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**Combustion chamber design for a high-performance natural gas engine:
CFD modeling and experimental investigation**

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ABSTRACT

The present paper is focused on the development of a high-performance, monofuel, spark ignition engine running on natural gas, featuring a high volumetric compression ratio and a variable valve actuation system. More specifically, the cylinder head geometry effect has been analyzed and the compression ratio has been optimized by means of steady-state and transient simulation activity, as well as of an extensive experimental campaign. The compression ratio effect was mainly investigated by means of experimental tests but a few 3D simulations were also run in order to quantify its impact on the in-cylinder tumble and turbulence. The main novelty of the paper are, first, the adoption of very high engine compression ratio values, second, the combined optimization of the cylinder head design and compression ratio. The main results can be summarized as follows. The engine configuration with mask showed a decrease in the average discharge coefficient by 20-30% and an increase in the tumble ratio by around 200% at partial load. Moreover, the simulation of the engine cycle indicated that the presence of the piston modifies the tumble structure with respect to the steady-state simulation case. An increase in the tumble number and turbulence intensity by around 90% and 10%, respectively, are obtained for the case with mask at 2000 rpm and 4 bar. With reference to the combustion duration, on an average, the presence of the masking surface led to a reduction of the combustion duration (from 1% to 50% of mass fraction burned) between 2 and 6 degrees. As far as the engine compression ratio is concerned, the value of 13 was finally selected as

25 the best compromise between combustion variability, engine performance at full load and fuel
26 consumption at partial load.

27

28 **KEYWORDS**

29 Natural gas, SI engines, Tumble flow, CFD simulation.

30

31 **NOMENCLATURE**

32	B	cylinder bore
33	bmep	brake mean effective pressure
34	CA	crank angle
35	C_D	discharge coefficient
36	CFD	computational fluid dynamics
37	CNG	compressed natural gas
38	CoV	coefficient of variation
39	CR	compression ratio
40	deg	degree
41	ECFM	extended coherent flamelet model
42	EGR	exhaust gas recirculation
43	GHG	greenhouse gases
44	imep	indicated mean effective pressure
45	k	turbulent kinetic energy
46	MBT	maximum brake torque
47	MFB	mass-fraction burned
48	MFB1-50	combustion duration from 1% to 50% of heat released

49	MFB50	'combustion barycenter' position
50	NG	natural gas
51	N_T	tumble number
52	PFP	peak firing pressure
53	PMAX0	ensemble-averaged peak firing pressure
54	PMAXmx	maximum cycle-resolved peak firing pressure
55	SI	spark ignition
56	TN	in-cylinder tumble number
57	TR	tumbling ratio
58	v_{is}	isentropic flow velocity
59	VVA	variable valve actuation
60	x	coordinate for tumble moment of momentum calculation
61	y^+	normalized distance from wall
62		
63	Greek symbols	
64	ε	turbulence dissipation rate
65	θ	crank angle position
66	$\omega_{AV,EXH}$	equivalent angular speed to the exhaust side
67	$\omega_{AV,INT}$	equivalent angular speed to the intake side

68

69 **1. INTRODUCTION**

70 Nowadays, the design of modern internal combustion (IC) engines represents a challenging task, due to the
71 raising concern for the global warming as well as to the stringent constraints set by the current pollutant
72 regulations. The use of gasoline or diesel in internal combustion engines is likely to remain the most cost-
73 effective overall ground-based transportation propulsion system for the near future. Furthermore, hybrid
74 and electric vehicles are gaining considerable market share. However, as far as IC engines are concerned,

75 natural gas (NG) represents a factual alternative to traditional fuels thanks to the reduced pollutant and
76 carbon dioxide emissions [1,2]. Moreover, the development of engines compatible with biofuels (for
77 example, natural gas from biomasses) can provide enormous benefits compared to fossil fuels, in terms of
78 greenhouse gases (GHG) emissions [3,4], although attention has to be paid to the fuel properties and their
79 dependence on the blend composition. With specific reference to natural gas, the effect of biogas
80 composition on the engine operating characteristics has been widely studied by the researchers. In [5] it
81 was found that methane concentration in the biogas significantly improves performance and reduces
82 emissions of hydrocarbons. The lean operation limit is also extended. Similarly, investigations carried out in
83 [6] showed that the methane-enriched biogas performed similarly to compressed natural gas (CNG). Along
84 with methane, other inert species, such as carbon dioxide and nitrogen, can be present in the biogas
85 composition. Furthermore, hydrogen derived from biomass gasification can be blended to natural gas as an
86 additive. As a matter of fact the high speed of flame propagation of hydrogen improves the stability of the
87 combustion process when added to natural gas [7,8].

88 The development of highly efficient engines cannot withstand the adoption of advanced design methods.
89 As a matter of fact, the introduction of advanced engine concepts, such as, variable valve actuation,
90 turbocharging or direct injection leads to an increase in the complexity of the engine design process, as the
91 number of the design variables is remarkably higher. Moreover, with reference to biofuels dedicated
92 control algorithms might be necessary to make up for the variability in the fuel properties due to the
93 dispersion in the blend composition. As far as the optimization of the combustion chamber and the intake
94 port geometry is concerned, the adoption of computational fluid dynamics (CFD) represents an effective
95 means to support the design process, allowing the time and cost of the associated experimental activity to
96 be reduced. Appreciable benefits in terms of combustion stability, efficiency and pollutant emissions can be
97 obtained if a suitable intensity of swirl and/or tumble motion is targeted. With specific reference to spark
98 ignition (SI) engines, the tumble motion is usually generated in order to increase the turbulence level in the
99 combustion chamber, thus enhancing the combustion stability and the exhaust gas recirculation (EGR)
100 tolerance. Amer and Reddy [9] carried out a multidimensional optimization of the in-cylinder tumble

101 motion for an engine featuring hemispherical combustion chamber. They found that large-scale tumbling
102 flow structures, if persistent and coherent, can be effective in the turbulence enhancement at spark timing,
103 provided that they are dissipated right before ignition. In addition, they underlined that the dominant flow
104 structures through the compression phase are significantly different than those occurring in a steady-state
105 intake flow in a flow test rig. This was also remarked in [10]. Berntsson et al. [11] performed engine tests as
106 well as CFD simulations on a 500 cc single-cylinder engine with different tumble levels. A positive effect of
107 increased tumble on efficiency was highlighted, and advantages were also found as far as knock resistance
108 and EGR tolerance are concerned. Similar results are also reported in [12], where the enhancement of
109 tumble intensity led to an extension of the lean burn range of the engine, which in turn allowed a benefit in
110 fuel economy to be achieved. Accordingly, in [13] the increase in tumble allowed the lean operation limit to
111 be extended up to $\lambda = 1.55$, leading to benefits in fuel consumption as well as in NO_x and CO emissions. In
112 [14], the effects of tumble combined with EGR on the combustion and emissions in a spark ignition engine
113 were investigated. In addition to the advantages in fuel consumption due to combustion enhancement, it
114 was also pointed out that EGR allows a de-throttling effect to be obtained, which reinforces the fuel
115 consumption reduction. Similarly, in [15] it was evidenced that the intake tumble can extend the allowable
116 EGR rate, thus largely improving its effectiveness in reducing fuel consumption and emissions.

117 Furthermore, the existence of an optimal tumble level can be identified in different engine working
118 conditions, as far as fuel consumption and combustion efficiency are concerned [16]. The synergic effect of
119 tumble enhancement and mixture dilution by EGR in reducing fuel consumption and NO_x emissions is also
120 testified in [17]. These effects are largely due to the increase in the flame propagation speed, which is
121 obtained through tumble enhancement. As a matter of fact, in [18] a flame propagation increase by 35%
122 was evidenced, when the non-dimensional tumble was increased from 0.5 to 2.2.

123 Several technical solutions have been proposed for the tumble enhancement in SI engines in the last two
124 decades. The common target of such solutions is the deviation from the flow balance between two halves
125 of the intake valve curtain area. The flow is in fact mostly conveyed to the cylinder through the upper
126 curtain area portion. A few practical examples are the intake valve masking [19], the adoption of restriction

127 and flow-separating plates [11], the use of an adapter for the intake runner [20], the offset of the intake
128 valve [12] as well as the optimization of the port geometry [21, 22]. The application of a masking surface
129 downstream of the intake valve was also investigated in [23]. However, in this case the flow was inhibited
130 in the upper curtain area portion, so that the so called 'reverse tumble' was promoted. The benefit in terms
131 of turbulence intensity around the spark location was of around 100% with respect to the baseline design.
132 Finally, it is worth pointing out that the turbulence level at spark timing is influenced also by the tumble
133 evolution during intake and compression, which can be affected by the piston shape and position [24].

134 The present paper aims to give a further contribution to the assessment of design solutions for the tumble
135 improvement, by considering a purposely designed masking surface downstream of the intake valve. The
136 main novelty of the paper is, on one hand, the adoption of very high engine compression ratio (CR) values
137 (as explained in the next section), which determine an apparent influence between the induced tumble and
138 the piston. On the other hand, the combined optimization of the cylinder head design and CR, as well as the
139 correlation between numerical and experimental results, represents an added value.

140

141 **2. PRESENT WORK**

142 The present paper reports part of the outcomes of a research activity carried out by Politecnico di Torino
143 (PoliTo) and Fiat Research Center (CRF) within the Biomethair regional research project (Automotive
144 platform of Regione Piemonte, Italy, <http://www.biomethair.it/index.php>). The activity has been aimed at
145 giving a contribution to a new urban-mobility solution with ultra-low environmental impact. This ambitious
146 target has been pursued by means of the development and integration of a number of advanced
147 technologies, including hybrid propulsion, high-performance engines as well as biofuel production and
148 utilization.

149 The activities performed by PoliTo and CRF have been focused on the development of a high-performance
150 engine specifically dedicated to CNG fueling and featuring a variable valve actuation (VVA) system as well as
151 very high compression ratios. The main engine characteristics are reported in Table 1. The engine is derived

152 from the production gasoline-fueled TwinAir engine and the compression ratio (CR) was increased from the
153 baseline value of 10 up to the range 12-14, whose optimization was part of the design process. The results
154 of the Biomethair engine development activity are presented in this paper, as well as in [10]. More
155 precisely, the results of the experimental and numerical characterization of the steady-state tumble flow
156 from the Biomethair engine head were presented in [10]. In addition, a numerical model for the engine-
157 cycle transient simulation was developed and preliminarily assessed. The present paper is focused on the
158 design and optimization activity of the Biomethair combustion chamber. The activity was carried out by
159 combining 3D simulation results to performance and emission data from the dyno test rig at CRF.

160 Table 1 – Biomethair engine characteristics

Feature	Value/specification
Displacement [cm ³]	875
Number of cylinders	2
Compression ratio	12-14 (production engine: 10)
Turbocharger	WG-controlled
Target torque	140 Nm @2000 rpm
Target power	60 kW @5000 rpm

161

162 3. ENGINE DEVELOPMENT PROCEDURE

163 The engine development activity described in the present paper is divided into three parts. First, two
164 variants for the cylinder head geometry were considered and compared, with specific reference to their
165 performance in terms of permeability and tumble intensity. More specifically, the influence of a purposely
166 designed masking surface is analyzed through the comparison with the baseline cylinder head configuration
167 without mask. As a matter of fact, as widely discussed in the Introduction section, the enhancement of the
168 tumble intensity caused by the masking wall can lead to an increase in the turbulence intensity and, in turn,
169 to remarkable benefits in terms of combustion speed, efficiency and repeatability. On the other hand, the

170 presence of an additional obstacle might lead to a detriment in the volumetric efficiency. A steady-state
 171 cylinder head numerical model ('virtual flow rig' model), previously developed and validated [10], was
 172 applied for this analysis. Second, the selected cylinder head geometry was used to assemble the prototype
 173 engine, by considering three different piston variants which corresponded to three different CR values,
 174 ranging from 12 to 14. The CR effect was then analyzed by combining experimental and 3D simulation
 175 results. Third, the selected compression ratio was finally considered to verify the overall effect of the
 176 cylinder head geometry on the in-cylinder tumble, in the presence of combustion.

177 The baseline versions for the "virtual flow rig" model and the complete engine model adopted in the
 178 current study were extensively described and validated in [10], some details are anyhow summarized
 179 hereafter for the reader's convenience. The main model features are also summarized in Table 2, along
 180 with the associated average calculation time.

181 Table 2. CFD model summary

	'Virtual flow rig' model	Engine model
Cell count	~4,000,000	~800,000 (at BDC)
Cell size	min. 0.3 mm, max. 2.5 mm	min. 0.4 mm, max. 1 mm
Turbulence model	Realizable k- ϵ	RNG k- ϵ
Near wall treatment	'Two layer all y^+ '	Angelberger law of the wall [25]
Combustion model	-	ECFM-3z [26]
Average calculation time	~16h on a 24 CPU workstation	~48h per cycle, on a 24 CPU workstation

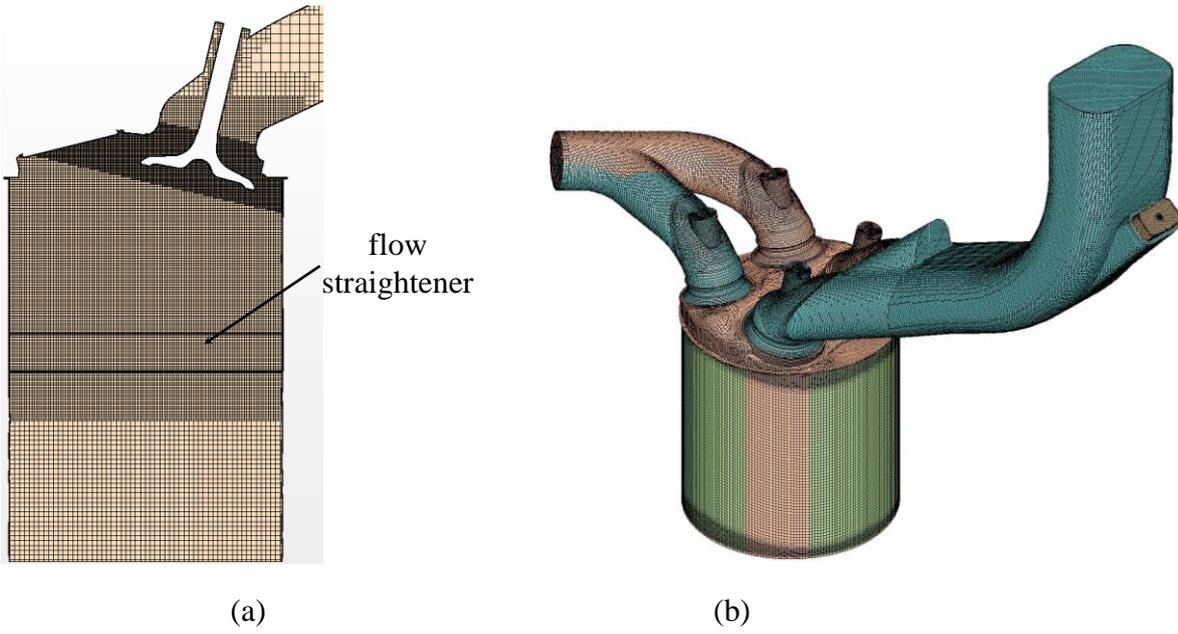
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183 The steady-state flow rig model was developed within StarCCM+ v.8.06 and features around 4 million of
 184 cells, the mesh size ranging between 1.25-2.5 mm in the intake ports and 0.3 mm in the valve curtain
 185 region (Fig. 1a). The Realizable k- ϵ model turned out to be the best compromise between model accuracy,
 186 stability and computational cost, within the Reynolds-Averaged Navier-Stokes (RANS) framework, and was

187 thus selected for the analyses discussed in the present paper. For the near wall treatment, a two-layer
188 approach named 'all y^+ ' was selected and 5 cell layers were placed at the wall boundaries. Such an
189 approach is claimed to provide a reliable solution in the entire y^+ range.

190 The transient engine model has been developed by means of the commercial code Es-ICE version 4.20 and
191 features around 800 000 cells at bottom dead center, with a cell size between 0.4 and 1 mm (Fig. 1b). The
192 RNG k - ϵ model was adopted, along with the Angelberger law of the wall [25], with a near wall extrusion
193 layer of 0.2 mm, which insures a y^+ value ranging between 30 and 100. The three-zone extended coherent
194 flamelet model (ECFM-3z) [26] was used in order to simulate the in-cylinder combustion process. The
195 potential of the model in the engine simulation have been recently further demonstrated in [27,28], with
196 reference to a dual-fuel, partially stratified, SI combustion. In the present work, the model coefficients were
197 calibrated based on experimental data in seven engine working conditions with different engine
198 compression ratios. A maximum error of 3% and 2 deg CA was detected on peak firing pressure and
199 'combustion barycenter' (MFB50) position, respectively. An example of comparison between experimental
200 and CFD data is provided in Fig. 2, where an operation point at 3500 rpm, full load (upper row) and another
201 one at 2000 rpm, bmep=4 bar (lower row) are considered. The calibrated model was applied to the
202 different geometry variants under study by keeping the ECFM coefficients unchanged, thus giving
203 consistency to the analysis.

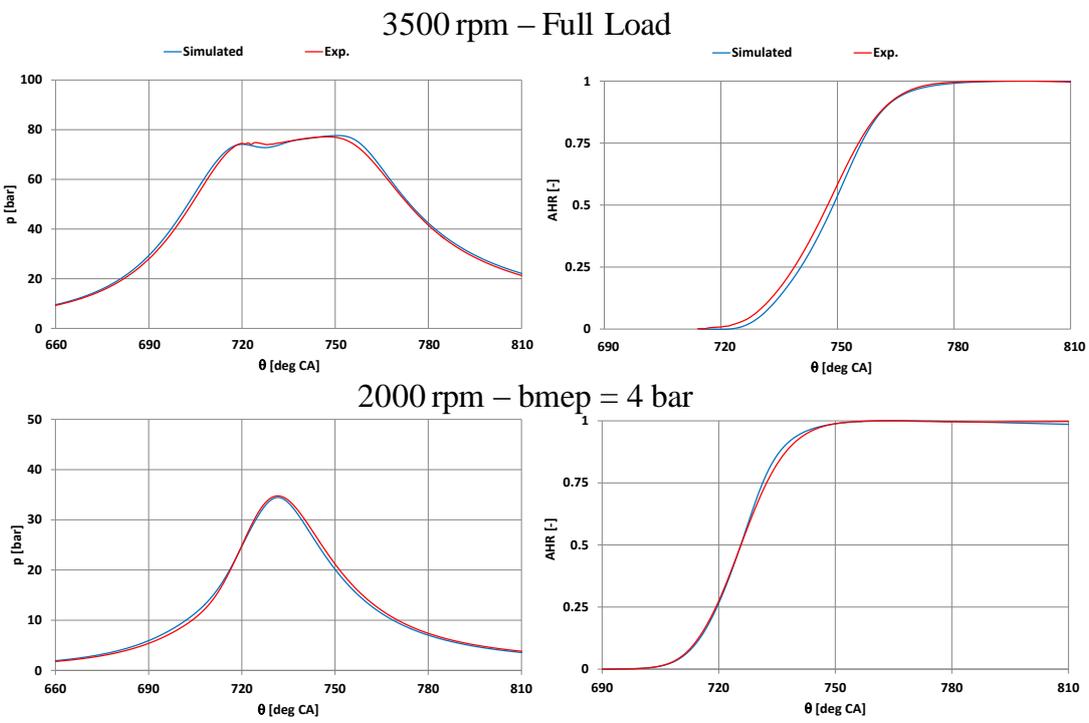
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205

206 Figure 1. CFD numerical models: cross- section of the steady-state cylinder head numerical model ('virtual
 207 test rig') (a); full view of the transient engine model (b).

208



209

210 Figure 2. Engine numerical model validation results: pressure (left) and heat release (right) profiles.

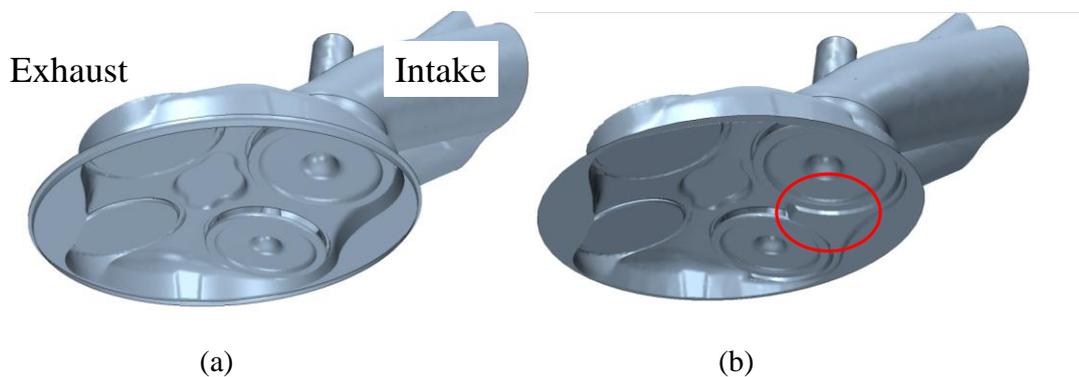
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212 **4. RESULTS AND DISCUSSION**

213 **4.1 Steady-state flow CFD simulation**

214 The first step of the combustion chamber design process was the comparison of two variants for the head
215 dome, which are represented in Fig. 3. In this phase, only the cylinder head is considered, without any
216 piston combined to it, according to the approach of the steady-state cylinder head numerical model
217 (Section 3). The first variant is the baseline one (Fig. 3a), which is adopted in the production gasoline
218 engine. The second variant was obtained by creating a masking wall right downstream of the intake valve,
219 to the wall side, as can be seen in Fig. 3b where the masking wall is highlighted with the red oval. The
220 chamber variants were compared through the simulation of the steady-state flow from the intake valve, by
221 considering the CFD model in Fig. 1a.

222



223

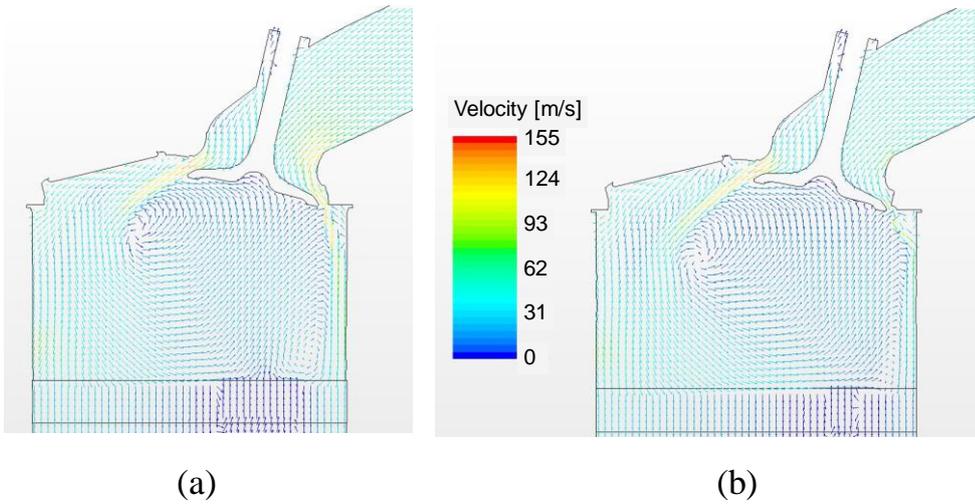
224 Figure 3. Design variant: baseline without mask (a) and with mask (b).

225

226 The results of the comparison are reported in Figs. 4-6. Fig. 4 shows the steady-state velocity field in the
227 intake valve plane, which was obtained from both variants at the intermediate valve lift of 4 mm. Such a lift
228 value is close to the height of the masking surface in the variant with mask. The figure shows that in the
229 baseline configuration the curtain area of the intake valve is almost entirely exploited and inlet velocities of
230 100-120 m/s can be observed at both sides of the intake valve (Fig. 4a). The overall tumble intensity thus

231 results from the difference in angular momentum contributions of both the 'direct' and the 'reverse'
 232 tumble. Conversely, the 'reverse' tumble is obstructed by the presence of the masking wall in the variant
 233 with mask, as it is clearly shown in Fig. 4b. In such a case, the negative contribution due to the flow issuing
 234 from the intake valve to the wall side is inhibited to a great extent, thus increasing the overall tumble
 235 intensity.

236



237

238 Figure 4. Steady state intake velocity field at the intermediate lift of 4 mm: baseline without mask (a) and
 239 with mask (b) configurations.

240

241 The effect of the combustion chamber geometry on the valve performance is summarized in Fig. 5 in terms
 242 of discharge coefficient and tumble number. The tumble number is given by ([10]):

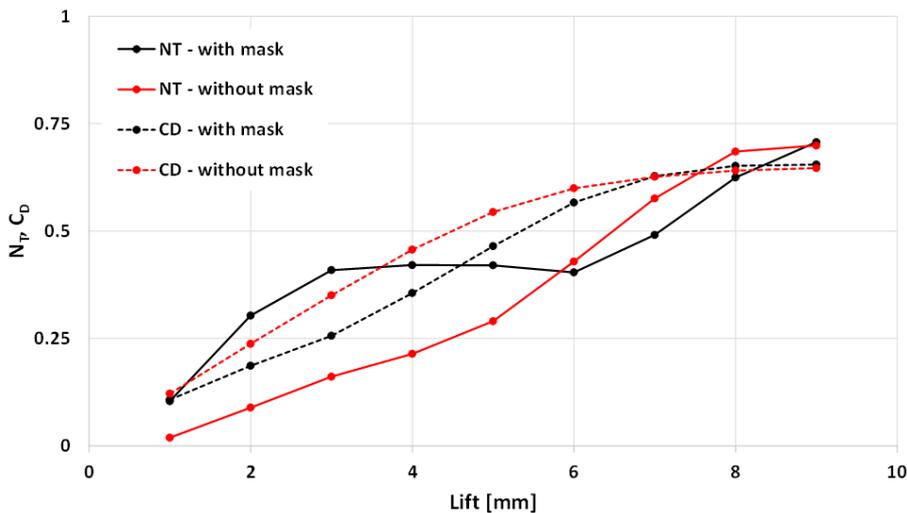
$$243 \quad N_T = \frac{-(\omega_{av,INT} + \omega_{av,EXH}) \cdot B}{v_{is}} \quad (1)$$

244 where $\omega_{av,INT}$ and $\omega_{av,EXH}$ are equivalent angular speed referred to the intake and the exhaust side,
 245 respectively (see Fig. 3), according to the equation below:

$$246 \quad \omega_{av,EXH} = \frac{\sum_{e=1}^{N_e} V_{z,e} X_e}{\sum_{e=1}^{N_e} X_e^2}; \quad \omega_{av,INT} = \frac{\sum_{i=1}^{N_i} V_{z,i} X_i}{\sum_{i=1}^{N_i} X_i^2} \quad (2)$$

247 and v_{is} is the isentropic flow velocity corresponding to the actual pressure ratio. The formulas above are
 248 applied with reference to a measurement plane located 2 mm below the flow straightener (Fig. 1a). The
 249 position $x=0$ is the cylinder axis position, and the indices i and e are related to the intake and the exhaust
 250 side, respectively. As far as the influence of the chamber design is concerned, for low and intermediate
 251 valve lift values the presence of the masking wall gives rise to a decrease of the valve discharge coefficient
 252 by around 10-20%, whereas the tumble number is increased up to two-three times its original value, due to
 253 the reverse tumble inhibition discussed above. At high lift (above 5 mm), the intake valve results to be
 254 displaced beyond the extension of the masking surface, consequently its effect virtually disappears as is
 255 testified by the comparable values of both C_D and N_T for the baseline and the 'masked' design.

256



257

258 Figure 5. Tumble number (NT) and discharge coefficient (CD) versus valve lift.

259

260 The results in Fig. 5 can be used as input to estimate the effect of the mask presence on the global tumble
 261 and permeability of the valve in the real engine installation. Following the procedure in [29], with reference
 262 to the intake valve lift profile for the considered engine working point, the average discharge coefficient
 263 and the steady-state tumble ratio at IVC can be defined as follows:

$$264 \quad \overline{C_D} = \frac{\int_{\vartheta_1}^{\vartheta_2} C_D \cdot d\vartheta}{\vartheta_2 - \vartheta_1} \quad (3)$$

$$265 \quad TR = \frac{B \cdot s}{N_v D_v^2} \cdot \frac{\int_{\vartheta_1}^{\vartheta_2} C_D \cdot N_T \cdot d\vartheta}{\left(\int_{\vartheta_1}^{\vartheta_2} C_D \cdot d\vartheta \right)^2} \quad (4)$$

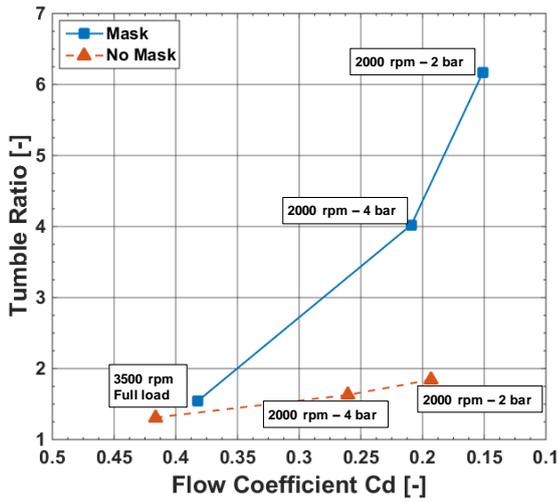
266 where θ_1 and θ_2 represent the intake valve opening and closure crank angle positions, respectively. The
 267 considered coefficients were calculated in three engine working points, as reported in Table 3. The results
 268 are reported in Fig. 6. The valve lift profile considered in each of the working points can be found in Fig. 7.

269

270 Table 3. Engine working points for tumble ratio evaluation.

Speed [rpm]	bmep [bar]
2000	2
2000	4
3500	Full load

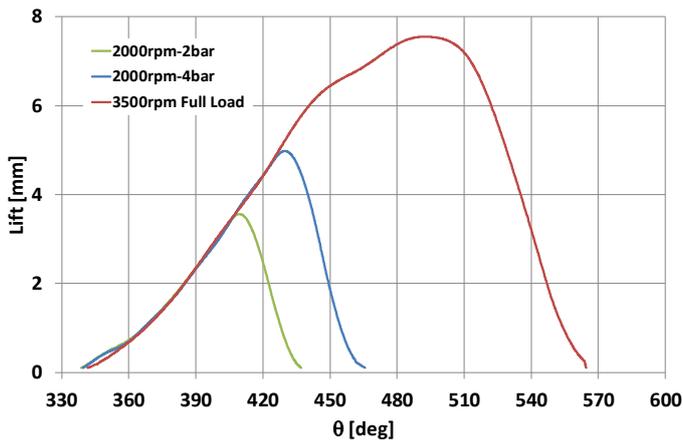
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272

273 Figure 6. Average flow coefficient and tumble ratio in different engine working points.

274



275

276 Figure 7. Valve lift profiles.

277

278 The results in Fig. 6 show that the presence of the mask determines a decrease in the average discharge
 279 coefficient by around 20-30%, mainly due to the reduced effective flow area caused by the obstruction
 280 effect of the wall. As far as the tumble ratio defined by Eq. 4 is concerned, the effect is actually dependent
 281 on the engine load. At partial load, the valve opening time and maximum lift are highly reduced by the
 282 action of the VVA device (Fig. 7). Consequently, the valve position is kept within the range corresponding to
 283 the extension of the masking surface, thus maximizing its effect on the flow unbalance. As a matter of fact,

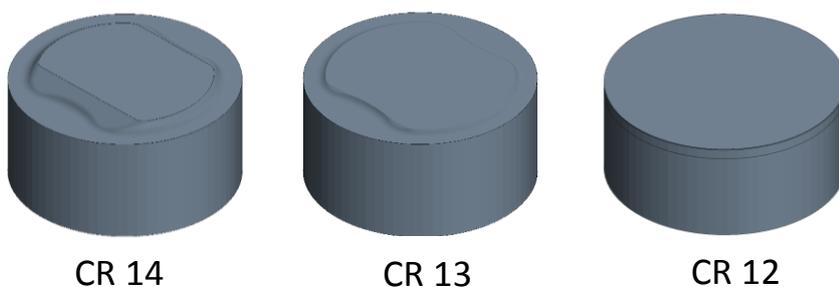
284 the tumble ratio at partial load is increased by 150% in the 2000rpm-4bar working point, and by 235% in
285 the 2000rpm-2bar one. At full load, the valve lift is kept above 5 mm for about half of the total opening
286 time. It is worth recalling that the mask is virtually ineffective in for high lift, and observing that such lift
287 values affect the integral at the numerator of Eq. 4 to a great extent, due to the high value of C_D in that
288 range. For this reason, the tumble ratio benefit is limited to 18%. Although the tumble ratio estimated by
289 steady-state flow data might not be fully representative of the flow behavior in the real engine [10], their
290 significance is usually sufficient to assess for the suitability of steady flow tests during the early design
291 stages of tumble-generating induction systems [29]. Consequently, based on the results discussed above, it
292 was decided to adopt the configuration with mask for assembling the Biomethair engine prototype, given
293 the minor penalty in the discharge coefficient which accompanies the remarkable tumble increase

294

295 4.2 Experimental tests

296 The experimental results presented in this paper were acquired by CRF and shared with Politecnico di
297 Torino within the Biomethair project. Three values of the compression ratio (namely, 12, 13 and 14) were
298 actually tested, by assembling different piston design variants with the same cylinder head (see Fig. 3). The
299 piston design variants are represented in Fig. 8. The tests aimed at defining the optimal engine CR as a
300 compromise between performance at full load and fuel consumption at partial load.

301



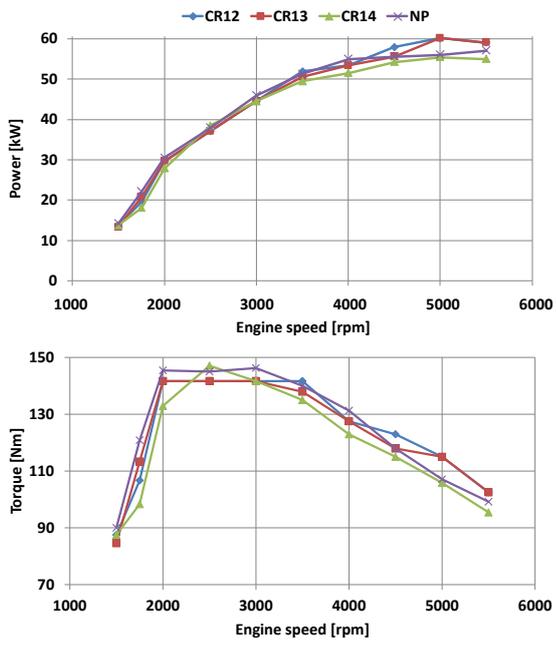
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303 Figure 8. Piston shapes corresponding to the considered compression ratio values.

304

305 Figs. 9 and 10 show the results obtained at full load for the three compression ratios. More specifically, Fig.
306 9 compares the torque and power curves obtained with the three considered CR to the reference curve of
307 the normal production (NP) engine, whereas Fig. 10 reports the CoV of the imep, the ensemble-averaged
308 peak firing pressure (P_{MAX0}) and the maximum cycle resolved peak firing pressure (P_{MAXmx}). In all the
309 cases, the engine calibration was aimed at maximizing the engine load, by taking the compressor surge limit
310 into account. Moreover, the threshold for the ensemble value of the peak firing pressure was set at 85 bar,
311 allowing the single 'upper' cycles to reach 100 bar. Such limits led to the limitation of the spark advance
312 (SA) to 5-6 deg CA in most cases. The target performance data were set at 140 Nm and 60 kW. The results
313 showed that the target torque value is achieved with all the CRs. However, the higher one (CR=14) does not
314 allow the power target to be fulfilled. As far as the cyclic variation of the engine is concerned, an increasing
315 trend of the imep coefficient of variation against CR was found (Fig. 10). This is due to the combination of
316 two effects. First, as CR is increased, the spark timing (ST) had generally to be reduced to keep the peak
317 firing pressure (PFP) within its limit. Second, for a given ST, the increase in CR negatively affects the
318 combustion regularity. This is to be ascribed to the detriment in the tumble intensity evolution during the
319 intake and the compression stroke, as will be shown in Section 4.3, and is evidenced in Fig 11. In the figure,
320 the in-cylinder pressure acquisitions are showed for different CR values in the operating point at 3500 rpm,
321 full load, with the same SA setting. The pressure traces pertaining to individual cycles are represented by
322 light gray lines, whereas the red thick lines show the results of the ensemble average of acquired cycles.
323 The red, dashed line indicates the angular position of the spark timing. As can be seen, the in-cylinder
324 pressure at spark timing increases as CR increases. Moreover, the cycle-resolved pressure traces show a
325 higher dispersion in the CR=14 case, which features both very fast combustion events and misfire cycles. It
326 is thus necessary to further reduce the spark timing in order to reduce the PFP of fast burning cycles.
327 Although the precise control of the limit on the maximum cycle-resolved PFP was rather difficult, and thus
328 the threshold of 100 bar was slightly exceeded in many cases, the obtained results can be considered
329 acceptable as far as the structural integrity of the engine is concerned.

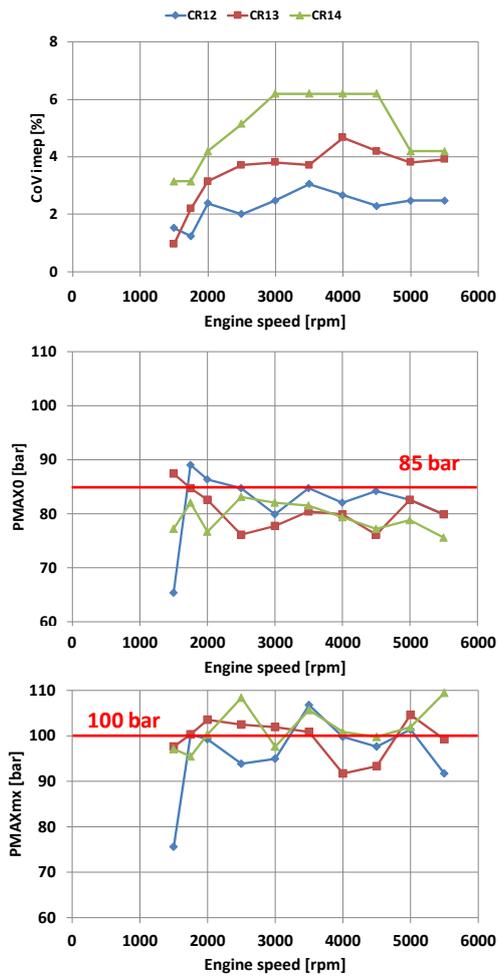
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331

332 Figure 9. Full load performance curves for the three CR values compared to NP engine.

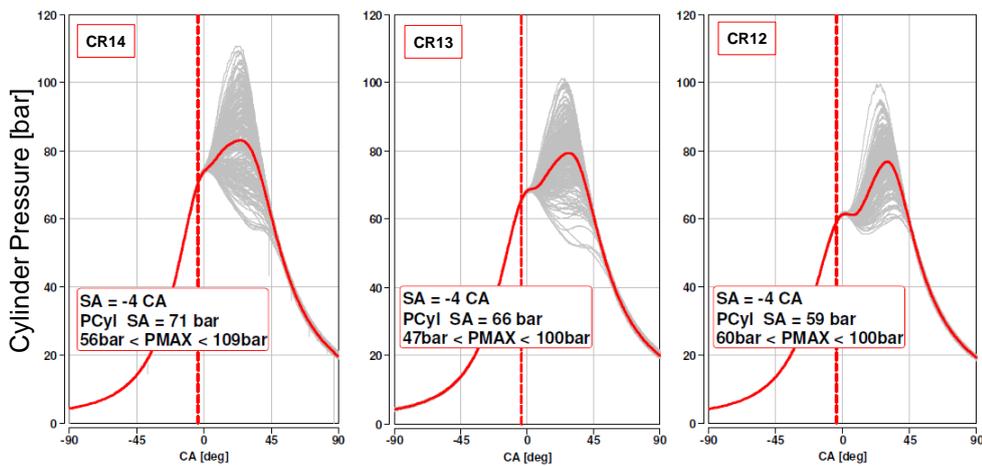
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334

335 Figure 10. Full load performance curves: CoV imep, average PFP (PMAX0) and maximum cycle-resolved PFP
 336 (PMAXmx).

337



338

339 Figure 11. Cycle-by-cycle and average in-cylinder pressure at 3500 rpm, Full load, for CR=14 (left), CR=13
340 (middle) and CR=12 (right).

341

342 The CR effect on engine performance and efficiency was also investigated at partial load. The engine was
343 run in a few selected working points, as detailed in Table 4.

344

345 Table 4. Engine working points for experimental tests at partial load.

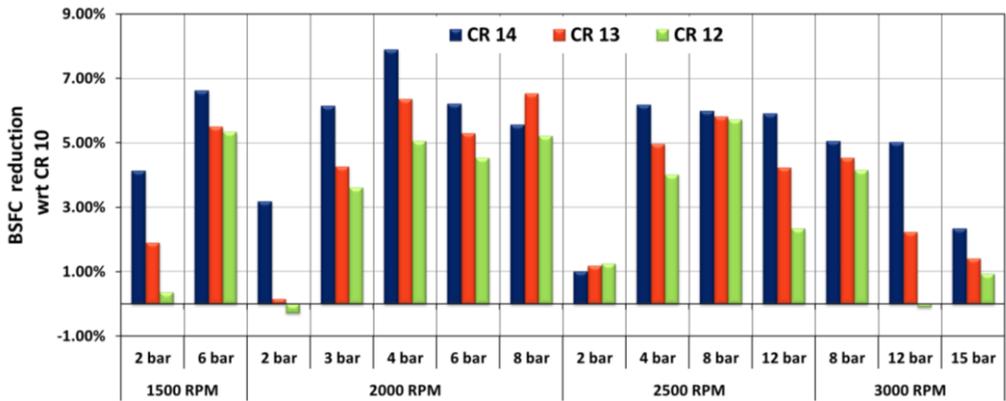
Speed [rpm]	bmep [bar]
1500	2, 6
2000	2, 3, 4, 6, 8
2500	2, 4, 8, 12
3000	8, 12, 15

346

347 The results are presented in Figs. 12 and 13. Fig. 12 shows the engine bsfc reduction, with respect to the
348 base engine with CR=10. As a matter of fact, as CR increases, the efficiency of the reference
349 thermodynamic Otto cycle increases. However, the impact of the thermodynamic losses due to imperfect
350 or untimely combustion process might affect the overall engine behavior. At partial load, no issues about
351 the PFP limit arise, thus the combustion timing can be always set to its optimal value (usually corresponding
352 to MFB50 ranging from 5 to 10 deg after top dead center), corresponding to the maximum brake torque
353 (MBT) conditions. Consequently, the effect of combustion untimeliness is similar for the three CR values,
354 and the dominant effect is given by the increase in the Otto cycle efficiency. Consistently, a benefit in
355 engine fuel consumption was obtained experimentally in almost all the working points at it is shown in Fig.
356 12. The impact of the engine CR on the combustion cycle-to-cycle variation is represented in Fig. 13 for a
357 few selected engine operating conditions, amongst those included in Table 4. Similarly to the full load case,

358 the combustion process gets less regular as CR increases, again suggesting that a detriment in the
 359 turbulence level at combustion start has occurred.

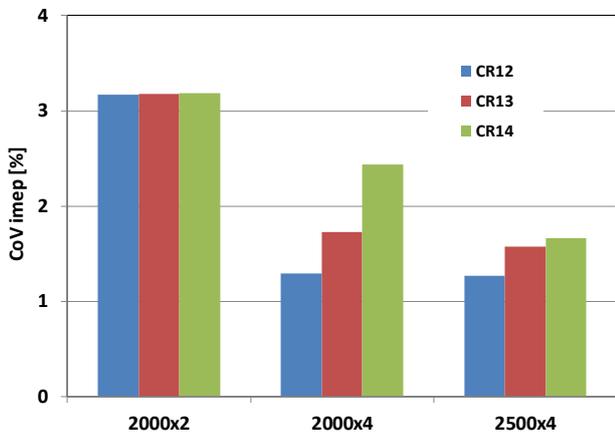
360



361

362 Figure 12. Percentage bsfc reduction with respect to the baseline engine with CR=10, for various working
 363 points at MBT timing.

364



365

366 Figure 13. CoV imep in a few selected working points for the different CRs.

367

368 The experimental activity carried out by CRF evidenced the following main effects as the compression ratio
 369 is increased:

- 370 1. The maximum engine power decreases;

- 371 2. The bsfc at partial load decreases;
- 372 3. The benefit in bsfc at full load are hidden by the non-optimal combustion timing, mainly due to the
- 373 occurrence of the PFP limitations;
- 374 4. The cycle-to-cycle variability of combustion increases both at partial load and at full load.

375 The CR=13 value was finally selected for equipping the demonstrator vehicle, as the best compromise

376 between fuel consumption at partial load, combustion quality and engine performance at full load.

377

378 **4.3 Engine transient CFD simulations**

379 A set of CFD simulations was planned aside the experimental activity, focused on investigating the in-

380 cylinder flow and combustion process in the engine cycle. The work was aimed at giving a deeper insight to

381 the combustion behavior in the engine prototype, as well as at verifying the consistency of the steady-state

382 flow simulation results as far as the effect of the masking surface is concerned.

383 First of all, as a dependence of the combustion speed and cycle-to-cycle variation on the CR was observed,

384 as it is shown in Section 4.2, the engine configuration with mask was simulated with different compression

385 ratio values in order to have an insight into the tumble and turbulence evolution. The results are shown in

386 Figs. 14-15. Fig. 14 reports the in-cylinder velocity field at an intermediate instant of the induction stroke,

387 with reference to the combustion chamber variant with mask. As a matter of fact, for a given crank angle a

388 difference in CR (and, in turn, in the clearance volume) gives rise to a different position of the piston top

389 with respect to the cylinder head. In the CR=14 case, the piston is closer to the head and the intake flow

390 impinges on it, resulting in a decrease in the tumble vortex size and reduction of its overall intensity.

391 Contrariwise, in the lower compression ratio case, the resultant size of the direct tumble structure is bigger

392 and better defined. Fig. 15 shows the tumble number and the mass-averaged turbulence intensity

393 evolution versus crank angle, for the three CR values at 3500 rpm and full load. The in-cylinder tumble

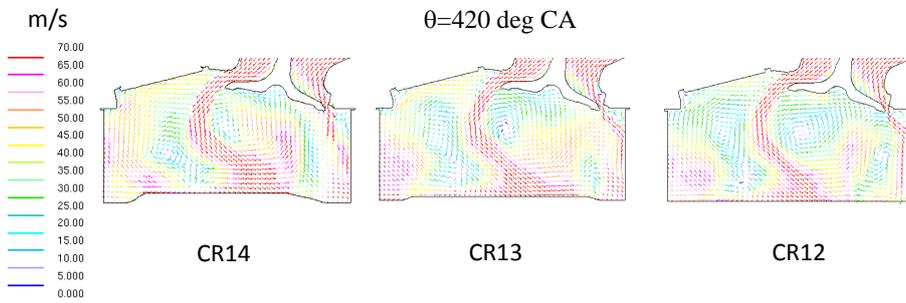
394 number is given by:

395

$$TN = \frac{\int [-v_z (x - x_m) + v_x (z - z_m)] \cdot dm_{cyl}}{\frac{2\pi N}{60} \int_{m_{cyl}} [(x - x_m)^2 + (z - z_m)^2] \cdot dm_{cyl}} \quad (5)$$

396 where v_x, v_z are the x- and z- components of the velocity, x_m, z_m are the x- and z- coordinates of the cylinder
 397 center of mass and N is the engine speed in rpm. As the piston exerts a disturbance effect on the direct
 398 tumble vortex throughout the first part of the induction stroke, the TN generation is the higher in the
 399 CR=12 case. This happens between around 360 and 450 deg CA, and is the cause of the difference in the TN
 400 curves, which can be appreciated in Fig. 15. The higher tumble strength in the case with CR=12 in turn
 401 determines a higher turbulence level (by around 20%) in correspondence to the spark timing, hence
 402 contributing to the explanation of the observed differences in the combustion speed and stability (Figs. 10,
 403 11 and 13).

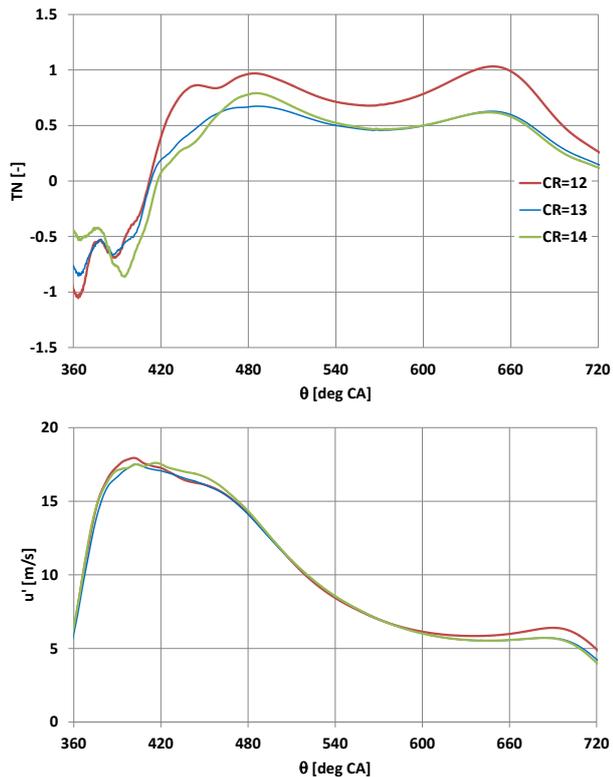
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406 Figure 14. In-cylinder velocity field during the intake stroke for different CR values – 3500 rpm, Full load.

407



408

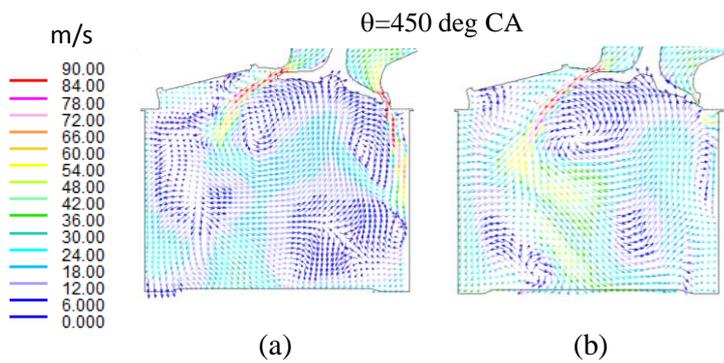
409 Figure 15. Tumble number and mass-averaged turbulence intensity versus crank angle – 3500 rpm, Full
 410 load.

411

412 Further simulation work was carried out, in order to assess for the differences in fluid-dynamic and
 413 turbulence flow features between the baseline configuration and the one with masked intake valve. Fig. 16
 414 shows the effect of the combustion chamber variants on the in-cylinder flow field structure at 450 deg CA,
 415 for the working point at 2000 rpm and 4 bar, with CR=13. As discussed above, the piston presence affects
 416 the overall size of the direct tumble vortex, however the relative effect between the configuration without
 417 mask and that with mask is qualitatively the same as the one observed in the steady-state analysis (see Fig.
 418 4). In the considered working point, the actuated valve lift profile is represented by the blue line in Fig. 7.
 419 Since the maximum lift is kept within the size of the masking wall, the latter is able to exert its influence
 420 over the whole intake process. Consequently, a remarkable benefit is obtained in terms of both tumble
 421 number and turbulence as can be inferred from Fig. 17. In correspondence to the spark timing position
 422 (about 690 deg CA) an increase by around 90% and 10% have been obtained for TN and for the turbulence

423 intensity, respectively, relative to the baseline variant. As far as the full-load conditions are concerned, a
424 considerably lower effect is obtained, due to the higher inlet valve lift. In fact, as discussed in Section 4.1,
425 the masking surface is virtually ineffective when the valve lift is greater than the surface extension. Fig. 18
426 shows an overall evaluation of the mask effect, including full-load as well as partial load cases, for CR=12
427 and CR=13. As can be seen in the figure, with the exception of the full load case with CR=13, the presence
428 of the mask increases the tumble level in the cylinder and, in turn, the turbulence intensity. However, at a
429 first sight a detriment in tumble was also obtained in the 2000 rpm, bmep=2 bar case with CR=12. Still, in
430 such a case the virtually nil TN is actually the result of the compensation of two opposite moment
431 contributions and does not represent a penalty, as it is confirmed by the comparable turbulence level
432 obtained. Concerning the turbulence effect on burning speed, except the CR=13 configuration at full load
433 conditions, a benefit on the combustion duration from 1% to 50% of heat released (MFB1-50) between 2
434 and 6 deg CA was found. This is in agreement with the observed experimental combustion behavior, also
435 from the point of view of the cycle-to-cycle stability, and confirms the overall benefit that is obtained by
436 adopting the tumble oriented cylinder head design.

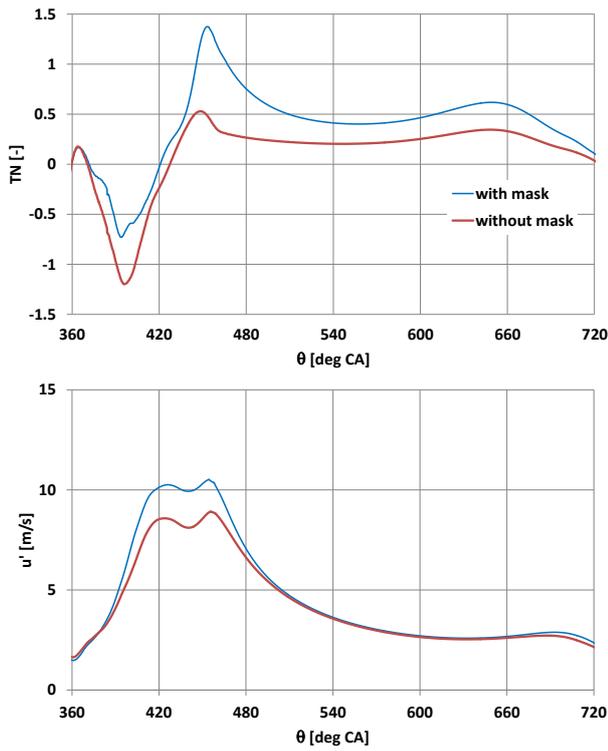
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439 Figure 16. Effect of the intake valve masking surface on in-cylinder flow field at 2000 rpm, bmep=4 bar.

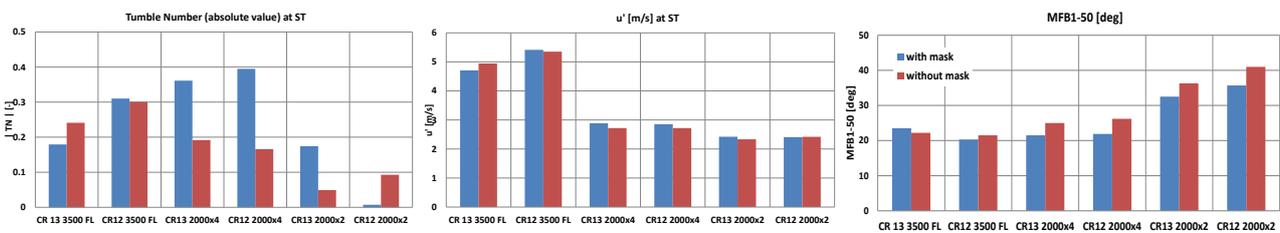
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442 Figure 17. Tumble number and turbulence evolution versus crank angle for the variants with and without
 443 mask – 2000 rpm, bmep=4 bar.

444



445

446 Figure 18. Tumble number, turbulence intensity and MFB1-50 combustion interval for the variants with and
 447 without mask.

448

449 **6. CONCLUSION**

450 The activity presented in this paper was focused on the development of a monofuel, high performance, NG
 451 engine. More specifically, the design of the engine combustion chamber was described, with reference to

452 the optimization of the engine CR and to the trade-off between engine permeability and tumble
453 characteristics of the intake port. The activity was carried out by combining 3D simulations and
454 experimental tests. The main conclusions are as follows.

- 455 – The steady-state simulations indicated that the engine configuration with mask features a decrease
456 in the average discharge coefficient by around 20-30%, whereas an increase in the tumble ratio by
457 around 200% is obtained at partial load.
- 458 – The simulations of the engine cycle led to the same conclusion from a qualitative point of view,
459 though the presence of the piston modifies the tumble intensity of the induced flow with respect to
460 the ‘undisturbed’ flow in the virtual steady-state flow rig. In the 2000x4 working point, the increase
461 in the tumble number at spark timing was of around 90%, which lead to a 10% increase of the
462 turbulence intensity.
- 463 – Overall, the presence of the masking surface determined a benefit in the turbulence intensity at
464 spark timing in almost all the cases at partial load, and a reduction of the MFB1-50 interval
465 between 2 and 6 deg CA was correspondingly obtained.
- 466 – With reference to the optimization of the engine CR, the experimental activity carried out at CRF
467 showed that CR=13 was the best compromise between fuel consumption at partial load, engine
468 performance at full load, and combustion quality.
- 469 – The cycle-to-cycle variability of combustion increased with the increase in the engine CR, due to the
470 detriment of the tumble number and of the turbulence intensity. The latter is higher by around
471 20% in the CR=12 case.

472

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**Combustion chamber design for a high-performance natural gas engine:
CFD modeling and experimental investigation**

Mirko Baratta, Daniela Misul, Ludovico Viglione, Jiajie Xu

ANSWER TO REVIEWERS' AND EDITOR'S COMMENTS

Reviewer #4

Authors have made a lot efforts to address the reviewers' comments and the quality of paper has been improved. I recommend publication after a 'minor revision':

Thank you very much for the appreciation of our efforts.

1. Avoid using abbreviations in the title, CFD is well known but NG is not.

As requested, 'NG' has been replaced with 'natural gas' in the paper title.

2. Abstract is usually in one paragraph. I recommend combine the two paragraphs into one, and shorten the background information a little bit.

The abstract has been revised considering the Reviewer's comment.

3. Please hide the outer borders of Figs. 5 and 7. In addition, right side border of Fig. 13 is missing.

The borders of the figures 5, 7 and 13 have been fixed, thank you.

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**Combustion chamber design for a high-performance natural gasNG engine:
CFD modeling and experimental investigation**

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ABSTRACT

The present paper ~~describes a part of a research activity aimed at giving a contribution to a solution for urban mobility with very low environmental impact, through the development and integration of a number of advanced technologies. The activity have been~~is focused on the development of a high-performance, monofuel, spark ignition engine running on natural gas, featuring a high volumetric compression ratio and a variable valve actuation system ~~for the air metering~~. More specifically, ~~the paper is focused on the analysis of~~the cylinder head geometry effect has been analyzed and the compression ratio optimization has been optimized by means of ~~Steady-state and transient simulation activity, as well as of an extensive experimental campaign, were carried out with this purpose~~. The compression ratio effect was mainly investigated by means of experimental tests but a few 3D simulations were also run in order to quantify its impact on the in-cylinder tumble and turbulence. The main novelty of the paper are, first, the adoption of very high engine compression ratio values, second, the combined optimization of the cylinder head design and compression ratio. The main results can be summarized as follows. The engine configuration with mask showed a decrease in the average discharge coefficient by 20-30% and an increase in the tumble ratio by around 200% at partial load. Moreover, the simulation of the engine cycle indicated that the presence of the piston modifies the tumble structure with respect to the steady-state simulation case. An increase in the tumble number and turbulence intensity by around 90% and 10%, respectively, are obtained for the case with mask at 2000 rpm and 4 bar. With reference to the combustion duration, on an average, the presence of the masking surface led to a reduction of the combustion duration (from 1% to 50% of mass fraction burned) between 2 and 6 degrees. As far as the engine compression ratio is concerned, the value of 13 was finally selected as the best compromise between combustion variability, engine performance at full load and fuel consumption at partial load.

KEYWORDS

Natural gas, SI engines, Tumble flow, CFD simulation.

NOMENCLATURE

B	cylinder bore
bmep	brake mean effective pressure
CA	crank angle
C _D	discharge coefficient

39	CFD	computational fluid dynamics
40	CNG	compressed natural gas
41	CoV	coefficient of variation
42	CR	compression ratio
43	deg	degree
44	ECFM	extended coherent flamelet model
45	EGR	exhaust gas recirculation
46	GHG	greenhouse gases
47	imep	indicated mean effective pressure
48	k	turbulent kinetic energy
49	MBT	maximum brake torque
50	MFB	mass-fraction burned
51	MFB1-50	combustion duration from 1% to 50% of heat released
52	MFB50	'combustion barycenter' position
53	NG	natural gas
54	N_T	tumble number
55	PFP	peak firing pressure
56	PMAX0	ensemble-averaged peak firing pressure
57	PMAXmx	maximum cycle-resolved peak firing pressure
58	SI	spark ignition
59	TN	in-cylinder tumble number
60	TR	tumbling ratio
61	v_{is}	isentropic flow velocity
62	VVA	variable valve actuation
63	x	coordinate for tumble moment of momentum calculation
64	y+	normalized distance from wall
65		
66	Greek symbols	
67	ε	turbulence dissipation rate
68	θ	crank angle position
69	$\omega_{AV,EXH}$	equivalent angular speed to the exhaust side
70	$\omega_{AV,INT}$	equivalent angular speed to the intake side
71		

72 1. INTRODUCTION

73 Nowadays, the design of modern internal combustion (IC) engines represents a challenging task, due to the
74 raising concern for the global warming as well as to the stringent constraints set by the current pollutant
75 regulations. The use of gasoline or diesel in internal combustion engines is likely to remain the most cost-
76 effective overall ground-based transportation propulsion system for the near future. Furthermore, hybrid
77 and electric vehicles are gaining considerable market share. However, as far as IC engines are concerned,
78 natural gas (NG) represents a factual alternative to traditional fuels thanks to the reduced pollutant and
79 carbon dioxide emissions [1,2]. Moreover, the development of engines compatible with biofuels (for
80 example, natural gas from biomasses) can provide enormous benefits compared to fossil fuels, in terms of
81 greenhouse gases (GHG) emissions [3,4], although attention has to be paid to the fuel properties and their
82 dependence on the blend composition. With specific reference to natural gas, the effect of biogas

83 composition on the engine operating characteristics has been widely studied by the researchers. In [5] it
84 was found that methane concentration in the biogas significantly improves performance and reduces
85 emissions of hydrocarbons. The lean operation limit is also extended. Similarly, investigations carried out in
86 [6] showed that the methane-enriched biogas performed similarly to compressed natural gas (CNG). Along
87 with methane, other inert species, such as carbon dioxide and nitrogen, can be present in the biogas
88 composition. Furthermore, hydrogen derived from biomass gasification can be blended to natural gas as an
89 additive. As a matter of fact the high speed of flame propagation of hydrogen improves the stability of the
90 combustion process when added to natural gas [7,8].

91 The development of highly efficient engines cannot withstand the adoption of advanced design methods.
92 As a matter of fact, the introduction of advanced engine concepts, such as, variable valve actuation,
93 turbocharging or direct injection leads to an increase in the complexity of the engine design process, as the
94 number of the design variables is remarkably higher. Moreover, with reference to biofuels dedicated
95 control algorithms might be necessary to make up for the variability in the fuel properties due to the
96 dispersion in the blend composition. As far as the optimization of the combustion chamber and the intake
97 port geometry is concerned, the adoption of computational fluid dynamics (CFD) represents an effective
98 means to support the design process, allowing the time and cost of the associated experimental activity to
99 be reduced. Appreciable benefits in terms of combustion stability, efficiency and pollutant emissions can be
100 obtained if a suitable intensity of swirl and/or tumble motion is targeted. With specific reference to spark
101 ignition (SI) engines, the tumble motion is usually generated in order to increase the turbulence level in the
102 combustion chamber, thus enhancing the combustion stability and the exhaust gas recirculation (EGR)
103 tolerance. Amer and Reddy [9] carried out a multidimensional optimization of the in-cylinder tumble
104 motion for an engine featuring hemispherical combustion chamber. They found that large-scale tumbling
105 flow structures, if persistent and coherent, can be effective in the turbulence enhancement at spark timing,
106 provided that they are dissipated right before ignition. In addition, they underlined that the dominant flow
107 structures through the compression phase are significantly different than those occurring in a steady-state
108 intake flow in a flow test rig. This was also remarked in [10]. Berntsson et al. [11] performed engine tests as
109 well as CFD simulations on a 500 cc single-cylinder engine with different tumble levels. A positive effect of
110 increased tumble on efficiency was highlighted, and advantages were also found as far as knock resistance
111 and EGR tolerance are concerned. Similar results are also reported in [12], where the enhancement of
112 tumble intensity led to an extension of the lean burn range of the engine, which in turn allowed a benefit in
113 fuel economy to be achieved. Accordingly, in [13] the increase in tumble allowed the lean operation limit to
114 be extended up to $\lambda = 1.55$, leading to benefits in fuel consumption as well as in NO_x and CO emissions. In
115 [14], the effects of tumble combined with EGR on the combustion and emissions in a spark ignition engine
116 were investigated. In addition to the advantages in fuel consumption due to combustion enhancement, it
117 was also pointed out that EGR allows a de-throttling effect to be obtained, which reinforces the fuel
118 consumption reduction. Similarly, in [15] it was evidenced that the intake tumble can extend the allowable
119 EGR rate, thus largely improving its effectiveness in reducing fuel consumption and emissions.
120 Furthermore, the existence of an optimal tumble level can be identified in different engine working
121 conditions, as far as fuel consumption and combustion efficiency are concerned [16]. The synergic effect of
122 tumble enhancement and mixture dilution by EGR in reducing fuel consumption and NO_x emissions is also
123 testified in [17]. These effects are largely due to the increase in the flame propagation speed, which is
124 obtained through tumble enhancement. As a matter of fact, in [18] a flame propagation increase by 35%
125 was evidenced, when the non-dimensional tumble was increased from 0.5 to 2.2.

126 Several technical solutions have been proposed for the tumble enhancement in SI engines in the last two
127 decades. The common target of such solutions is the deviation from the flow balance between two halves

128 of the intake valve curtain area. The flow is in fact mostly conveyed to the cylinder through the upper
129 curtain area portion. A few practical examples are the intake valve masking [19], the adoption of restriction
130 and flow-separating plates [11], the use of an adapter for the intake runner [20], the offset of the intake
131 valve [12] as well as the optimization of the port geometry [21, 22]. The application of a masking surface
132 downstream of the intake valve was also investigated in [23]. However, in this case the flow was inhibited
133 in the upper curtain area portion, so that the so called 'reverse tumble' was promoted. The benefit in terms
134 of turbulence intensity around the spark location was of around 100% with respect to the baseline design.
135 Finally, it is worth pointing out that the turbulence level at spark timing is influenced also by the tumble
136 evolution during intake and compression, which can be affected by the piston shape and position [24].

137 The present paper aims to give a further contribution to the assessment of design solutions for the tumble
138 improvement, by considering a purposely designed masking surface downstream of the intake valve. The
139 main novelty of the paper is, on one hand, the adoption of very high engine compression ratio (CR) values
140 (as explained in the next section), which determine an apparent influence between the induced tumble and
141 the piston. On the other hand, the combined optimization of the cylinder head design and CR, as well as the
142 correlation between numerical and experimental results, represents an added value.

143

144 2. PRESENT WORK

145 The present paper reports part of the outcomes of a research activity carried out by Politecnico di Torino
146 (PoliTo) and Fiat Research Center (CRF) within the Biomethair regional research project (Automotive
147 platform of Regione Piemonte, Italy, <http://www.biomethair.it/index.php>). The activity has been aimed at
148 giving a contribution to a new urban-mobility solution with ultra-low environmental impact. This ambitious
149 target has been pursued by means of the development and integration of a number of advanced
150 technologies, including hybrid propulsion, high-performance engines as well as biofuel production and
151 utilization.

152 The activities performed by PoliTo and CRF have been focused on the development of a high-performance
153 engine specifically dedicated to CNG fueling and featuring a variable valve actuation (VVA) system as well as
154 very high compression ratios. The main engine characteristics are reported in Table 1. The engine is derived
155 from the production gasoline-fueled TwinAir engine and the compression ratio (CR) was increased from the
156 baseline value of 10 up to the range 12-14, whose optimization was part of the design process. The results
157 of the Biomethair engine development activity are presented in this paper, as well as in [10]. More
158 precisely, the results of the experimental and numerical characterization of the steady-state tumble flow
159 from the Biomethair engine head were presented in [10]. In addition, a numerical model for the engine-
160 cycle transient simulation was developed and preliminarily assessed. The present paper is focused on the
161 design and optimization activity of the Biomethair combustion chamber. The activity was carried out by
162 combining 3D simulation results to performance and emission data from the dyno test rig at CRF.

163 Table 1 – Biomethair engine characteristics

Feature	Value/specification
Displacement [cm ³]	875
Number of cylinders	2

Compression ratio	12-14 (production engine: 10)
Turbocharger	WG-controlled
Target torque	140 Nm @2000 rpm
Target power	60 kW @5000 rpm

164

165 3. ENGINE DEVELOPMENT PROCEDURE

166 The engine development activity described in the present paper is divided into three parts. First, two
 167 variants for the cylinder head geometry were considered and compared, with specific reference to their
 168 performance in terms of permeability and tumble intensity. More specifically, the influence of a purposely
 169 designed masking surface is analyzed through the comparison with the baseline cylinder head configuration
 170 without mask. As a matter of fact, as widely discussed in the Introduction section, the enhancement of the
 171 tumble intensity caused by the masking wall can lead to an increase in the turbulence intensity and, in turn,
 172 to remarkable benefits in terms of combustion speed, efficiency and repeatability. On the other hand, the
 173 presence of an additional obstacle might lead to a detriment in the volumetric efficiency. A steady-state
 174 cylinder head numerical model ('virtual flow rig' model), previously developed and validated [10], was
 175 applied for this analysis. Second, the selected cylinder head geometry was used to assemble the prototype
 176 engine, by considering three different piston variants which corresponded to three different CR values,
 177 ranging from 12 to 14. The CR effect was then analyzed by combining experimental and 3D simulation
 178 results. Third, the selected compression ratio was finally considered to verify the overall effect of the
 179 cylinder head geometry on the in-cylinder tumble, in the presence of combustion.

180 The baseline versions for the "virtual flow rig" model and the complete engine model adopted in the
 181 current study were extensively described and validated in [10], some details are anyhow summarized
 182 hereafter for the reader's convenience. The main model features are also summarized in Table 2, along
 183 with the associated average calculation time.

184 Table 2. CFD model summary

	'Virtual flow rig' model	Engine model
Cell count	~4,000,000	~800,000 (at BDC)
Cell size	min. 0.3 mm, max. 2.5 mm	min. 0.4 mm, max. 1 mm
Turbulence model	Realizable k- ϵ	RNG k- ϵ
Near wall treatment	'Two layer all y+'	Angelberger law of the wall [25]
Combustion model	-	ECFM-3z [26]
Average calculation time	~16h on a 24 CPU workstation	~48h per cycle, on a 24 CPU workstation

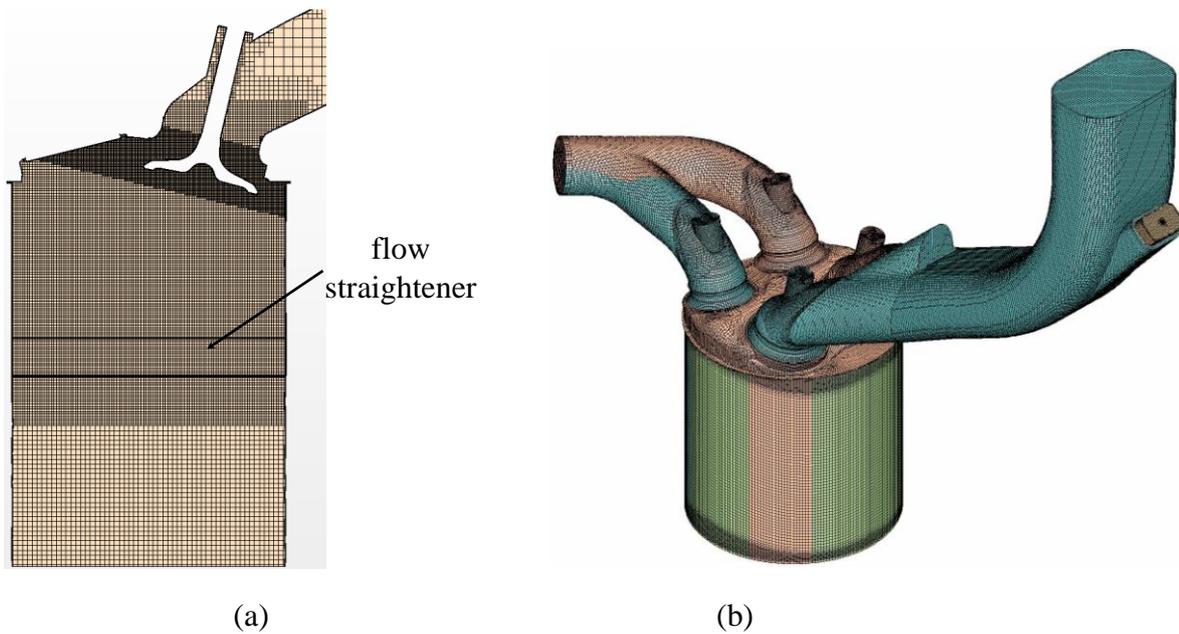
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186 The steady-state flow rig model was developed within StarCCM+ v.8.06 and features around 4 million of
 187 cells, the mesh size ranging between 1.25-2.5 mm in the intake ports and 0.3 mm in the valve curtain
 188 region (Fig. 1a). The Realizable k- ϵ model turned out to be the best compromise between model accuracy,
 189 stability and computational cost, within the Reynolds-Averaged Navier-Stokes (RANS) framework, and was
 190 thus selected for the analyses discussed in the present paper. For the near wall treatment, a two-layer

191 approach named 'all y^+ ' was selected and 5 cell layers were placed at the wall boundaries. Such an
192 approach is claimed to provide a reliable solution in the entire y^+ range.

193 The transient engine model has been developed by means of the commercial code Es-ICE version 4.20 and
194 features around 800 000 cells at bottom dead center, with a cell size between 0.4 and 1 mm (Fig. 1b). The
195 RNG $k-\varepsilon$ model was adopted, along with the Angelberger law of the wall [25], with a near wall extrusion
196 layer of 0.2 mm, which insures a y^+ value ranging between 30 and 100. The three-zone extended coherent
197 flamelet model (ECFM-3z) [26] was used in order to simulate the in-cylinder combustion process. The
198 potential of the model in the engine simulation have been recently further demonstrated in [27,28], with
199 reference to a dual-fuel, partially stratified, SI combustion. In the present work, the model coefficients were
200 calibrated based on experimental data in seven engine working conditions with different engine
201 compression ratios. A maximum error of 3% and 2 deg CA was detected on peak firing pressure and
202 'combustion barycenter' (MFB50) position, respectively. An example of comparison between experimental
203 and CFD data is provided in Fig. 2, where an operation point at 3500 rpm, full load (upper row) and another
204 one at 2000 rpm, $b_{mep}=4$ bar (lower row) are considered. The calibrated model was applied to the
205 different geometry variants under study by keeping the ECFM coefficients unchanged, thus giving
206 consistency to the analysis.

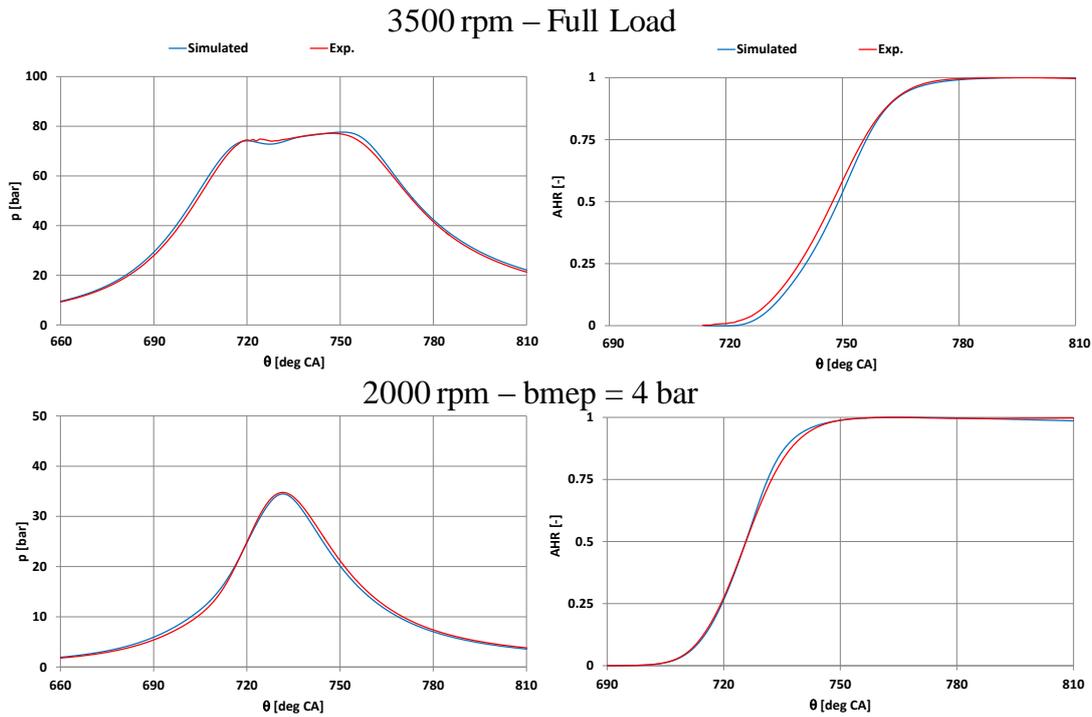
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208

209 Figure 1. CFD numerical models: cross- section of the steady-state cylinder head numerical model ('virtual
210 test rig') (a); full view of the transient engine model (b).

211



212

213 Figure 2. Engine numerical model validation results: pressure (left) and heat release (right) profiles.

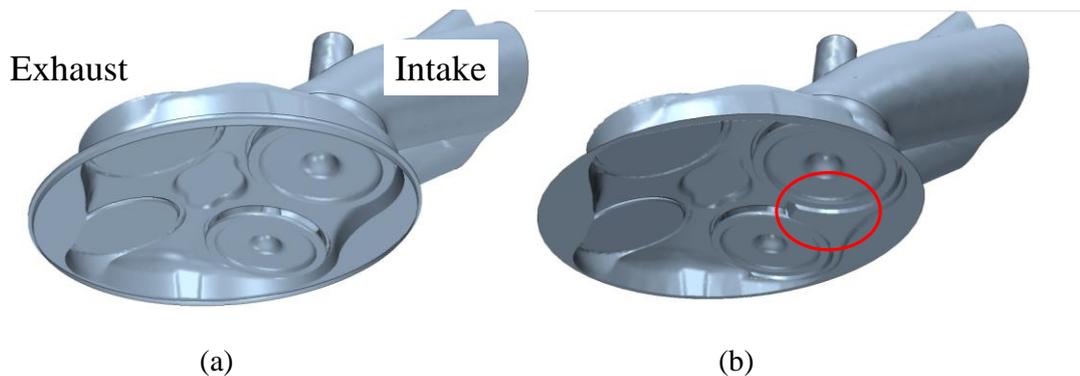
214

215 **4. RESULTS AND DISCUSSION**

216 **4.1 Steady-state flow CFD simulation**

217 The first step of the combustion chamber design process was the comparison of two variants for the head
 218 dome, which are represented in Fig. 3. In this phase, only the cylinder head is considered, without any
 219 piston combined to it, according to the approach of the steady-state cylinder head numerical model
 220 (Section 3). The first variant is the baseline one (Fig. 3a), which is adopted in the production gasoline
 221 engine. The second variant was obtained by creating a masking wall right downstream of the intake valve,
 222 to the wall side, as can be seen in Fig. 3b where the masking wall is highlighted with the red oval. The
 223 chamber variants were compared through the simulation of the steady-state flow from the intake valve, by
 224 considering the CFD model in Fig. 1a.

225



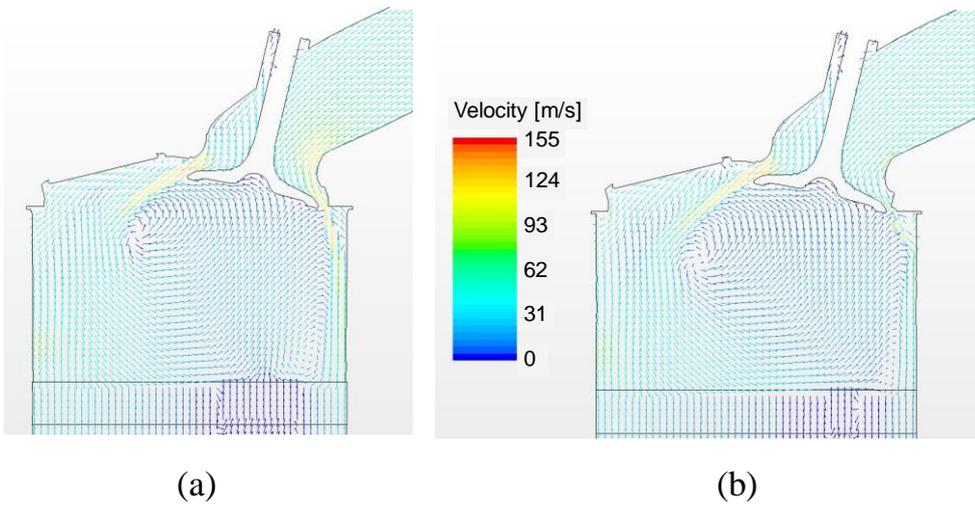
226

227 Figure 3. Design variant: baseline without mask (a) and with mask (b).

228

229 The results of the comparison are reported in Figs. 4-6. Fig. 4 shows the steady-state velocity field in the
230 intake valve plane, which was obtained from both variants at the intermediate valve lift of 4 mm. Such a lift
231 value is close to the height of the masking surface in the variant with mask. The figure shows that in the
232 baseline configuration the curtain area of the intake valve is almost entirely exploited and inlet velocities of
233 100-120 m/s can be observed at both sides of the intake valve (Fig. 4a). The overall tumble intensity thus
234 results from the difference in angular momentum contributions of both the 'direct' and the 'reverse'
235 tumble. Conversely, the 'reverse' tumble is obstructed by the presence of the masking wall in the variant
236 with mask, as it is clearly shown in Fig. 4b. In such a case, the negative contribution due to the flow issuing
237 from the intake valve to the wall side is inhibited to a great extent, thus increasing the overall tumble
238 intensity.

239



240

241 Figure 4. Steady state intake velocity field at the intermediate lift of 4 mm: baseline without mask (a) and
242 with mask (b) configurations.

243

244 The effect of the combustion chamber geometry on the valve performance is summarized in Fig. 5 in terms
245 of discharge coefficient and tumble number. The tumble number is given by ([10]):

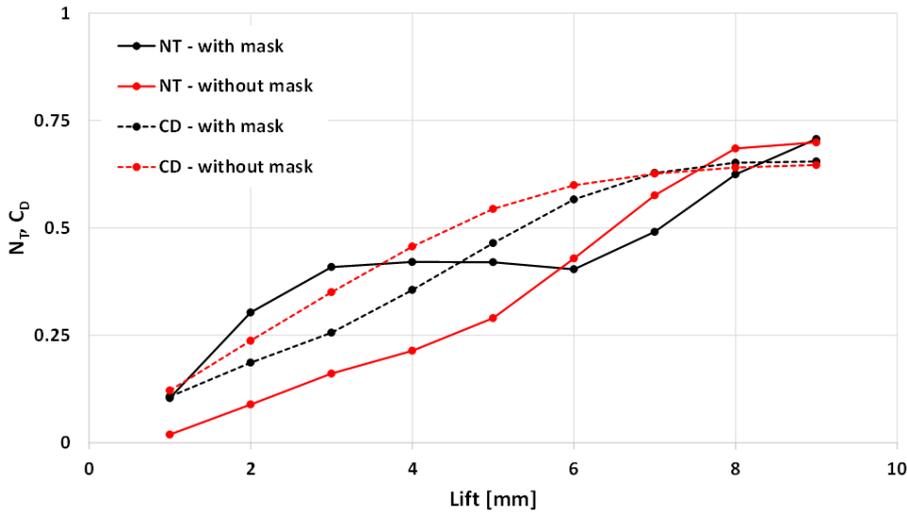
$$246 \quad N_T = \frac{-(\omega_{av,INT} + \omega_{av,EXH}) \cdot B}{v_{is}} \quad (1)$$

247 where $\omega_{av,INT}$ and $\omega_{av,EXH}$ are equivalent angular speed referred to the intake and the exhaust side,
248 respectively (see Fig. 3), according to the equation below:

$$249 \quad \omega_{av,EXH} = \frac{\sum_{e=1}^{N_e} V_{z,e} X_e}{\sum_{e=1}^{N_e} X_e^2}; \quad \omega_{av,INT} = \frac{\sum_{i=1}^{N_i} V_{z,i} X_i}{\sum_{i=1}^{N_i} X_i^2} \quad (2)$$

250 and v_{is} is the isentropic flow velocity corresponding to the actual pressure ratio. The formulas above are
 251 applied with reference to a measurement plane located 2 mm below the flow straightener (Fig. 1a). The
 252 position $x=0$ is the cylinder axis position, and the indices i and e are related to the intake and the exhaust
 253 side, respectively. As far as the influence of the chamber design is concerned, for low and intermediate
 254 valve lift values the presence of the masking wall gives rise to a decrease of the valve discharge coefficient
 255 by around 10-20%, whereas the tumble number is increased up to two-three times its original value, due to
 256 the reverse tumble inhibition discussed above. At high lift (above 5 mm), the intake valve results to be
 257 displaced beyond the extension of the masking surface, consequently its effect virtually disappears as is
 258 testified by the comparable values of both C_D and N_T for the baseline and the 'masked' design.

259



260
 261 Figure 5. Tumble number (NT) and discharge coefficient (CD) versus valve lift.

262

263 The results in Fig. 5 can be used as input to estimate the effect of the mask presence on the global tumble
 264 and permeability of the valve in the real engine installation. Following the procedure in [29], with reference
 265 to the intake valve lift profile for the considered engine working point, the average discharge coefficient
 266 and the steady-state tumble ratio at IVC can be defined as follows:

$$267 \quad \overline{C_D} = \frac{\int_{\vartheta_1}^{\vartheta_2} C_D \cdot d\vartheta}{\vartheta_2 - \vartheta_1} \quad (3)$$

$$268 \quad TR = \frac{B \cdot s}{N_v D_v^2} \cdot \frac{\int_{\vartheta_1}^{\vartheta_2} C_D \cdot N_T \cdot d\vartheta}{\left(\int_{\vartheta_1}^{\vartheta_2} C_D \cdot d\vartheta \right)^2} \quad (4)$$

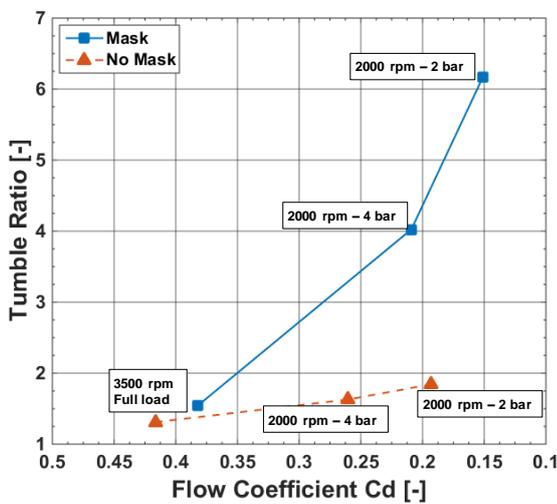
269 where θ_1 and θ_2 represent the intake valve opening and closure crank angle positions, respectively. The
 270 considered coefficients were calculated in three engine working points, as reported in Table 3. The results
 271 are reported in Fig. 6. The valve lift profile considered in each of the working points can be found in Fig. 7.

272

273 Table 3. Engine working points for tumble ratio evaluation.

Speed [rpm]	bmep [bar]
2000	2
2000	4
3500	Full load

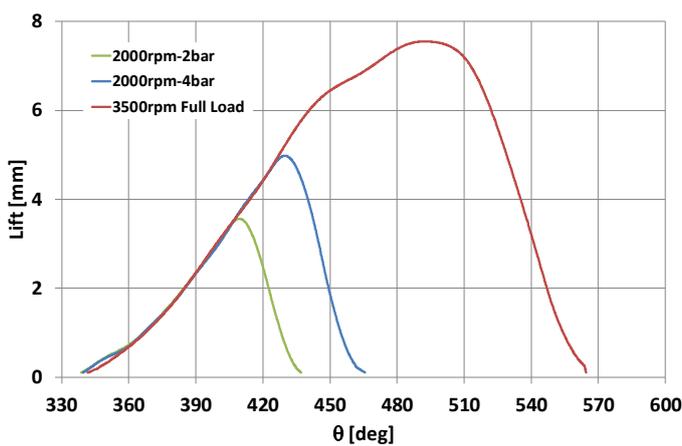
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275

276 Figure 6. Average flow coefficient and tumble ratio in different engine working points.

277



278

279 Figure 7. Valve lift profiles.

280

281 The results in Fig. 6 show that the presence of the mask determines a decrease in the average discharge
 282 coefficient by around 20-30%, mainly due to the reduced effective flow area caused by the obstruction

283 effect of the wall. As far as the tumble ratio defined by Eq. 4 is concerned, the effect is actually dependent
284 on the engine load. At partial load, the valve opening time and maximum lift are highly reduced by the
285 action of the VVA device (Fig. 7). Consequently, the valve position is kept within the range corresponding to
286 the extension of the masking surface, thus maximizing its effect on the flow unbalance. As a matter of fact,
287 the tumble ratio at partial load is increased by 150% in the 2000rpm-4bar working point, and by 235% in
288 the 2000rpm-2bar one. At full load, the valve lift is kept above 5 mm for about half of the total opening
289 time. It is worth recalling that the mask is virtually ineffective in for high lift, and observing that such lift
290 values affect the integral at the numerator of Eq. 4 to a great extent, due to the high value of C_D in that
291 range. For this reason, the tumble ratio benefit is limited to 18%. Although the tumble ratio estimated by
292 steady-state flow data might not be fully representative of the flow behavior in the real engine [10], their
293 significance is usually sufficient to assess for the suitability of steady flow tests during the early design
294 stages of tumble-generating induction systems [29]. Consequently, based on the results discussed above, it
295 was decided to adopt the configuration with mask for assembling the Biomethair engine prototype, given
296 the minor penalty in the discharge coefficient which accompanies the remarkable tumble increase

297

298 4.2 Experimental tests

299 The experimental results presented in this paper were acquired by CRF and shared with Politecnico di
300 Torino within the Biomethair project. Three values of the compression ratio (namely, 12, 13 and 14) were
301 actually tested, by assembling different piston design variants with the same cylinder head (see Fig. 3). The
302 piston design variants are represented in Fig. 8. The tests aimed at defining the optimal engine CR as a
303 compromise between performance at full load and fuel consumption at partial load.

304



306

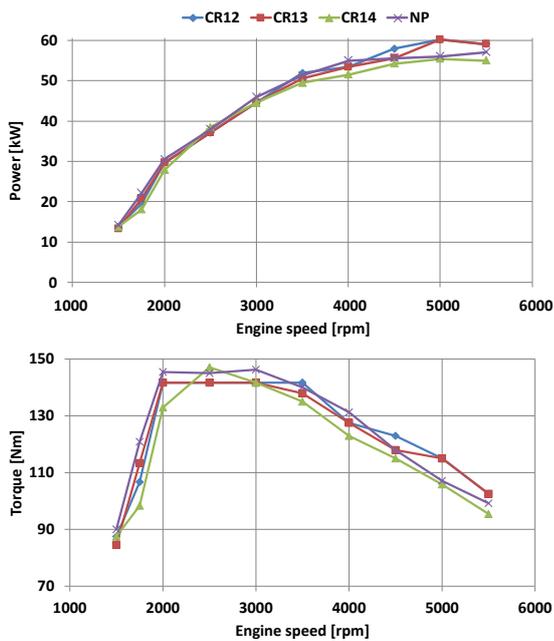
306 Figure 8. Piston shapes corresponding to the considered compression ratio values.

307

308 Figs. 9 and 10 show the results obtained at full load for the three compression ratios. More specifically, Fig.
309 9 compares the torque and power curves obtained with the three considered CR to the reference curve of
310 the normal production (NP) engine, whereas Fig. 10 reports the CoV of the imep, the ensemble-averaged
311 peak firing pressure (P_{MAX0}) and the maximum cycle resolved peak firing pressure (P_{MAXmx}). In all the
312 cases, the engine calibration was aimed at maximizing the engine load, by taking the compressor surge limit
313 into account. Moreover, the threshold for the ensemble value of the peak firing pressure was set at 85 bar,
314 allowing the single 'upper' cycles to reach 100 bar. Such limits led to the limitation of the spark advance
315 (SA) to 5-6 deg CA in most cases. The target performance data were set at 140 Nm and 60 kW. The results
316 showed that the target torque value is achieved with all the CRs. However, the higher one (CR=14) does not

317 allow the power target to be fulfilled. As far as the cyclic variation of the engine is concerned, an increasing
 318 trend of the imep coefficient of variation against CR was found (Fig. 10). This is due to the combination of
 319 two effects. First, as CR is increased, the spark timing (ST) had generally to be reduced to keep the peak
 320 firing pressure (PFP) within its limit. Second, for a given ST, the increase in CR negatively affects the
 321 combustion regularity. This is to be ascribed to the detriment in the tumble intensity evolution during the
 322 intake and the compression stroke, as will be shown in Section 4.3, and is evidenced in Fig 11. In the figure,
 323 the in-cylinder pressure acquisitions are showed for different CR values in the operating point at 3500 rpm,
 324 full load, with the same SA setting. The pressure traces pertaining to individual cycles are represented by
 325 light gray lines, whereas the red thick lines show the results of the ensemble average of acquired cycles.
 326 The red, dashed line indicates the angular position of the spark timing. As can be seen, the in-cylinder
 327 pressure at spark timing increases as CR increases. Moreover, the cycle-resolved pressure traces show a
 328 higher dispersion in the CR=14 case, which features both very fast combustion events and misfire cycles. It
 329 is thus necessary to further reduce the spark timing in order to reduce the PFP of fast burning cycles.
 330 Although the precise control of the limit on the maximum cycle-resolved PFP was rather difficult, and thus
 331 the threshold of 100 bar was slightly exceeded in many cases, the obtained results can be considered
 332 acceptable as far as the structural integrity of the engine is concerned.

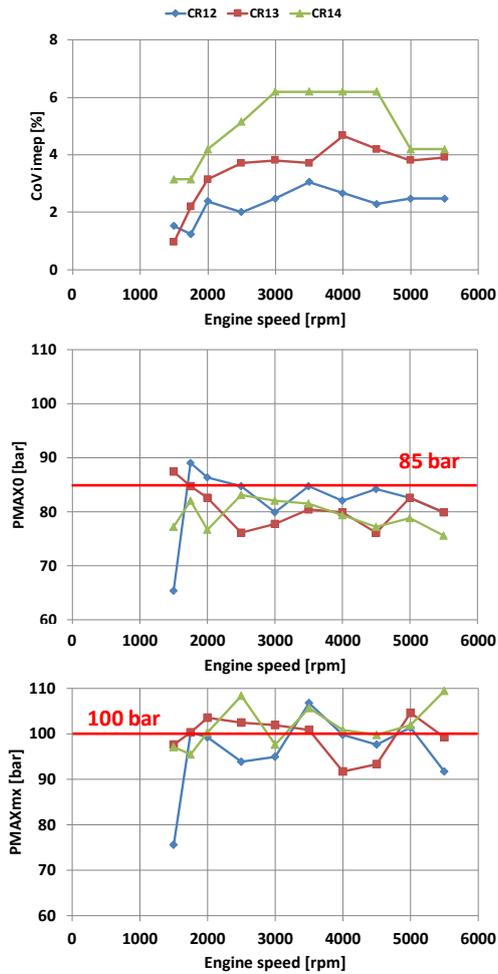
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335 Figure 9. Full load performance curves for the three CR values compared to NP engine.

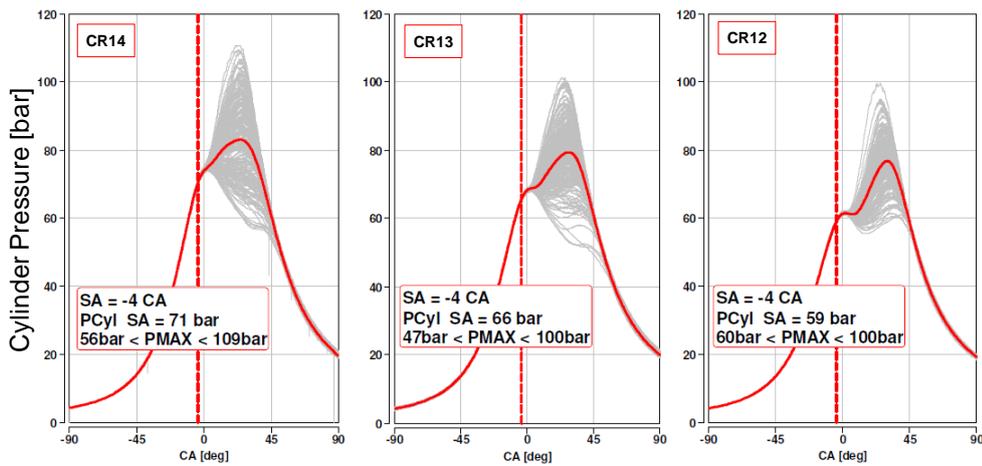
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337

338 Figure 10. Full load performance curves: CoV imep, average PFP (PMAX0) and maximum cycle-resolved PFP
 339 (PMAXmx).

340



341

342 Figure 11. Cycle-by-cycle and average in-cylinder pressure at 3500 rpm, Full load, for CR=14 (left), CR=13
 343 (middle) and CR=12 (right).

344

345 The CR effect on engine performance and efficiency was also investigated at partial load. The engine was
 346 run in a few selected working points, as detailed in Table 4.

347

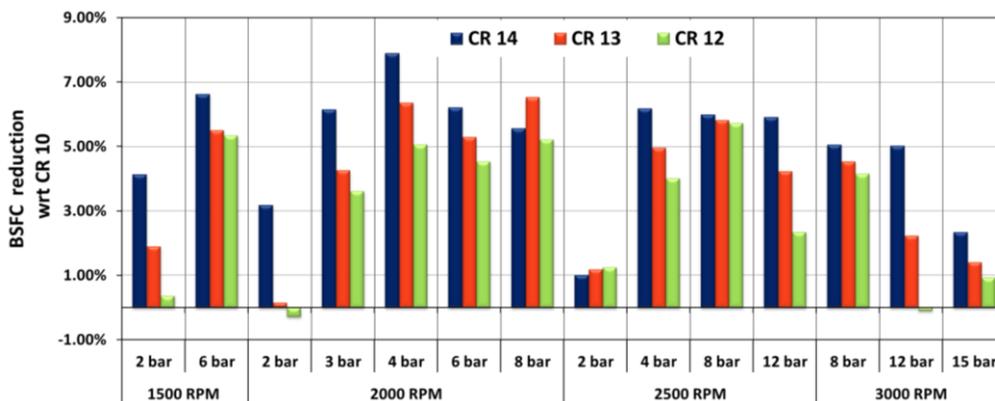
348 Table 4. Engine working points for experimental tests at partial load.

Speed [rpm]	bmeq [bar]
1500	2, 6
2000	2, 3, 4, 6, 8
2500	2, 4, 8, 12
3000	8, 12, 15

349

350 The results are presented in Figs. 12 and 13. Fig. 12 shows the engine bsfc reduction, with respect to the
 351 base engine with CR=10. As a matter of fact, as CR increases, the efficiency of the reference
 352 thermodynamic Otto cycle increases. However, the impact of the thermodynamic losses due to imperfect
 353 or untimely combustion process might affect the overall engine behavior. At partial load, no issues about
 354 the PFP limit arise, thus the combustion timing can be always set to its optimal value (usually corresponding
 355 to MFB50 ranging from 5 to 10 deg after top dead center), corresponding to the maximum brake torque
 356 (MBT) conditions. Consequently, the effect of combustion untimeliness is similar for the three CR values,
 357 and the dominant effect is given by the increase in the Otto cycle efficiency. Consistently, a benefit in
 358 engine fuel consumption was obtained experimentally in almost all the working points at it is shown in Fig.
 359 12. The impact of the engine CR on the combustion cycle-to-cycle variation is represented in Fig. 13 for a
 360 few selected engine operating conditions, amongst those included in Table 4. Similarly to the full load case,
 361 the combustion process gets less regular as CR increases, again suggesting that a detriment in the
 362 turbulence level at combustion start has occurred.

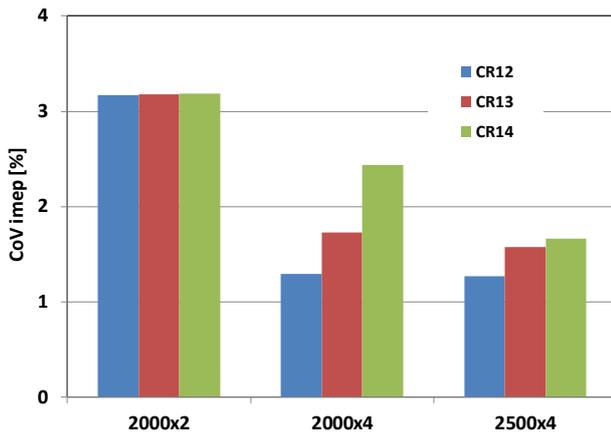
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364

365 Figure 12. Percentage bsfc reduction with respect to the baseline engine with CR=10, for various working
 366 points at MBT timing.

367



368
369 Figure 13. CoV imep in a few selected working points for the different CRs.

370

371 The experimental activity carried out by CRF evidenced the following main effects as the compression ratio
372 is increased:

- 373 1. The maximum engine power decreases;
374 2. The bsfc at partial load decreases;
375 3. The benefit in bsfc at full load are hidden by the non-optimal combustion timing, mainly due to the
376 occurrence of the PFP limitations;
377 4. The cycle-to-cycle variability of combustion increases both at partial load and at full load.

378 The CR=13 value was finally selected for equipping the demonstrator vehicle, as the best compromise
379 between fuel consumption at partial load, combustion quality and engine performance at full load.

380

381 4.3 Engine transient CFD simulations

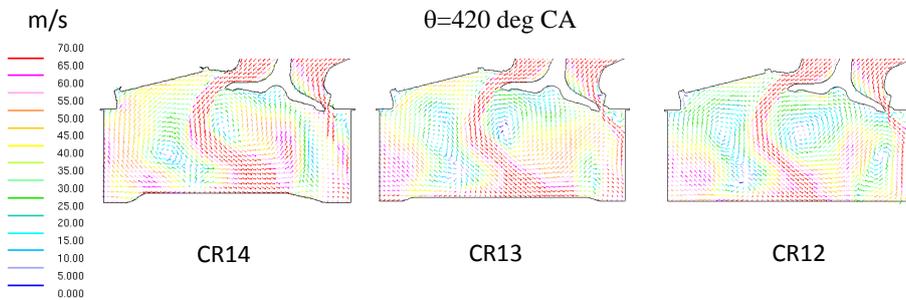
382 A set of CFD simulations was planned aside the experimental activity, focused on investigating the in-
383 cylinder flow and combustion process in the engine cycle. The work was aimed at giving a deeper insight to
384 the combustion behavior in the engine prototype, as well as at verifying the consistency of the steady-state
385 flow simulation results as far as the effect of the masking surface is concerned.

386 First of all, as a dependence of the combustion speed and cycle-to-cycle variation on the CR was observed,
387 as it is shown in Section 4.2, the engine configuration with mask was simulated with different compression
388 ratio values in order to have an insight into the tumble and turbulence evolution. The results are shown in
389 Figs. 14-15. Fig. 14 reports the in-cylinder velocity field at an intermediate instant of the induction stroke,
390 with reference to the combustion chamber variant with mask. As a matter of fact, for a given crank angle a
391 difference in CR (and, in turn, in the clearance volume) gives rise to a different position of the piston top
392 with respect to the cylinder head. In the CR=14 case, the piston is closer to the head and the intake flow
393 impinges on it, resulting in a decrease in the tumble vortex size and reduction of its overall intensity.
394 Contrariwise, in the lower compression ratio case, the resultant size of the direct tumble structure is bigger
395 and better defined. Fig. 15 shows the tumble number and the mass-averaged turbulence intensity
396 evolution versus crank angle, for the three CR values at 3500 rpm and full load. The in-cylinder tumble
397 number is given by:

398
$$TN = \frac{\int_{m_{cyl}} [-v_z (x - x_m) + v_x (z - z_m)] \cdot dm_{cyl}}{\frac{2\pi N}{60} \int_{m_{cyl}} [(x - x_m)^2 + (z - z_m)^2] \cdot dm_{cyl}} \quad (5)$$

399 where v_x, v_z are the x- and z- components of the velocity, x_m, z_m are the x- and z- coordinates of the cylinder
 400 center of mass and N is the engine speed in rpm. As the piston exerts a disturbance effect on the direct
 401 tumble vortex throughout the first part of the induction stroke, the TN generation is the higher in the
 402 CR=12 case. This happens between around 360 and 450 deg CA, and is the cause of the difference in the TN
 403 curves, which can be appreciated in Fig. 15. The higher tumble strength in the case with CR=12 in turn
 404 determines a higher turbulence level (by around 20%) in correspondence to the spark timing, hence
 405 contributing to the explanation of the observed differences in the combustion speed and stability (Figs. 10,
 406 11 and 13).

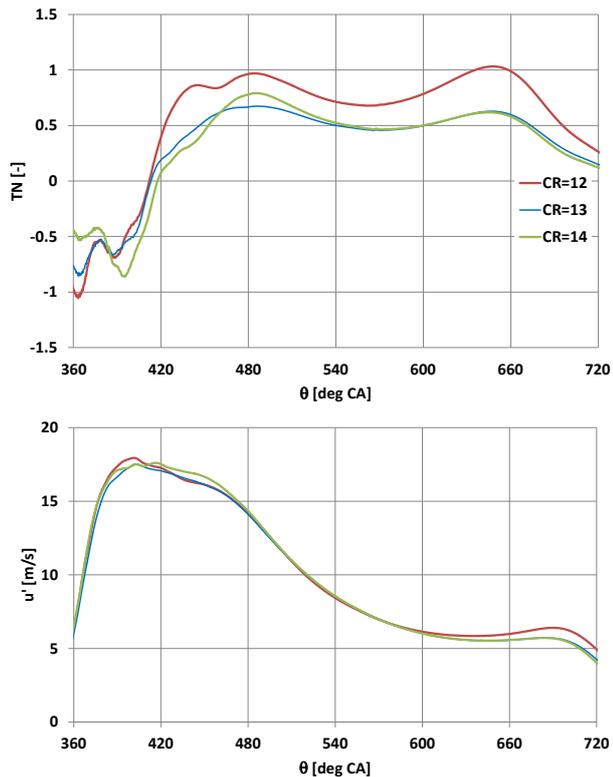
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408

409 Figure 14. In-cylinder velocity field during the intake stroke for different CR values – 3500 rpm, Full load.

410



411

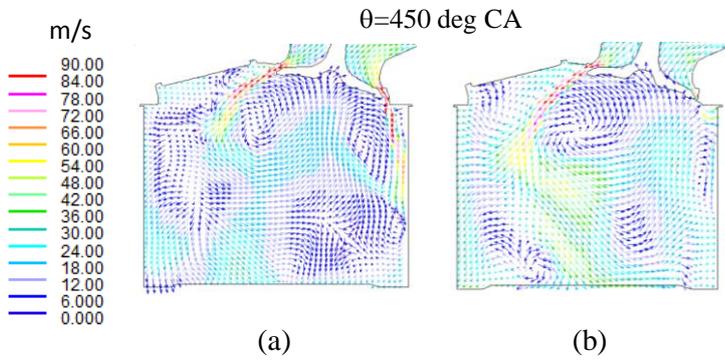
412 Figure 15. Tumble number and mass-averaged turbulence intensity versus crank angle – 3500 rpm, Full
 413 load.

414

415 Further simulation work was carried out, in order to assess for the differences in fluid-dynamic and
 416 turbulence flow features between the baseline configuration and the one with masked intake valve. Fig. 16
 417 shows the effect of the combustion chamber variants on the in-cylinder flow field structure at 450 deg CA,
 418 for the working point at 2000 rpm and 4 bar, with CR=13. As discussed above, the piston presence affects
 419 the overall size of the direct tumble vortex, however the relative effect between the configuration without
 420 mask and that with mask is qualitatively the same as the one observed in the steady-state analysis (see Fig.
 421 4). In the considered working point, the actuated valve lift profile is represented by the blue line in Fig. 7.
 422 Since the maximum lift is kept within the size of the masking wall, the latter is able to exert its influence
 423 over the whole intake process. Consequently, a remarkable benefit is obtained in terms of both tumble
 424 number and turbulence as can be inferred from Fig. 17. In correspondence to the spark timing position
 425 (about 690 deg CA) an increase by around 90% and 10% have been obtained for TN and for the turbulence
 426 intensity, respectively, relative to the baseline variant. As far as the full-load conditions are concerned, a
 427 considerably lower effect is obtained, due to the higher inlet valve lift. In fact, as discussed in Section 4.1,
 428 the masking surface is virtually ineffective when the valve lift is greater than the surface extension. Fig. 18
 429 shows an overall evaluation of the mask effect, including full-load as well as partial load cases, for CR=12
 430 and CR=13. As can be seen in the figure, with the exception of the full load case with CR=13, the presence
 431 of the mask increases the tumble level in the cylinder and, in turn, the turbulence intensity. However, at a
 432 first sight a detriment in tumble was also obtained in the 2000 rpm, bmep=2 bar case with CR=12. Still, in
 433 such a case the virtually nil TN is actually the result of the compensation of two opposite moment
 434 contributions and does not represent a penalty, as it is confirmed by the comparable turbulence level
 435 obtained. Concerning the turbulence effect on burning speed, except the CR=13 configuration at full load
 436 conditions, a benefit on the combustion duration from 1% to 50% of heat released (MFB1-50) between 2

437 and 6 deg CA was found. This is in agreement with the observed experimental combustion behavior, also
 438 from the point of view of the cycle-to-cycle stability, and confirms the overall benefit that is obtained by
 439 adopting the tumble oriented cylinder head design.

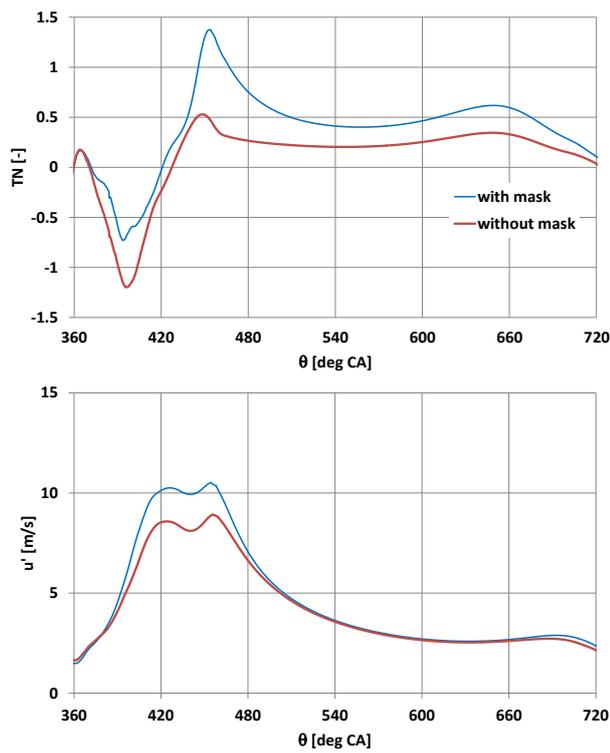
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441

442 Figure 16. Effect of the intake valve masking surface on in-cylinder flow field at 2000 rpm, bmep=4 bar.

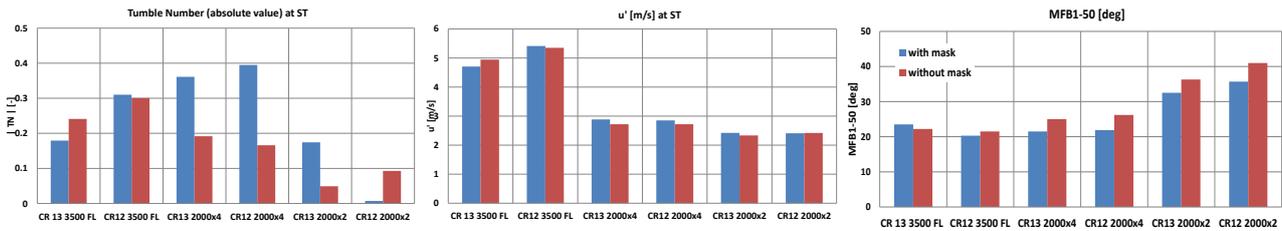
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444

445 Figure 17. Tumble number and turbulence evolution versus crank angle for the variants with and without
 446 mask – 2000 rpm, bmep=4 bar.

447



448

449 Figure 18. Tumble number, turbulence intensity and MFB1-50 combustion interval for the variants with and
 450 without mask.

451

452 6. CONCLUSION

453 The activity presented in this paper was focused on the development of a monofuel, high performance, NG
 454 engine. More specifically, the design of the engine combustion chamber was described, with reference to
 455 the optimization of the engine CR and to the trade-off between engine permeability and tumble
 456 characteristics of the intake port. The activity was carried out by combining 3D simulations and
 457 experimental tests. The main conclusions are as follows.

- 458 – The steady-state simulations indicated that the engine configuration with mask features a decrease
 459 in the average discharge coefficient by around 20-30%, whereas an increase in the tumble ratio by
 460 around 200% is obtained at partial load.
- 461 – The simulations of the engine cycle led to the same conclusion from a qualitative point of view,
 462 though the presence of the piston modifies the tumble intensity of the induced flow with respect to
 463 the ‘undisturbed’ flow in the virtual steady-state flow rig. In the 2000x4 working point, the increase
 464 in the tumble number at spark timing was of around 90%, which lead to a 10% increase of the
 465 turbulence intensity.
- 466 – Overall, the presence of the masking surface determined a benefit in the turbulence intensity at
 467 spark timing in almost all the cases at partial load, and a reduction of the MFB1-50 interval
 468 between 2 and 6 deg CA was correspondingly obtained.
- 469 – With reference to the optimization of the engine CR, the experimental activity carried out at CRF
 470 showed that CR=13 was the best compromise between fuel consumption at partial load, engine
 471 performance at full load, and combustion quality.
- 472 – The cycle-to-cycle variability of combustion increased with the increase in the engine CR, due to the
 473 detriment of the tumble number and of the turbulence intensity. The latter is higher by around
 474 20% in the CR=12 case.

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481 8. REFERENCES

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