

Reduced Convective Combustion Chamber Wall Heat Transfer Losses of Hydrogen-Fueled Engines by Vortex-Stratified Combustion - Part 1: Background and Optical Engine Observations

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ABSTRACT

A vortex-stratified combustion process for hydrogen-fueled reciprocating internal combustion engines is introduced to increase the thermal efficiency by reducing the convective heat transfer losses to the surrounding walls during combustion. The process imposes a highly ordered rotational field upon the charge in a separate, transverse, cylindrically shaped combustion chamber by means of channels that connect with the main chamber enclosed by the engine cylinder and piston. Gaseous hydrogen is injected directly during the compression stroke, while air enters into the combustion chamber tangentially and preferentially along the circumference due to the Coandă effect. The two streams entrain one another and develop into a vigorous vortex by virtue of the chamber and channel geometries. As mixing proceeds, the fuel is confined radially from the combination of finite-time diffusion being outpaced by the replenishment of pure air at the periphery, and the centripetal field formed by the rotating flow acting on the different density gas mixture. Combustion takes place with a flame propagation that initially follows the rotation of the bulk flow, and then curls radially inward toward the center. This work investigates the process in a fired, optically accessible 2-stroke hydrogen-fueled direct-injected engine tested at up to 5000 RPM. This paper, the first of two parts, explains the theoretical background; presents the schlieren observations; results of zero-dimensional cylinder pressure indication; and apparent heat release measurements comparing two combustion chamber designs - one that actualizes a homogeneous mixture without specific charge motion directionality, and another with the here-introduced vortex-stratified approach.

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INTRODUCTION

With the conventional spark-ignited reciprocating ICE being under constant development and improvement for over a century, it has become apparent that a technological barrier is asymptotically approaching from being able to extract further step-wise thermal efficiency improvements. Doing so will necessitate novel approaches to reduce thermodynamic losses, namely incomplete and real combustion, wall heat transfer, pumping losses and friction, as shown in Eq. 1:

$$\eta_{th,brake} = \underbrace{\eta_{th,ideal\,cyc.} - \Delta\eta_{inc.\,comb.} - \Delta\eta_{real\,comb.} - \Delta\eta_{wall\,heat} - \Delta\eta_{pumping}}_{\eta_{th,ndnet}} - \Delta\eta_{friction} \quad (1)$$

Of these, Verhelst and Wallner (2009) [1], Eichlseder et al (2003) [2], Wimmer et al (2005) [3], Shudo (2007) [4] and several other researchers [5, 6, 7, 8, 9] identified wall-heat transfer as the predominant factor of reduced efficiency in hydrogen-fueled engines, and a key factor to its improvement. Oppenheim (2002) proposed an air-blast atomizer to direct the combustible charge away from the walls to prevent contact of the latter with hot combustion products

and reduce heat transfer losses [10]. Heitland et al (1998) [11] showed several concepts of confining the combustion in a fireball surrounded by a layer of residual gas using air blast valves similar to those proposed by Oppenheim. Shudo and Oba (2009) [8] also stressed the importance of reducing heat transfer from the burning gas to the combustion chamber wall for improving the thermal efficiency in hydrogen engines. They found that the cooling loss fraction with hydrogen was about double that of methane (both operating stoichiometrically) over a range of tested ignition timings, and employed a split-injection technique to direct high equivalence ratio mixtures at a desirable position such as the spark plug, and slow the diffusion toward the walls in order to control the spatial distribution of the mixture for achieving cooling loss reduction and thermal efficiency improvement in hydrogen combustion engines.

Therefore, the main overall objective of the present work is the systematic mitigation of wall heat transfer losses by some means of imposing a designed regime of charge and flame extent stratification in the combustion chamber for reduced thermal convection. Here it is proposed to achieve this by a novel method of confining the fuel-concentrated charge in the geometric center, located directly down with an insulating layer of essentially pure air at the periphery

adjacent to the walls that is substantially maintained during combustion. A theoretical framework describing the flow dynamics of the proposed system is provided. Schlieren observations from an experimental optically accessible engine are presented. The visualizations demonstrate the effectiveness of the vortex-stratified concept in setting up the vigorous rotational flow field that forms a radial density gradient on the prepared charge mixture before ignition, which indicates a gas species stratification. The second part that proceeds this paper provides an understanding of the basis for heat transfer loss reduction by correlating the experimental observations presented here with CFD analysis that illustrates the vortex-stratification of gas species in greater detail than is possible from schlieren images alone, and quantifies the heat flux, which is found to be 50% less compared to a combustion chamber design that actualizes a homogeneous mixture without specific charge motion directionality, with injection timing and all other model parameters remaining equal.

BACKGROUND

Wall Heat Transfer Losses

In the absence of appreciable bulk motion, turbulence, mixture composition non-uniformity and local temperature variations in the unburned charge, a premixed, spark-initiated flame front expands roughly spherically from the point source of ignition with a thin reaction sheet at the laminar flame speed S_L . Increased turbulence levels cause a wrinkling and convolution of the flame front and greatly enhances the burning rate [12]. The flame front propagates throughout the combustion chamber until extinguished by one or more factors such as oxygen depletion, fuel availability within combustible limits, or by quenching. Norton and Vlachos (2003) state that flames are quenched because of two primary mechanisms: thermal and radical [13]. Thermal quenching dominates here and occurs when sufficient heat is removed through the walls that combustion cannot be self-sustained.

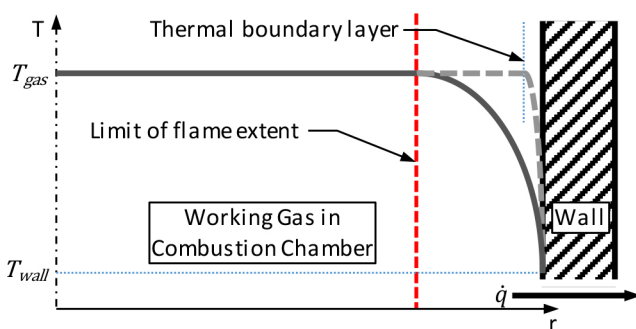


Figure 1. Schematic showing in-cylinder temperature profiles. The long-dash curve indicates the temperature profile in conventional combustion; the solid curve with limited flame extent.

The prevailing burned gas temperature can be approximated as substantially constant throughout the combustion chamber but with a steep gradient in the thermal boundary layer adjacent to the wall until it matches with that of the gas-side of the wall surface, as shown with the long-dashed curve in Fig. 1. If the extent of the flame can be limited to some distance from the wall (red dashed line) - greater than the thermal boundary layer thickness and inherent flame quenching

distance but without leaving any unnecessary unburned fuel to affect the combustion efficiency deleteriously - the temperature profile would take the shape as sketched qualitatively with the solid curve with a resultant reduced heat flux to the wall.

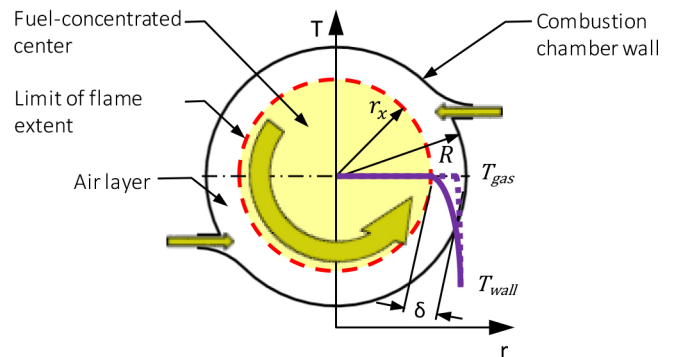


Figure 2. Schematic showing the flame-extent stratification process. Incoming air entering into the combustion chamber through the two side channels impart a rotational flow as indicated. Temperature profiles are sketched over with the dashed curve indicating conventional combustion; the solid curve with limited flame extent.

Vortex-Stratified Combustion

Figure 2 shows a 2D schematic of a cylindrical combustion chamber of radius R , although in general it could be of arbitrary geometry. Here, it is realized as separate from the main chamber containing the piston and cylinder, and connected with channels, of which there have been many different design embodiments over the years, variously called divided-chamber, auxiliary-chamber, turbulent-chamber, pre-chamber, swirl-chamber, etc. In the proposed process, a rotational flow would be imparted from incoming jets of air from the main cylinder entering into the combustion chamber through two side channels offset vertically from the center. The directly injected fuel would be concentrated within combustible limits - which also limits the extent of the flame - to a radius r_x , and the difference δ makes up the width of the air layer. The flow is said to be highly ordered because the channels and geometric symmetry impart momentum in 2-dimensions, while the component along the centerline axis is negligibly small. The resulting motion is one of bulk rotation and minimal cross flow.

Toulson et al (2010) gives an extensive review of pre-chamber initiated jet-ignition combustion systems derived from SI engines [14]. While the present work can be considered a form of turbulent jet or "torch" ignition system, important distinctions also become apparent:

1. The review focuses upon small pre-chamber systems whose volume comprises <3% of the total clearance volume. Here, it is in the order of 50% and furthermore, it is preferable that this proportion be maximized. In fact, in the ideal, limiting case, there is no divided chamber and there is no criteria for one at all; the principle described in this work can completely dispense with the separate volume and ostensibly be realized as an open combustion chamber of arbitrary shape formed by the geometry of the cylinder, head and piston crown that avoids additional surface area, as well as the throttling and thermal losses associated with the narrow connecting passages, thereby further

improving the thermal efficiency in the same manner seen in direct-injected Diesel engines over the indirect-injected ones;

2. Torch-ignition systems are premised upon a stoichiometric to slightly rich fuel-air mixture inside the pre-chamber located within or in close vicinity to the spark plug electrode gap in order to establish a robust flame kernel, which in turn issues into and burns up a much leaner mixture in the main cylinder volume at faster rates than can be achieved with uniformly lean mixtures; the overall or global mixture trapped and burned in each cycle remains lean or stoichiometric. Here, all the fuel is injected into the divided chamber and the main cylinder is desirably composed of only pure air, like an indirect-injected Diesel engine. Therefore, the heat release takes place and completes substantially within this chamber, so that only already burned gas issues through the connecting channels, which transfers heat to the main cylinder via mass transfer, mixing, conduction and convection rather than by a secondary combustion process;
3. Pre-chamber concepts have one or more connecting orifices designed to produce a highly turbulent flow but no ordered motion within the chamber [12].

At least since the mid-1970s, there has been work on a different classification of divided-chamber SI engines resembling the Ricardo Comet swirl chambers commonly seen in indirect-injection Diesel engines [15, 16, 17]. Like the Diesel counterpart, charge air enters from the cylinder into the swirl chamber tangentially, imparting a rotational flow. Unlike the Diesel process, however, the main cylinder charge still contains a lean fuel-air mixture rather than air alone. Additional fuel is introduced directly into the swirl chamber by means of an injector or valve. Peterson and Alkidas (1983) [18] show that the velocity near TDC in a divided Ricardo Comet swirl chamber using a rapid compression machine is in the order of $15\text{--}20 \pm 5$ m/s at the center and outer extents of the chamber, respectively. Since the velocity does not scale with the radius, the air motion cannot be characterized as a solid-body rotation. In contrast, the charge motion in this work will be shown to behave closely to solid-body rotation through a wide range of radii at up to 5-10 times higher tangential velocities, and by consequence much higher angular accelerations.

Arcoumanis et al. showed the advantages of extending the lean combustion limit and enhanced burn rate offered by local charge stratification near the spark plug within an overall ultra-lean rotating mixture. The constant volume chamber had a tangential port for admission of a lean charge and the rotating bulk flow had mean velocity of up to 8 m/s [19].

Although superficial similarities might be noted between the surveyed and the present works, the authors know of no literature or working concept to date that specifically exploit the combined mechanisms of the gravitational effects of a rapidly rotating vortex flow on different-density gases and the Coandă effect to achieve the proposed simultaneous charge confinement and stratification in premixed-charge engines.

THEORETICAL FRAMEWORK

Flow Dynamics

Diffusion J of any species combination is explained by Fick's first law as given in Eq. 2:

$$J = -D\nabla c \quad (2)$$

The diffusive coefficient is denoted D and the negative sign indicates that the mass flux follows along a decreasing spatial concentration gradient ∇c . If one considers two initially separated chambers each containing pure, quiescent gas of one type or another, when the partition is removed, diffusion of the two streams will take place at the prevailing diffusive coefficient - for hydrogen-air, this is given as $0.61\text{E-}4$ m²/s at 300 K and 1 atm [1] - until the concentrations of both gases reach equilibrium spanning the combined volume, thus $\nabla c \rightarrow 0$.

Turbulence and charge motion greatly enhance diffusion, which allow homogenization of the introduced fuel-air mixture over the space of the combustion chamber in the very short timescales encountered in engines. Heywood states that turbulence levels scale linearly with engine speed (specifically mean piston speed) [12]. Increased turbulent flame speeds and burning rates therefore follow, such that the combustion duration in SI engines have been observed not to increase dramatically in crank angle degrees at higher engine speeds, but take place proportionally quicker in the time domain.

Three predominant forces act upon the motion of a fluid: Buoyancy acts in the direction of Earth's gravity; molecular diffusion in all directions; and centripetal acceleration force radially from the axis of rotation. Where these forces are in balance, per Newton's first law of motion, there is nothing to compel a change in the state of motion of a particle or body. Importantly, diffusion can be hindered in the radial direction of a polar coordinate system if centripetal forces dominate. Also, diffusion can be slowed or reversed in a fixed frame if the velocity of one entraining species exceeds that at which diffusion proceeds; in effect, the rate at which species 1 (here assumed to be hydrogen filling the volume initially for illustration) diffuses into the entraining species 2 (e.g. air) is exceeded by the replenishment of air behind the interface of the two species.

Centripetal Flame Confinement

Lapsa and Dahm (2009) investigated hyperacceleration effects on turbulent combustion in premixed step-stabilized flames [20]. In that work, premixed propane and air is introduced into a U-shaped channel with a semicircular combustion zone at varying flow velocities, so that the centripetal acceleration is related by Eq. 3 and exceeds the range of ± 10000 g.

$$a_c \equiv \frac{v^2}{r} \quad (3)$$

They report that high centripetal accelerations induce large body forces on the high-density cold reactants and high-density products. The direction of the body force facing step - radially

outward or inward in the channel - have different effects, either to force high density reactants into the recirculation zone and lower density products radially inwards into the reactant stream in the first case where $|a_c| \rightarrow +\infty$, or vice versa. This first case gives rise to a virtuous centrifugal pumping mechanism - a region of vigorous mixing and flame convection across the channel at dramatically enhanced rates. Conversely, for $|a_c| < 0$ using a radially inward step, as the acceleration level is increased the resulting body forces become sufficiently large that flame propagation is suppressed by the forced segregation of the reactants and products. The result is that the flame becomes nearly flat as large-scale distortions of the interface between high-density reactants and low-density products become essentially impossible; the flame is forced increasingly close to the radially inward wall as the body forces impede it from propagating across the channel. Although this latter case is considered inferior in terms of combustion efficiency for the U-shaped channel in the work of Lapsa and Dahm, here it is the desired mechanism to be exploited.

Coandă Effect

Dumitrache et al (2012) give a detailed analytical solution that approximates a two-dimensional Coandă flow for both laminar and turbulent regimes in curvilinear coordinates [21]. The phenomenon that is exploited is the tendency for a flow to attach to and follow over a convex surface: The incoming flow from the main cylinder, taken to be pure air, thus remains substantially attached to the peripheral wall of the combustion chamber. A critical point is reached where the flow detaches or lifts-off from the convex surface, which is related to the free-stream velocity, viscosity of the fluid and the radius of curvature. Here, the Coandă effect introduces an additional degree-of-freedom for the optimization of wall heat transfer. Convection is greatly affected by the turbulence level and therefore velocity fluctuations in the thermal boundary layer. Absent any stratification, with burning of the fuel-air mixture until the flame is quenched by the wall, convection is further enhanced by high flow velocities. In an optimized design, the Coandă effect could be exploited using fillet radii in the transition from the channels to the combustion chamber to set up an initial attachment of the pure air flow to the surrounding chamber walls to promote charge stratification and favor rotation in the desired direction. As the compression stroke proceeds and velocity increases, the flow would detach from the surface and the incoming fluid momentum is imparted to the inner radii of the rotating flow, forming another stratification, this time of tangential velocity with respect to the radius. Thus, the fuel-concentrated core would have a high velocity for rapid mixing and combustion, but the flow of pure air at the periphery would rotate at a relatively lower angular speed to inhibit convection.

DESIGN

The basic geometry of the conceived divided combustion chamber is a cylinder with connecting channels to the main cylinder volume that are vertically offset from the centerline to impart a rotating vortex flow in a counterclockwise direction from the frame of observation. This is illustrated in Fig. 3 (left-half). One side of the interface between each channel and the chamber is radiused, while the other side is left sharp to promote attachment of the flow to the radial periphery of the cylindrical wall along the direction of rotation due to the Coandă effect. Ports in the two-stroke engine are not shown.

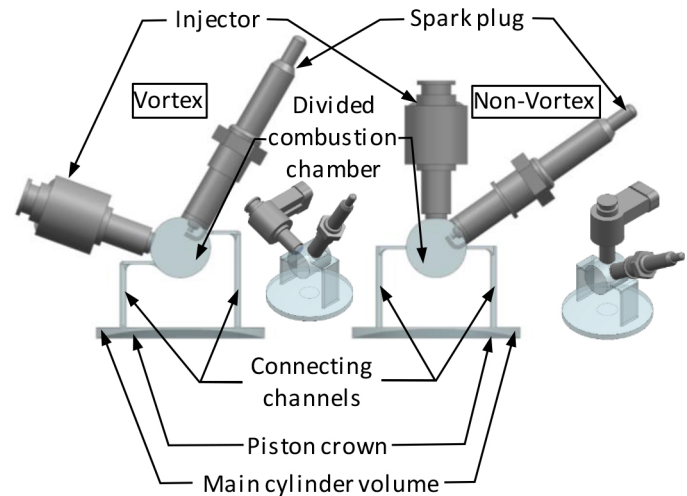


Figure 3. CAD renderings of vortex (left-half) and non-vortex (right-half) divided combustion chambers with connecting channels, injector, sparkplug main cylinder volume and piston crown depicted at TDC.

For comparative purposes to the vortex-stratified approach described above, a combustion chamber design that represents current engine practice with homogeneous charge mixture is provided, as shown in Fig. 3 (right-half). The directly opposed layout of the side channels cause the incoming air jets to impinge upon one another during the compression stroke, resulting in high turbulence, but no particularly ordered motion as defined in the introduction - although noting that high-tumble designs are presently commonplace for SI engines.

The choices of significantly raised, transverse, cylindrically shaped divided chambers and straight, diametrically positioned channels are compromises between the need to realize optical access, and achieve thorough mixing and high turbulence levels of the prepared charge before ignition. The resulting long, narrow channels and right angles connecting the divided chamber to the main cylinder are also compromises to be able to realize optical access while achieving a high compression ratio, and also to introduce a well-developed flow into the combustion chamber with a minimum of undesired charge motion in other directions - cross-swirl and cross-tumble - apart from the plane of observation. The high flow velocities through the channels and 90° turns would result in high thermal and pressure losses. However, this was accepted because the objective was not for a geometry optimized for efficiency or performance per se, but rather to be able to study the flow phenomena in the visible cylindrical cross section of the combustion chamber. Both vortex and non-vortex designs are otherwise very similar, employing the same diameter (20 mm) and length (20 mm) of the cylindrical portion, and nearly identical total clearance volumes; the only significant differences being the vertical positioning of the connecting channels and, due to packaging constraints, orientations of the bespoke Synerject Strata gas injector and NGK CPR9EA extended nose insulator spark plug. Both designs yield calculated nominal geometric and effective (trapped) compression ratios of 10.5 ± 0.25 and 7.3 ± 0.17 , respectively, and k-factor - defined here as the ratio of the volume of the cylindrical chamber and the total enclosed fluid clearance volume at piston TDC - of 0.5.