the piston crevice is reduced, a point may be reached where the crevice HC will not be oxidized in the expansion stroke. These conclusions are in qualitative agreement with the much earlier experimental findings of Weiss and Keck [53].

[11] The crevice HC are predominantly unburned fuel components, and their composition may be significantly different from the in-cylinder fuel, which may have undergone fractional distillation [51].

[12] Based on the work of Min and Cheng [21,47], the initial thickness of the HC layer may be approximately taken as the radial clearance of the piston, the value of which is about 0.4 mm for production pistons. This thickness of this HC layer is of the same order as the thickness of the thermal boundary layer measured by Lucht and coworkers [58]. However, Lyford-Pike and Heywood [59], using Schlieren photography in their square cross-section visualization engine, found that the thermal boundary layer thickness on the cylinder wall of their engine reached a maximum thickness of 2 mm near the end of the expansion stroke.

[13] In contrast, Eng [55] argued that exhaust-port oxidation is relatively small in comparison to the in-cylinder oxidation of HC for low-speed, part-load, near-stoichiometric engine operating conditions.

[14] Also Tonse [72], using CFD simulation of the flow of piston crevice gases into the combustion-chamber concluded that HC outflow which occurs early is totally consumed.

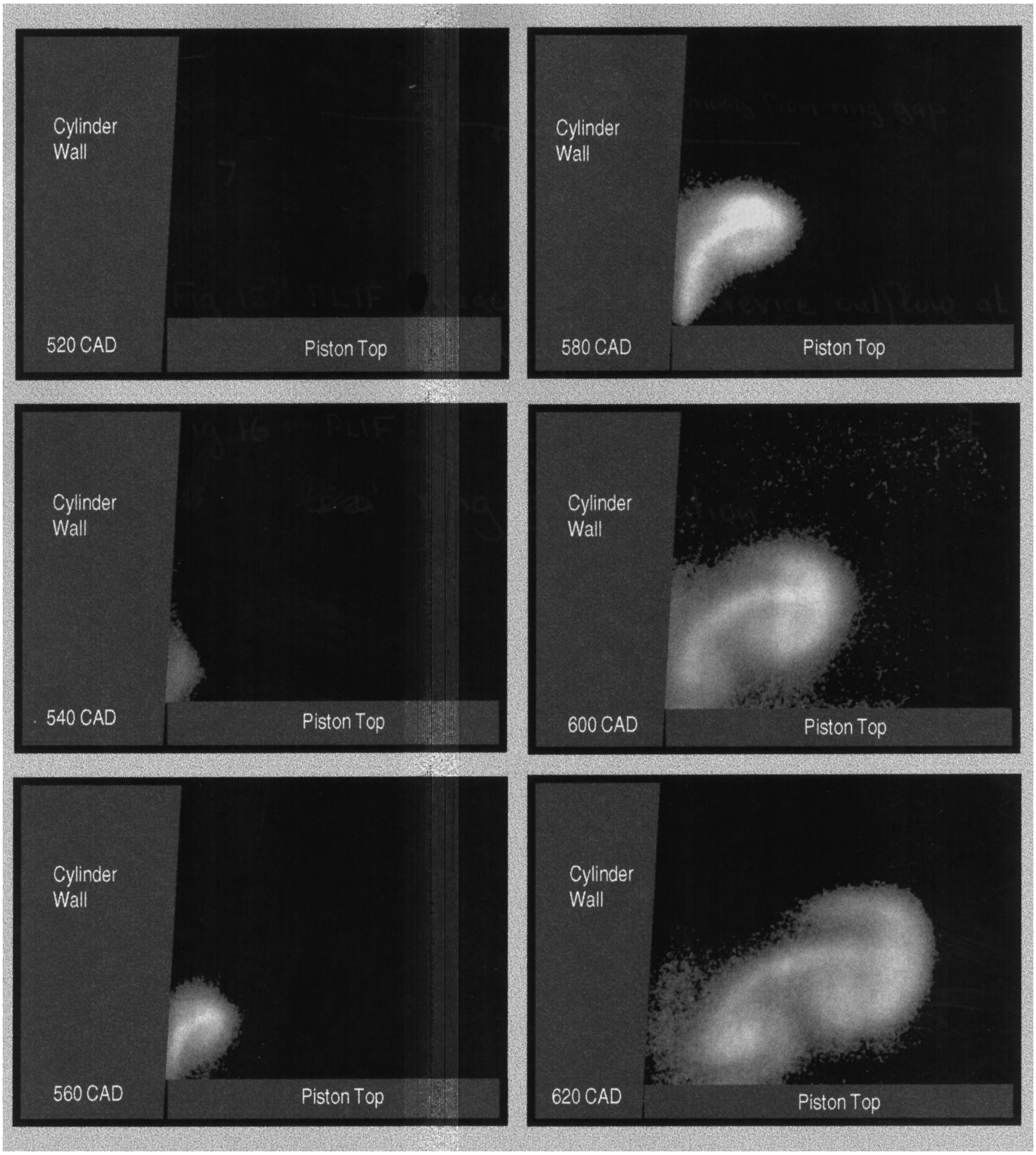

Fig. 15. PLIF images of piston crevice outflow at a location away from ring gap.

The importance of in-cylinder (post-combustion) oxidation of HC is unquestionable. A large fraction of the unburned HC is oxidized prior to leaving the cylinder, a fraction is retained in the combustion-chamber as part of the residual gas, and the remaining fraction, which leaves the cylinder, may undergo further oxidation in the exhaust port. However, the earlier estimates of in-cylinder oxidation and exhaust-port oxidation should be considered with much caution because of the large uncertainties in the mixing and oxidation rates, as well as, in the gas-temperature field of the engine's combustion-chamber.

5. Closure

Of the combustion-chamber crevices, the piston crevices are the main contributors to engine-out HC emissions from present production engines. The head gasket crevice,

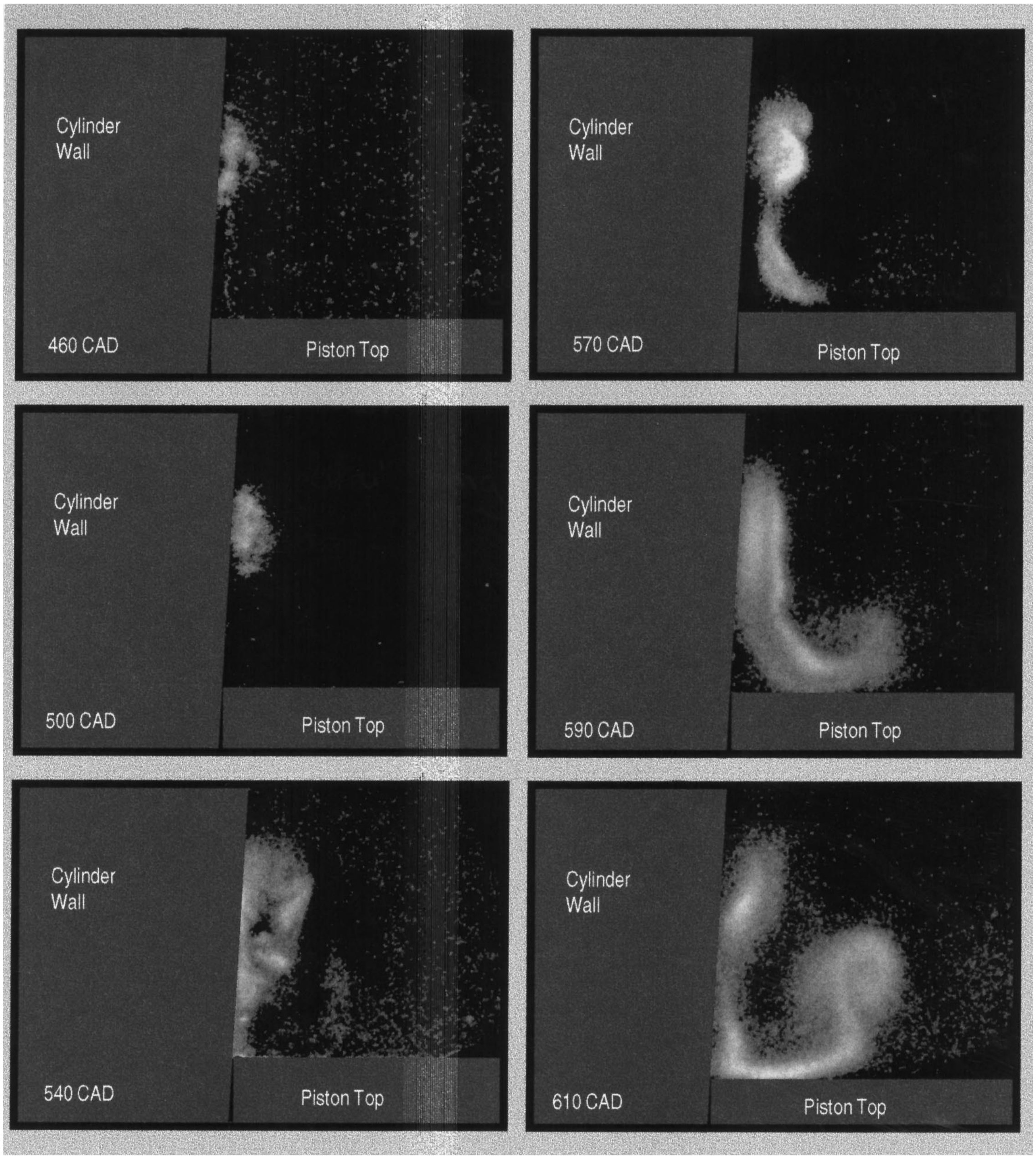

Fig. 16. PLIF images of piston crevice outflow at the ring-gap location.

because of the relative large thickness (1–1.5 mm) of the head gasket, is an important contributor only under high-dilution combustion conditions, such as the idle condition. However, with the recent advancements in thin (~0.4 mm) multi-layer steel head gaskets, which may result in their application to production engines, the head gasket crevice may also become an important contributor to engine-out HC emissions.

The primary strategy to reduce engine-out HC emissions that originate from the piston crevices is to reduce the top-land height and the volume behind the top compression ring. Reducing the top-land radial clearance from its production value (~0.35–0.45 mm) does not have much effect on engine-out HC emissions, except at the idle condition. In contrast, increasing the top-land radial clearance reduces engine-out HC emissions by allowing the flame to propagate deeper into the piston crevice and consume crevice HC; however, this practice is unacceptable because it may

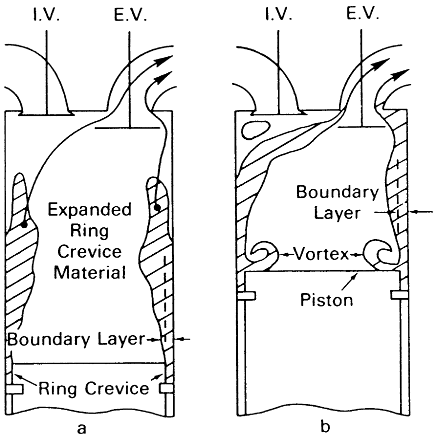

Fig. 17. Schematic of flow processes by which piston crevice HC exit the cylinder: (a) exhaust blowdown process; (b) during exhaust stroke; and (c) end of exhaust stroke.

dramatically reduce the life of the top compression ring. An indirect strategy is to minimize the amount of unburned HC in the piston crevice that return to the combustion-chamber by minimizing the end-gap of the top ring and maximizing the end-gap of the second ring. However this strategy is presently not effective as in most production engines the compression rings are already sized such that the end-gap of the top ring is much smaller than the end gap of the second ring. Further reduction of the end-gap of the top ring was found to have small effects on engine-out HC emissions.

The effectiveness of the volume reduction of piston crevices in reducing engine-out HC emissions is decreased with higher content of burned gases (higher burned gas fraction) in the crevice gases. This burned gas fraction, in turn, is strongly dependent on the location of the spark-plug in the combustion-chamber and on the flow field in the combustion-chamber, which affects the flame propagation. The contribution of piston crevices to HC emissions is highest for a typical four-valve combustion-chamber that has a centrally located spark-plug and a relatively quiescent (low-velocity flow field) combustion-chamber. As the location of the spark-plug is moved towards the periphery of the combustion-chamber and the velocity flow field is augmented by introducing swirl or tumble motion the effectiveness of reducing the piston crevice volume on reducing engine-out HC emissions is diminished.

6. Conclusions

Based on this critical review of past studies on combustion-chamber crevices the following conclusions were reached:

(1) For top-land radial clearances which do not permit the flame to enter the piston crevices, the engine-out HC are linearly related to piston crevice volume. Decreasing the crevice volume decreases engine-out HC emissions. The sensitivity of HC to piston crevices, which is defined as the percent change in HC emissions per unit percent change in piston crevice volume, was found to vary from 0.2 to 0.6. This sensitivity depends strongly on the size of the piston crevices, on the crevice gas composition (unburned gas mass fraction), and on the engine conditions. It decreases with decreasing crevice volume, with decreasing unburned mass fraction of the crevice gases, with decreasing load and speed and with increasing EGR.

(2) The crevice gas composition is strongly dependent on the location of the spark-plug in the combustion-chamber and on the combustion-chamber flow field. The unburned fraction of the crevice gas decreases as the location of the spark-plug moves away from the axis of symmetry of the bore.

(3) The variation of HC emissions with radial clearance has a maximum at a critical value of the radial clearance. The critical value coincides with the onset of the flame penetration into the crevice. For clearances smaller than the critical value, increasing the radial clearance increases HC emissions because of the increase in crevice volume. For clearances larger than the critical value, increasing the clearance decreases HC emissions because it increases the penetration of the flame into the crevice volume.

(4) Increasing charge dilution dramatically increases the two-wall quench distance by reducing the laminar flame speed. This suggests an advantage of stoichiometric-engine combustion over lean-engine combustion with regard to the crevice HC.

(5) Chamfering of the piston crown appears to be a very effective way to reduce engine-out HC emissions. This is believed to be because of primarily the smooth entrance transition section that allows the flame to propagate deeper into the crevice, and may also be as a result of the direction of the crevice outflow gases towards the hot bulk gases, which may promote their oxidation.

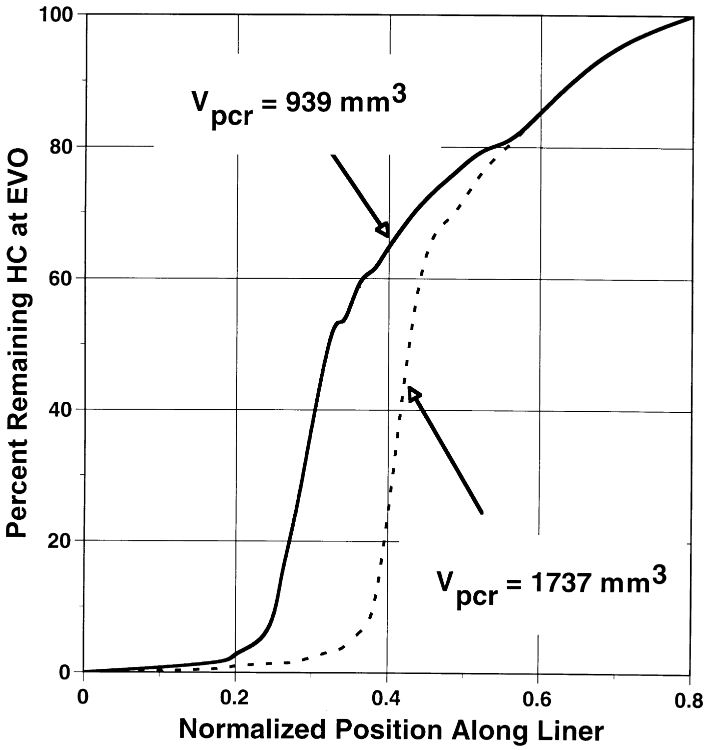

Fig. 18. Percentage of the crevice HC that survives oxidation in the expansion stroke [47].

(6) There is no evidence to suggest that the size of the end gaps of the piston compression rings significantly affect engine-out HC emissions. Nevertheless, the practice of making the end-gap of the second ring much wider than the end-gap of the top ring, which is intuitively correct for minimizing the crevice HC returning to the combustion-chamber, should continue. Also, increasing the volume of the piston second land appears to have little effect on engine-out HC emissions.

(7) The head gasket crevice of current production gaskets of thickness of 1–1.5 mm does not contribute significantly to engine-out HC emissions. However, the crevice of head gaskets of reduced thickness (~0.4 mm) is expected to increase significantly engine-out HC emissions because of the reduced oxidation potential in comparison to piston crevices.

(8) Reducing the central-electrode crevice (scavenge volume between electrode and plug body) results in a modest decrease in engine-out HC emissions. A four-fold reduction in this crevice resulted in 5–11% reduction in HC emissions. However, spark-plug thread crevice was found to have no detectable effects.

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