Axial Pressure and Wall Heat Flux Distribution of a Porous Injector Head (API)

J. Deeken⋆† *and D. Suslov*⋆
⋆*German Aerospace Center - DLR*
Hardthausen, Germany, Email: Jan.Deeken@dlr.de
†Corresponding author

Abstract

Injector design is of utmost importance for the performance and stability of liquid rocket engines. The design of the injection system determines the combustion efficiency as well as the thermal loads to the combustion chamber wall. The wall heat flux is an important parameter for the design of a combustion chamber, especially in the case of an expander or expander-bleed engine cycle like Vinci or LE-5B. Recent investigations showed that a porous injector head (API) can provide a higher total wall heat flux compared to a conventional coaxial injector, resulting in a reduced chamber length and mass for an expander-type engine.[2] The location of the main heat releases zone in the combustion chamber marks the onset of the high wall heat flux region. The heat release distribution in the combustion chamber can be linked to the axial pressure profile. The influence of injection parameters and geometry of API-style porous injectors on the axial pressure profile was investigated in multiple hot-fire test campaigns. They were conducted using 50 mm sub-scale combustion chambers at chamber pressures ranging from 30 to 100 bar and O2/H2 mixture ratios ranging from 4 to 6. This article reports the methodology used to compare the axial pressure distributions and identifies the main parameters governing their shape.

1. Introduction

1.1 Characterization of injection systems

The performance of an injector system for liquid propellant rocket engines (LPRE) is usually given by the achievable combustion efficiency η_{c^*}. Apart from this main performance parameter, other parameters are of relevance for the characterization of a liquid propellant injection system. Including the aforementioned combustion efficiency, these are:

- Combustion efficiency
  This main parameter represents the ratio of actually attained to theoretically attainable characteristic velocity c^*. A value close to unity indicates a complete combustion of the injected propellants inside of the combustion chamber volume.

- Combustion roughness
  The combustion roughness is usually given as the RMS value of the pressure fluctuation normalized by the mean pressure, measured in the combustion chamber close to the injector face plate. Values smaller than $5\,\%\bar{p}_{CC}$ indicate a smooth combustion.

- Wall heat flux profile
  The heat flux to the combustion chamber liner is determined by the rate of heat release due to the reaction and other factors like the injector element to wall spacing, the injector/injector spacing in the outer row of elements, film cooling measures or chamber curvature.

- Axial pressure distribution
  The axial pressure evolution is related to the axial heat release profile and the geometric features of the combustion chamber itself. Its relevance for the characterization of injection concepts will be emphasized in this publication.

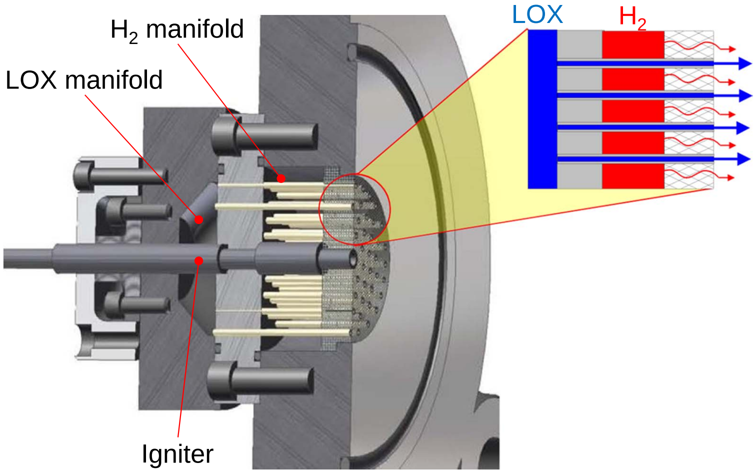

Figure 1: Principle layout of a porous injector head (API)

In practice, the achieved combustion efficiency and the heat flux profile are the most important injector-related parameters for the design of a thrust chamber assembly. The combustion efficiency of a liquid propellant injection system determines the achievable combustion chamber pressure and therefore the performance of the whole engine. It can be directly measured using sub scale test hardware. The results are representative of the full scale application. The wall heat flux profile dictates the cooling method and amount of coolant applied to protect the combustion chamber from failure. The integral wall heat flux is an important parameter for the layout of expander cycles and its variants, where the heat picked up in the cooling channels is needed for the operation of the turbomachinery. The wall heat flux profile can also be determined by sub-scale testing. The actual heat flux profile is also influenced by the geometrical features of the injection system and the combustion chamber. Depending on the specific injection system used for the sub-scale investigations, important geometrical features may not be readily scalable between the full-scale and the sub-scale case. For a coaxial injector these geometrical features could be the injector/wall and the injector/injector distance. The combination of values for the full-scale injector is often hard to match in a sub-scale test hardware. Still, sub-scale test are often employed to investigate the heat flux distribution of a given injector system.
The axial pressure distribution inside the combustion chamber is directly related to the rate of propellant conversion into hot gases and to the shape of the chamber contraction. The pressure drop in a cylindrical combustion chamber is depending on the nozzle contraction ratio and the hot gas properties. For typical nozzle contraction ratios and gas compositions, this pressure drop is about 5 to 10 % of the chamber pressure at the injector end. The shape of the pressure profile in the cylindrical chamber section contains useful information about the position and shape of the main heat release zone. A steep slope indicates a region of intense reaction, whereas an almost constant pressure level indicates a gas composition at near equilibrium conditions. For the porous injector, the axial pressure profile and therefore the heat release distribution changes with varying injection conditions and injector layouts. As the pressure can be assumed to be uniform across a cross section of the combustion chamber, the actual injector/wall distance has only minor influence on the axial pressure profile. Therefore, the results obtained in sub-scale tests are representative for full-scale injector configurations.

1.2 Porous injectors (API)

The API (*Advanced Porous Injector*) concept was developed at the DLR Institute of Space Propulsion in Lampoldshausen. It aims at reducing the overall complexity of the injector component compared to a conventional coaxial injector while at the same time retaining the high combustion performance. This injector concept was investigated in multiple publications by different authors over the last decade.[1–7] A porous injector consists of a multitude of small diameter tubes for LOX injection and a porous face plate covering the entire cross section of the combustion chamber, which is used for a homogeneous injection of the gaseous fuel (e.g. hydrogen). This basic layout is illustrated in figure 1. The exact location of the individual LOX injector elements is of only minor importance for the combustion performance of the whole injector assembly. Tight manufacturing tolerances are not required for this injector design.
This injector layout results in multiple striking differences regarding the propellant injection in comparison to a conventional coaxial injector. First, the entire fuel mass flow is injected through the porous face plate. This results in

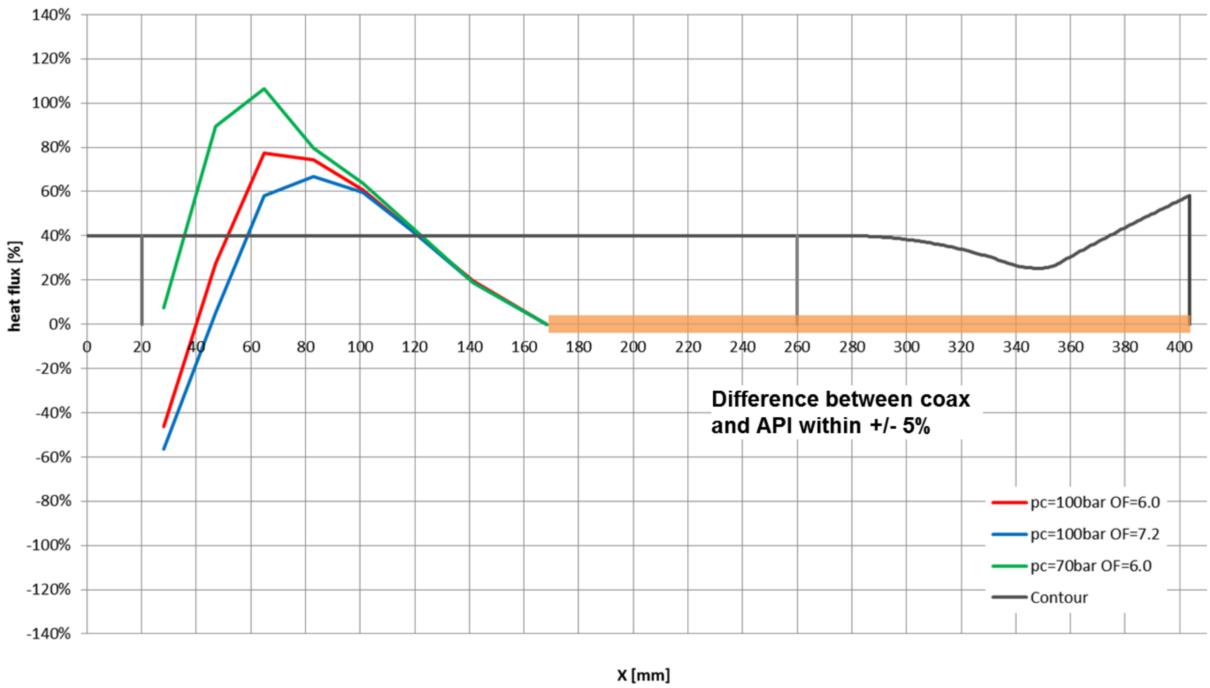

Figure 2: Axial heat flux distribution of an API-style porous injector configuration in relation to a state-of-the-art coax configuration at identical operating conditions[2]

exceedingly low injection velocities on the fuel side. For typical MCC conditions, the hydrogen injection velocity is about 10 m/s. The number and size of the LOX injector tubes is chosen to provide for typical injection velocities ranging from 10 to 30 m/s. The resulting shear forces at the injector tip are very low compared to those for a coaxial injector. Another difference is the large number and small inner diameter of the LOX injector tubes. Compared to conventional coaxial injectors this results in an about three times larger contact surface between the injected LOX and hydrogen. These two main differences in injection conditions between porous and coaxial injectors indicate an entirely different atomization mechanism for the API. Former investigations led to the conclusion, that increased vaporization rates (due to the large contact surface) and shear forces between the slow, high-inertia LOX jets and the accelerating combustion gases are the main drivers of propellant atomization for a porous injector. The mean chamber flow is accelerated from the injection velocity (about 10 m/s) to the mean velocity of the reacted flow before entering the nozzle contraction (typically about 300 to 500 m/s, depending on contraction ratio) over a distance of approximately 100 mm. The necessary shear forces for an efficient propellant atomization are therefore imposed by the combustion chamber flow field and not by the injector itself.
The feasibility of this concept has been proven in multiple hot-fire test campaigns at the test bench P8 in Lampoldshausen. It showed a slight increase in combustion efficiency compared to a state-of-the-art coaxial injector.[2] Another important difference to the behavior of a coaxial injector is illustrated in figure 2. This graph shows the axial wall heat flux profile of a porous injector normalized by the heat flux profile of a coaxial injector at the same operating conditions. At about 170 mm distance from the injector face plate, the heat flux profile is almost identical for both injector configurations. The porous injector shows a higher wall heat flux in the upstream part of the combustion chamber. The main heat release zone is located closer to the injector face plate compared to a coaxial injector. This is due to the very low injection velocities. The flame is not carried as far downstream by the high fuel momentum as in the case of a coaxial injector. The relative heat flux profile is illustrated for three load points. The increase in wall heat flux for the porous injector gets stronger with decreasing injection momentum. Two conclusions can be drawn from these results:

1. A porous injector is a good choice for an injection system for expander or expander-bleed cycle engines, which rely on a sufficiently high heat flux to the cooling fluid in order to drive the turbomachinery. An earlier onset of the high wall heat flux region results in shorter combustion chamber lengths and accompanying weight saving.

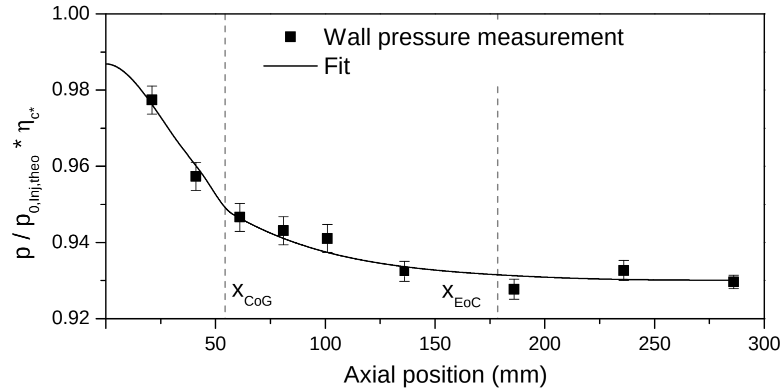

Figure 3: Axial pressure profile of a porous injector head

2. The position of the main heat release zone and therefore the shape of the axial heat flux profile can be controlled by a suitable design of the porous injector.

The influence of injector related parameters on the position and extend of the main heat release zone has been investigated by an evaluation of the axial pressure profile under various conditions. The methods applied to characterize the axial pressure profile and the results from multiple hot-fire test campaigns are presented in this paper.

2. Axial pressure profile evaluation

A typical axial pressure profile of a porous injector operated with a cylindrical combustion chamber is given in figure 3. A large number of static pressure measurements along the chamber wall is desirable for an evaluation of the axial pressure profile. These pressure taps are concentrated in a region of the combustion chamber where the largest axial pressure gradients are expected. In the case of a porous injector, this region stretches from approximately 30 to 130 mm downstream of the face plate. Typically, most of the pressure measurements are concentrated in this region of the most intense heat release.
To compare the axial pressure profile at different operating conditions, it is convenient to transfer the gathered pressure data at various locations into a small number of scalar parameters. These scalar parameters should capture the essential features of the pressure distribution. Since designers are mostly interested in the heat release distribution of an injector concept, these parameters should be based on the axial pressure gradient rather than on the axial pressure profile itself. The pressure gradient indicates regions of intense or negligible reaction and therefore heat release. Two parameters are defined to characterize the axial pressure distribution:

1. The center of gravity of the axial pressure gradient profile: x_{CoG}
   This parameter indicates whether the pressure drop in a combustion chamber occurs close to the injector face plate or further downstream. It is calculated as a simple center of gravity of the pressure gradient derived from static pressure measurements:

$$x_{\mathrm{CoG}} = \frac{\int x \cdot p'(x)\, dx}{\int p'(x)\, dx} \tag{1}$$

   Figure 4 shows some examples of arbitrary pressure profiles and their corresponding values of this parameter x_{CoG}. An early onset of a steep pressure drop results in a small value of x_{CoG}, whereas a constant negative pressure gradient results in a larger value of x_{CoG}.

2. The position at which pressure losses become negligible: x_{EoC}
   This parameter indicates the position at which the pressure is approaching a constant level. In a cylindrical combustion chamber this is equivalent to a negligible rate of propellant conversion. The chamber mean flow has reached its maximum velocity in the cylindrical part of the combustion chamber and any mixing imperfection is likely to persist beyond the nozzle throat. Such a combustion chamber could be truncated to that length without major penalty in combustion efficiency. This position is arbitrarily defined as the position where the remaining pressure drop is smaller than 2.5 % of the total pressure drop in the cylindrical chamber section.

   Both parameters are also illustrated in figure 3.

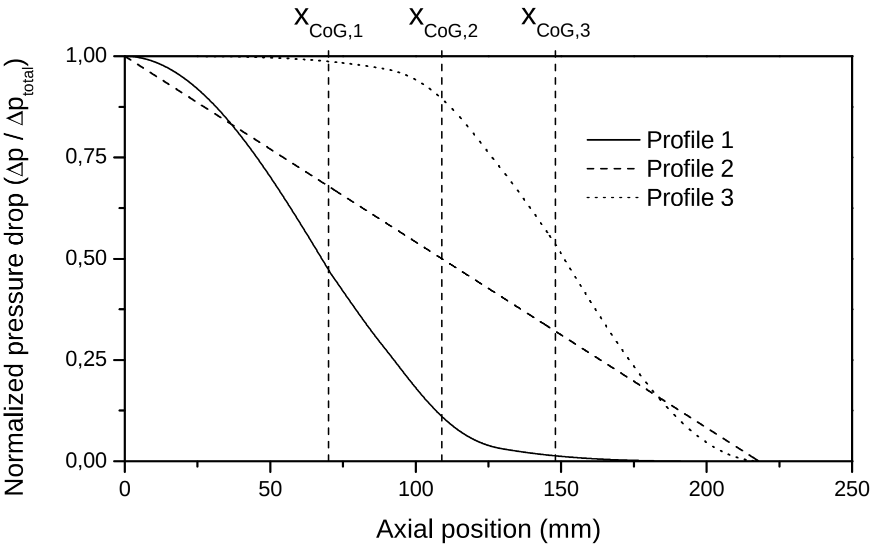

Figure 4: Examples of pressure distributions and corresponding values of x_{CoG}

3. Experimental setup

The experiments reported here were performed with 50 mm sub-scale combustion chambers and injectors. Different injector configurations were tested to investigate the influence of changes in the injector geometry. The combustion chamber hardware was changed to investigate the influence of contraction ratio variations.

3.1 Injector

Figure 5 shows the layout of the porous injectors used for these tests. All injector configurations feature a 50 mm diameter porous face plate for H_2-injection and a large number of stainless-steel tubes as LOX-injectors. The central configuration (API50-68) features 68 LOX-injectors with outer and inner diameters of 2.0 mm and 1.5 mm, respectively. It was used to investigate the influence of injection velocities and contraction ratio on the shape of the axial pressure profile and the corresponding heat release distribution. The injector configurations API50-126 and API50-36 (left and right) were designed to have similar total LOX-injection areas with different numbers of individual LOX-injectors (126 vs. 36). These designs result in comparable LOX injection velocities with different injector geometries. The corresponding outer and inner injector diameters are 1.6 mm 1.1 mm for API50-126 and 2.6 mm and 2.0 mm for API50-36. The relevant injector dimensions for the configurations presented here are listed in table 1.

Figure 5: Investigated porous injector configurations (from left to right): API50-126, API50-68, API50-36

Table 1: Injector configurations

	API50 -68	API50 -126	API50 -36
Number of LOX-injectors N_{LOX}	68	126	36
LOX jet diameter d_{LOX} (mm)	1.5	1.1	2.0
LOX injection area in relation to API50-68 (%)	100	99,7	94,1
Sum of LOX jet surface in relation to API50-68 (%)	100	135,9	70,6
LOX-post wall thickness t_{LOX} (mm)	0.25	0.25	0.3
LOX-post length / d_{LOX}	30	40.1	22.5

3.2 Combustion chamber

The DLR sub-scale combustion chambers model B and E were used for the hot-fire tests reported here. Both combustion chamber models feature water-cooled inner liners made from a copper alloy (Elbrodur) and stainless-steel outer casings.
The combustion chamber model B is a segmented chamber design and consists of a variable number of 50 mm long cylindrical chamber segments and a nozzle segment with interchangeable inserts for different nozzle throat diameters. For the investigations presented here, the first two segments were replaced by an 100 mm long water-cooled cylindrical chamber segment featuring multiple pressure taps for a high resolution measurement of the axial pressure distribution close to the injector face plate. In order to investigate the influence of the chamber flow Mach number on the evolution of the pressure profile, multiple test runs with different nozzle throat diameters were conducted. Depending on the chosen nozzle contraction ratio, one or more cylindrical chamber segments were removed to keep the characteristic chamber length L^* approximately constant. These chamber configurations are depicted in figure 6. The contraction ratios are 2.0, 2.5 and 3.2, from top to bottom. The characteristic chamber length varies between 665 and 725 mm.
The combustion chamber model E features a similar nozzle segment as the combustion chamber model B, but a different cylindrical chamber section. The cylindrical section consists of a single segment of 250 mm length. It features a number of pressure taps in axial direction with a focus on the first half of the chamber length. The nozzle contraction ratio is 3.2. This chamber configuration was used for the comparison of the two injector designs API50-126 and API50-36. This series of hot fire test runs investigated the influence of the LOX injector diameter.

3.3 Test campaigns

All tests were conducted at the European research test bench P8 in Lampoldshausen. This facility allows the operation of research combustion chambers with interface pressures at the injector of up to 400 bar. The test results presented here were focused on the investigation of LOX/H_2 combustion processes in a pressure range of 30 to 100 bar and oxidizer to fuel mixture ratios of 4 to 6.

4. Results

4.1 Injection velocities

With a fixed chamber and injector geometry, a change in chamber pressure corresponds to change in the injection conditions. In the case of LOX/H_2 injection, varying injection mass flow rates result in a different behavior of the LOX and hydrogen injection velocities. Liquid oxygen behaves like an incompressible fluid with only minor changes in density at different injection pressures. Since the chamber pressure at constant mixture ration is directly proportional to the injected propellant mass flow rate, the injection velocity is also almost proportional to the chamber pressure. Hydrogen, on the other hand, behaves like a compressible gas. The hydrogen density at the injector is directly related to the chamber pressure. A change in chamber pressure does not lead to a change in the hydrogen injection velocity. This allows the investigation of the LOX injection velocity on the position of the main heat release zone in the combustion chamber.
Figure 7 shows the evolution of the pressure gradient center of gravity x_{CoG} with changing injection velocities. An increasing LOX injection velocity results in higher values of x_{CoG}. The main heat release zone in the combustion chamber is pushed further downstream. This result is in agreement with the heat flux measurements presented in figure

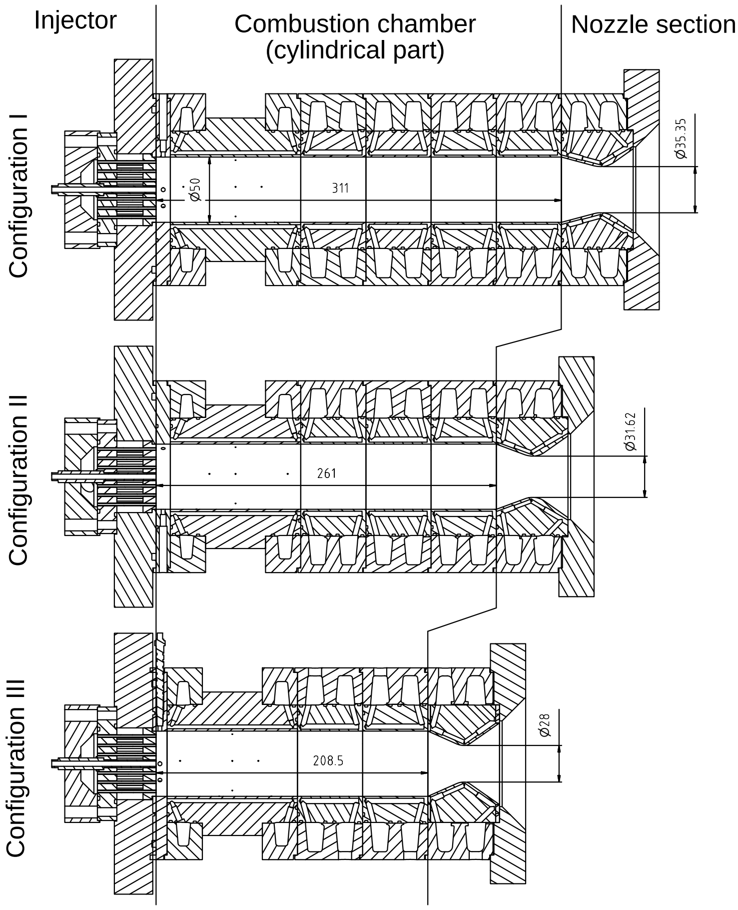

Figure 6: Combustion chamber model B in different configurations for the investigation of the chamber flow Mach number influence on the propellant atomization behavior

2. In this graph, decreasing LOX injection velocities correspond to higher relative heat fluxes (compared to the coaxial injector at the same injection conditions) closer to the injector face plate. The heat release in the combustion chamber is moved closer to the face plate. Figure 7 contains a similar information, but based on the axial pressure profile.

4.2 Chamber flow Mach number

The principle of porous injection leads to comparably low injection velocities. The necessary forces for the jet and droplet breakup and subsequent mixing of the propellants are generated by the increasing velocity lag between the high inertia oxygen and the accelerating combustion gases. The largest velocity lag depends on the maximum hot gas velocity in the atomization/combustion region of the combustion chamber. The hot gas velocity is determined by the gas properties (κ) and the chamber to throat area ratio or chamber contraction ratio ϵ_c. Lower contraction ratios result in higher hot gas velocities. Therefore, the contraction ratio is an important parameter for the performance of a porous injector. The influence of changing contraction ratios on the axial pressure profile produced by a porous injector is illustrated in figure 8. These pressure profiles were determined at identical chamber pressures and mixture ratios (80 bar, ROF = 5). The pressure profiles are similar considering the position of the main pressure drop and the onset of a more or less constant pressure level.

When applying the method described in section 2, the influence of the chamber Mach number becomes apparent. The influence of the chamber Mach number on the position of the axial pressure distribution is shown in figure 9. The hot gas properties at a mixture ratio of ROF = 5 and the chamber contraction ratios of 2.0, 2.5 and 3.2 result in chamber Mach number of about 0.18 to 0.3. A higher chamber Mach number results in lower values of x_{CoG}. The maximum velocity lag drives the atomization and mixing process. A high value results in a translation of the heat release zone towards the injector end side of the combustion chamber.

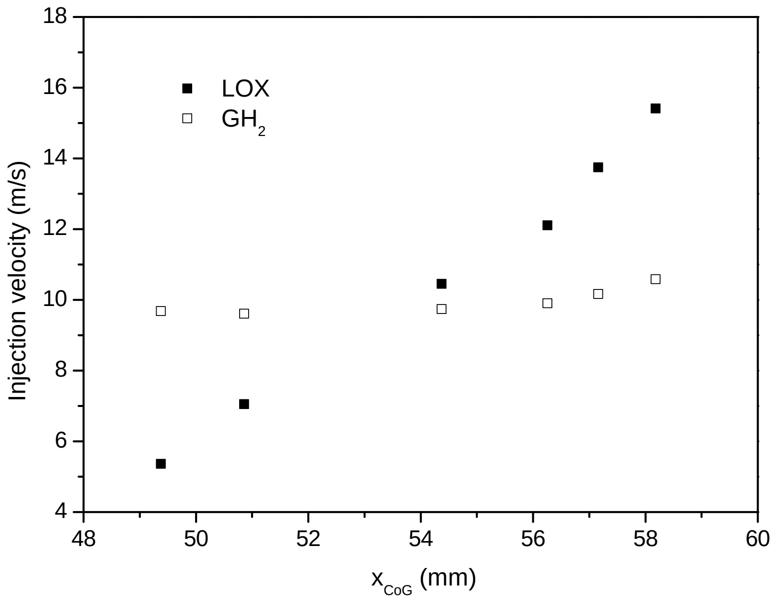

Figure 7: Influence of propellant injection velocities on the position of the center of gravity of the axial pressure gradient distribution x_{CoG}

4.3 LOX injector diameter

Another important parameter for jet breakup and mixing is the initial jet diameter. A positive influence on the mixing performance and overall efficiency of an injector can be expected for smaller initial jet diameters. The injector configurations API50-126 and -36 were designed to investigate the influence of the LOX jet diameter on the axial pressure profile. The larger number of smaller injectors of the API50-126 configuration compared to the API50-36 configuration increases the contact surface between the propellants at injection by about 92 %. The larger initial contact surface improves the reaction rates close to the injector. This is confirmed by the experimental findings.

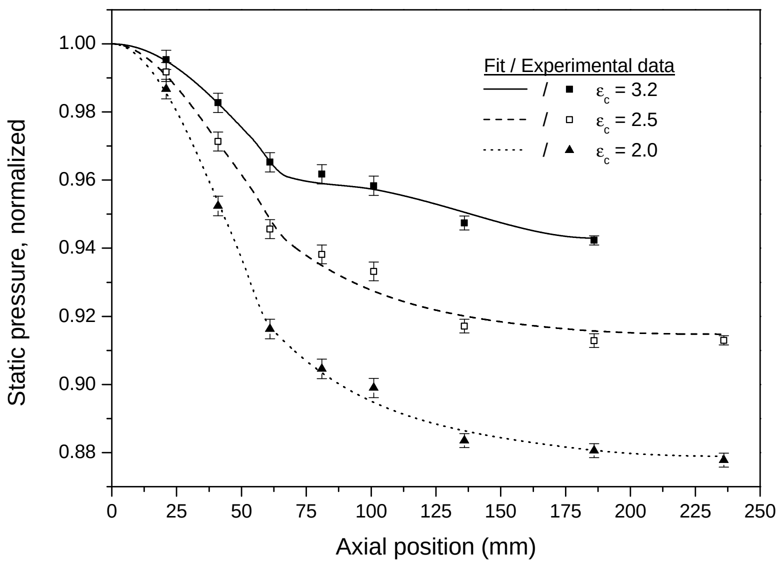

Figure 8: Axial pressure profiles in a cylindrical combustion chamber determined at 80 bar and ROF = 5 with three different nozzle contraction ratios

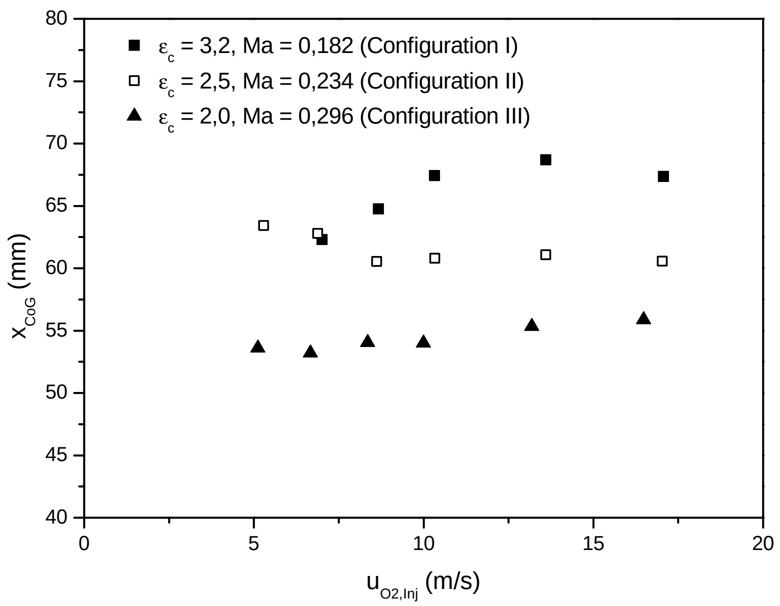

Figure 9: Influence of chamber flow Mach number on the position of the center of gravity of the axial pressure gradient distribution x_{CoG}

Figure 10 shows the axial pressure profiles of both injector configurations at identical operating conditions (60 bar, ROF = 5). The pressure data is normalized by the total pressure drop for each individual injector configuration to exclude the influence of different combustion efficiencies. This way, the different injector behavior becomes obvious. In addition to the axial pressure profiles, the positions x_{CoG} and x_{EoC} for both injectors are also given. For API50-126, the combustion chamber pressure drop occurs further upstream than in the case of the large diameter injector API50-36. The majority of the heat release takes place in this region. Consequently, the wall heat flux should reach its plateau value further upstream for the small diameter injector configuration. This behavior is consistent for different chamber pressure levels, as illustrated in figure 11. As already shown in figure 7 for API50-68, the position of the main heat release region is influenced by the LOX injection velocity and therefore depending on the chamber pressure for a given injector and chamber nozzle geometry. This trend is also observable for API50-126 and -36. As both injectors have approximately the same LOX injection area (see 1), the injection velocity is similar at identical operating conditions. It is therefore possible to investigate the influence of the LOX injector diameter alone.
Another important observation is the fact that the quasi-constant pressure level (x_{EoC}) is reached at a similar distance from the face plate for both injector configurations. In order to provide the maximum combustion efficiency, the combustion chamber must not be truncated below that length. Although the main heat release is occurring further upstream for API50-126, the reaction is not fully completed closer to the injector than in the case of API50-36.

5. Conclusion

Former experiments showed the dependency of the axial wall heat flux on parameters of injection for an API-style porous injector head.[2] This behavior is linked to the axial pressure profile in the combustion chamber. A better understanding of the parameters governing the shape of the axial pressure profile and the corresponding heat release distribution allows the design of improved porous injector heads for high wall heat flux applications, like expander-cycle engine types.
The position of the main heat release zone can be described by a scalar parameter: the center of gravity of the axial pressure gradient (x_{CoG}). The dependency of this parameter on the injection velocity, the combustion chamber Mach number and the LOX injector diameter has been investigated for porous injectors at representative operating conditions at the European research test bench P8 in Lampoldshausen.
The LOX injection velocity has a clear impact on the position of the main heat release zone. A higher LOX injection velocity results in a translation of the main heat release zone further downstream. The same trend can be expected for the wall heat flux distribution, as was already shown in a former publication.[2]

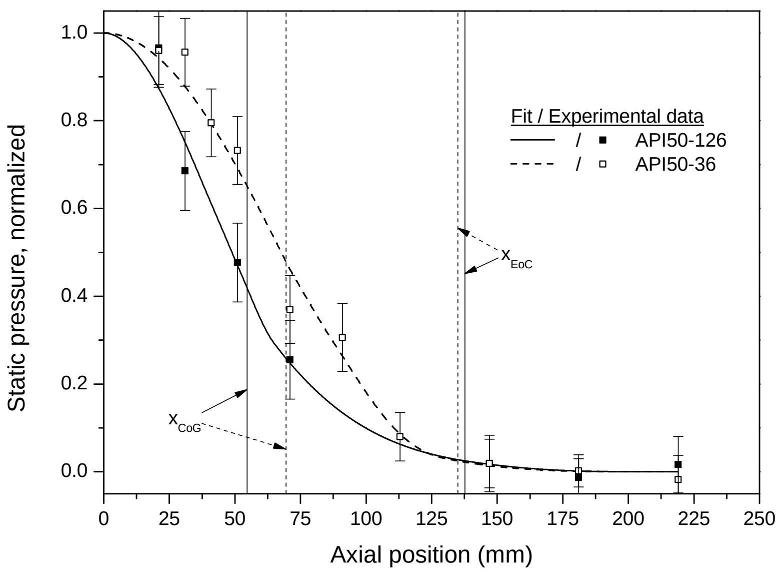

Figure 10: Static pressure evolution for API50-126 (solid line/symbols) and API50-36 (dashed line/open symbols) at 60 bar and ROF = 5 normalized by the total pressure drop occurring for the given injector configuration.

A change in the chamber contraction ratio also influences x_{CoG}, since the magnitude of the hot gas velocity is a driving parameter for the atomization in the case of a porous injector. Lower contraction ratios result in higher hot gas velocities, which in turn promote atomization and mixing. The heat release occurs earlier in the combustion chamber and the main heat release zone is pulled upstream towards the face plate.
The LOX injector diameter influences the axial pressure distribution by providing smaller or larger initial contact surfaces between the propellants. A larger number of small diameter injectors provide a large contact surface, which leads to an earlier onset of the region of the most intense reaction. The main heat release zone is located further upstream

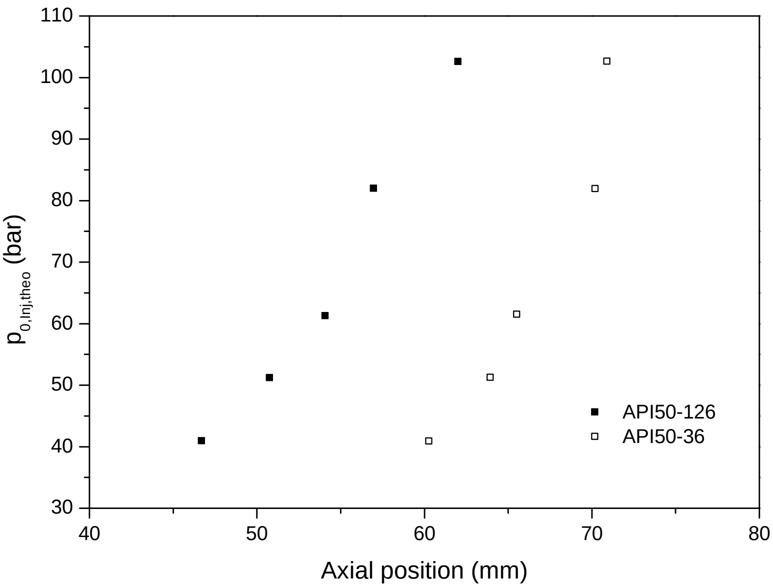

Figure 11: Position of the center of gravity of the axial pressure gradient distribution x_{CoG} for API50-126 (solid symbols) and API50-36 (open symbols) at ROF = 5

than in case of an injector with larger LOX injector diameters. This observation holds true regardless of changes in injection velocities.
These findings indicate that a qualitative assessment of the dependency of the axial wall heat flux distribution on different injection parameters can be made by an investigation of the axial chamber pressure distribution. The behavior of injector configurations with respect to the wall heat flux can be investigated using comparably cheap sub-scale hardware and pressure transducers. The identification of the most important parameters that govern the injector performance and wall heat flux enables the design of injector configurations for given requirements, e.g. high wall heat fluxes for expander-type cycles. The position of negligible pressure variations in a cylindrical combustion chamber x_{EoC} indicates the chamber length necessary for a high combustion efficiency and therefore possibilities to shorten the combustion chamber.

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