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Comparative analysis of the fluid dynamic efficiency of standard and alternative intake strategies for multivalve spark-ignition engines

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Abstract

The work aims at investigating the fluid dynamic performances of a multivalve spark-ignition engine and at evaluating the influence of the throttling process on the engine permeability. To this purpose, a production four-stroke internal combustion engine is analysed during the intake phase. The experimental characterisation is carried out at the steady flow rig in terms of dimensionless discharge and flow coefficients.

The global investigation illustrates the noticeable effect of the valve lift on the engine head breathability. Furthermore, the experimental analysis demonstrates that the throttling process has a significant influence on the volumetric efficiency of the intake system and this effect increases with the valve lift. Finally, alternative strategies are studied in order to improve the engine fluid dynamic efficiency at partial loads. Specifically, the research shows that inlet valve deactivation and the adoption of asymmetric intake valve lifts assure an increase in head permeability.

Keywords: *Asymmetric valve lifts, fluid dynamic efficiency, intake system, internal combustion engines, valve deactivation.*

1 Introduction

The design and the development of highly efficient internal combustion engines (ICEs) require a thorough investigation of the fluid dynamic processes [1-5]. In particular, the optimisation of the intake phase plays a basic role in reducing both fuel consumptions and exhaust emissions and in improving the performances of actual engines [6-10].

To this purpose, a special attention should focus on partial and low engine loads that represent usual urban driving conditions and typical operation in large part of the engine life. In diesel engines the power is controlled varying the amount of the fuel, while in stoichiometric spark ignition engines the throttle valve mainly controls the load. Unfortunately, the throttling process introduces significant decrease in the engine efficiency owing to the upsurge in pumping loss and induction work [11-13]. As a consequence, in the last decades automotive manufacturers and researchers are developing innovative valvetrain systems and alternative strategies to assess a more effective process, especially at low engine loads. Variable valve timing (VVT) systems are largely used to reduce the throttle effect. Specifically, early intake valve closure (EIVC), late inlet valve closing (LIVC), and reduced valve lift permit interesting improvement in fuel economy and exhaust emissions at partial load [14-17].

Furthermore, in multivalve engines, the deactivation of an intake valve and the possibility to impose different lifts between the inlet valves are considered promising strategies [18-20].

Patel et al. [21] analysed a single-cylinder direct injection spark ignition engine fuelled with 95 RON gasoline. The experimental investigation highlighted that, at low speed (2000 rpm) and load (2.7 bar), the inlet valve deactivation and the adoption of reduced valve lift assures a 5.8% decrease in the indicated specific fuel consumption compared with the standard engine operation. Moore et al. [22] found similar results adopting a 2-litre gasoline direct injection (GDI) engine fuelled with 91 RON gasoline. The analysis showed up to 11% reduction in brake specific fuel consumption at 2000 rpm and a significant improvement in fuel economy and combustion stability with respect to the base engine for loads lower than 6 bar.

Several research tools, based on CFD codes and/or experimental approaches, are available to examine in detail the fluid dynamic behaviour of real engines [23-26]. Specifically, the steady flow rig is a widely employed apparatus, owing to the proper characterisation of the real phases and the possibility of analysing real engines and components [27-29]. To this purpose, dimensionless flow coefficients are adopted to provide global information on the fluid dynamic efficiency of engines during the intake process [30-31] and supply useful advice to engine designers and tuners on the location and sizing of ducts and valves [32].

The present paper aims at analysing the fluid dynamic behaviour of a high performance multivalve spark-ignition engine during the intake phase and at estimating the effect of the throttling process on the head permeability. Moreover, alternative intake strategies are considered. Specifically, the attention is focused on the deactivation of an intake valve and on the adoption of asymmetric inlet valve lifts. In fact, few quantitative studies have analysed the influence of the valve deactivation and asymmetric valve lift strategies on the engine breathability, despite their fundamental impact on the engine performances. To this purpose, the intake system is characterised at a steady flow rig adopting the dimensionless discharge and flow coefficients both in standard and “non-standard” configurations.

2 Methodology

The experimental investigation is focused on a multivalve spark-ignition engine, whose main characteristics are listed in Table 1. The fluid dynamic efficiency of the intake system is analysed at a steady flow rig, enabling air to be forced through the system by means of a blower while the valve lift is fixed to a selected value. A by-pass valve permits to impose the pressure drop between the ambient and the combustion chamber. Temperature and pressure transducers are used to characterise the conditions of the ambient and inside the cylinder, while a laminar flow meter system is adopted to measure the global mass flow rate.

Table 1: Main engine characteristics

Engine	Production four-stroke spark-ignition
Number of cylinders, N_c	2
Number of intake valves per cylinder, N_v	2
Stroke/Bore, L/B	0.969
Intake valve diameter/Bore, D_i/B	0.347
Throttle diameter/Bore, D/B	0.510

The engine head is examined in terms of global performances. In particular, the discharge and flow coefficients are used to define the head breathability [33-34]. The configurations with both inlet valves open and with only one valve open are compared to study the effect of the valve deactivation strategy. Furthermore, in order to define the influence of the throttling process on the head permeability, the global analysis is repeated at several throttle valve positions. Finally, different valve lifts between the two intake valves are imposed to evaluate the influence of asymmetric valve opening on the fluid dynamic efficiency of the engine.

Measurements are taken for a fixed ambient-cylinder pressure drop (8.3 kPa), while the dimensionless valve lifts (L_v/D_v) are set in the 0.059÷0.294 interval. Table 2 summarises the analysed configurations and the corresponding measuring conditions.

Table 2: Analysed configurations and corresponding measuring conditions

Intake Strategy	Standard	Valve Deactivation	Asymmetric Valve Lifts
Pressure drop, Δp	8.3 kPa	8.3 kPa	8.3 kPa
Dimensionless “Valve 1” lift, L_v/D_v	0.059 ÷ 0.294	0.059 ÷ 0.294	0.059 ÷ 0.294
Dimensionless “Valve 1” step, $\Delta L_v/D_v$	0.029	0.029	0.029
Dimensionless “Valve 2” lift, L_v/D_v	0.059 ÷ 0.294	-	0.059 ÷ 0.294
Dimensionless “Valve 2” step, $\Delta L_v/D_v$	0.029	-	0.059
Throttle angle, F	30 ÷ 90°	30 ÷ 90°	90°

2.1 Discharge and flow coefficients

The discharge and flow coefficients are used to define the global fluid dynamic efficiency of the intake system [1]. Specifically, the dimensionless coefficients are defined as the ratio of the measured mass flow rate $\dot{m}_{meas}$ to reference mass flow rate $\dot{m}_r$:

$$C_f = \frac{\dot{m}_{meas}}{\dot{m}_r} \tag{1}$$

If the flow is subsonic, the reference mass flow rate is given by:

$$\dot{m}_r = A_r \cdot \frac{p_0}{\sqrt{R \cdot T_0}} \cdot \left(\frac{p_C}{p_0} \right)^{\frac{1}{\gamma}} \cdot \left\{ \frac{2 \cdot \gamma}{\gamma - 1} \cdot \left[1 - \left(\frac{p_C}{p_0} \right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{\frac{1}{2}} \tag{2}$$

while, if the flow is choked, the mass flow is formalized as follows:

$$\dot{m}_r = A_r \cdot \frac{p_0}{\sqrt{R \cdot T_0}} \cdot \gamma^{\frac{1}{2}} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{2 \cdot (\gamma-1)}} \tag{3}$$

where: p_0 is the intake system pressure;
p_T is the cylinder pressure;
T_0 is the intake system temperature;
A_{ref} is the reference area.

The difference between the discharge and flow coefficient lies in the definition of the reference area A_{ref} [35]. For the discharge coefficient this area is the valve curtain area and, therefore, it is a linear function of valve lift L_v:

$$A_r = \pi \cdot D_v \cdot L_v \tag{4}$$

For the flow coefficient, the reference area is given by the valve outer seat area:

$$A_r = \frac{\pi \cdot D_v^2}{4} \tag{5}$$

Furthermore, absolute flow coefficients C_{abs} are defined to characterise the intake system efficiency independently of the valve lift [36]:

$$C_{abs} = \frac{\varphi_{Am}}{\varphi_{Ad}} \tag{6}$$

where φ_{Ad} represents the dimensionless theoretical flow rate downstream of the valve, based on the isentropic flow condition:

$$\varphi_{Ad} = \sqrt{\frac{2}{\gamma - 1} \cdot \left[\left(\frac{p_C}{p_0} \right)^{\frac{2}{\gamma}} - \left(\frac{p_C}{p_0} \right)^{\frac{\gamma+1}{\gamma}} \right]} \tag{7}$$

while φ_{Am} is the dimensionless actual flow rate, averaged over the dimensionless valve lift:

$$\phi_{Am} = \frac{\int_0^{(L_v/D_v)_{\max}} \frac{\dot{m}_{meas}}{A_r \cdot \rho_0 \cdot a_0} \cdot d\frac{L_v}{D_v}}{\left(\frac{L_v}{D_v} \right)_{\max}} \tag{8}$$

where: ρ_0 is the air density;
a_0 is the sound speed.

The overall uncertainty of dimensionless flow coefficients and absolute flow coefficients - evaluated according to literature [37-38] - is always lower than 3%, and it decreases with valve lift and throttle angle.

3 Results

Figure 1 highlights the fluid dynamic efficiency of the intake system in terms of flow and discharge coefficients as a function of the dimensionless valve lift (L_v/D_v). Data refer to the wide-open throttle (WOT) condition and standard configuration with the same valve lift for the two intake valves. A progressive upsurge in the flow coefficient is observed when the valve lift increases, while decreasing values of the discharge coefficient are registered for L_v/D_v > 0.118. Results reflect the continuous raise in the mass flow rate entering the combustion chamber. For L_v/D_v > 0.206 the effects on the head breathability are lower owing to the dimensions of the intake ports and valve stems that define the minimum flow area at high valve lifts. Figure 1 reveals also the presence of different regions, characterised by decreasing slopes in the flow coefficient's curve, which corresponds to different flow regimes, according to literature [1,39]. Particularly, for low valve lift, the flow remains attached to the valve seat and head due to the high viscous phenomena. When the curtain area increases, it is possible to notice a flow separation, first, at the valve head and, successively, at the valve seat.

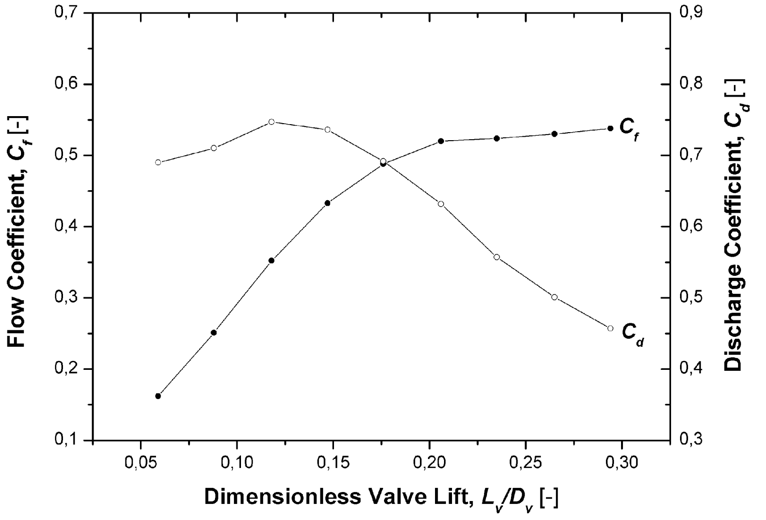


Fig. 1: Influence of valve lift on flow and discharge coefficient.
Standard configuration with both intake valves open and wide-open throttle (WOT) condition

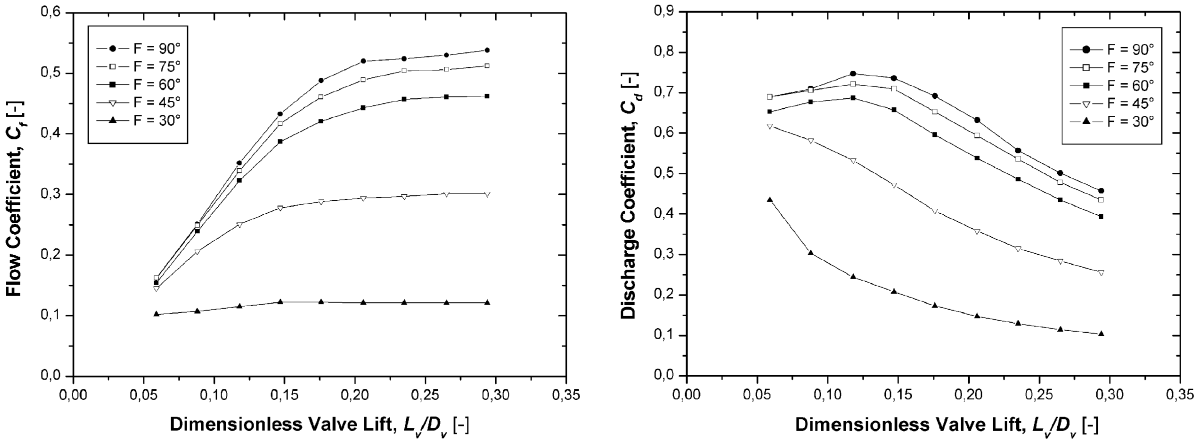
The fluid dynamic analysis is repeated at different throttle angles (Fig. 2) in order to investigate the influence of the throttling process on the intake system breathability. Table 2 shows the analysed configurations.

Experimental results illustrate similar behaviours for the different throttle angles and confirm the presence of the different flow regimes. It is possible to observe that the "transition" from a flow condition to another one is reached at lower valve lift values when the flow is throttled. As an example, the transition phenomena for the wide-open throttle configuration (F = 90°) occur at the valve lift $L_v/D_v \sim 0.15$ and $L_v/D_v \sim 0.18$, while for F = 45° they develop at $L_v/D_v \sim 0.09$ and $L_v/D_v \sim 0.15$, respectively.

Furthermore, the plot put in evidence the large influence of the throttling process on the volumetric efficiency of the intake system. As expected, a progressive decrease in the engine breathability is observed when the throttle angle reduces. The percentage variations between the WOT configuration (assumed as a reference) and the throttled configurations are reported in Fig. 3. The analysis highlights that the differences increase with the valve lift and by throttling the flow. Specifically, the values are always lower than 6% when the throttle angle passes from 90° to 75°. Conversely, by moving from the WOT configuration to F = 30°, the relative decrease in the fluid dynamic efficiency is significant, with values that are always higher than 37% and that become larger than 71% for L_v/D_v > 0.147. This trend is also visible in Table 3, which compares the absolute and the mean coefficients at the five throttle angles.

The previous analysis demonstrates the large influence of the throttling process on the engine fluid dynamic efficiency and the significant decrease in the intake system permeability when the flow is throttled. In order to analyse alternative strategy for partial load conditions, the experimental analysis is extended at "non-standard" configurations. Specifically, two alternative strategies are investigated: the "valve deactivation strategy" and the "asymmetric lift condition".

Figure 4 shows the flow and discharge coefficients as a function of the intake valve lift and throttle angle when only one intake valve is open (deactivation strategy) whereas Table 4 summarises the corresponding absolute and mean dimensionless coefficients.



a) b)

Fig. 2: Influence of throttle angle on engine permeability in terms of dimensionless flow (a) and discharge (b) coefficient. Standard configuration with both intake valves open

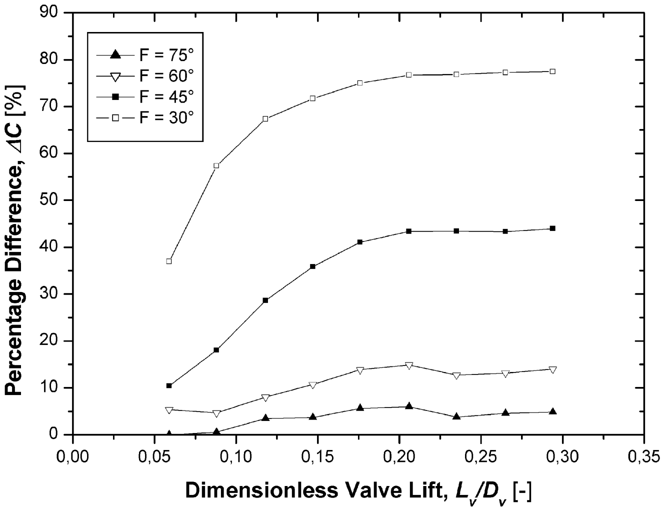


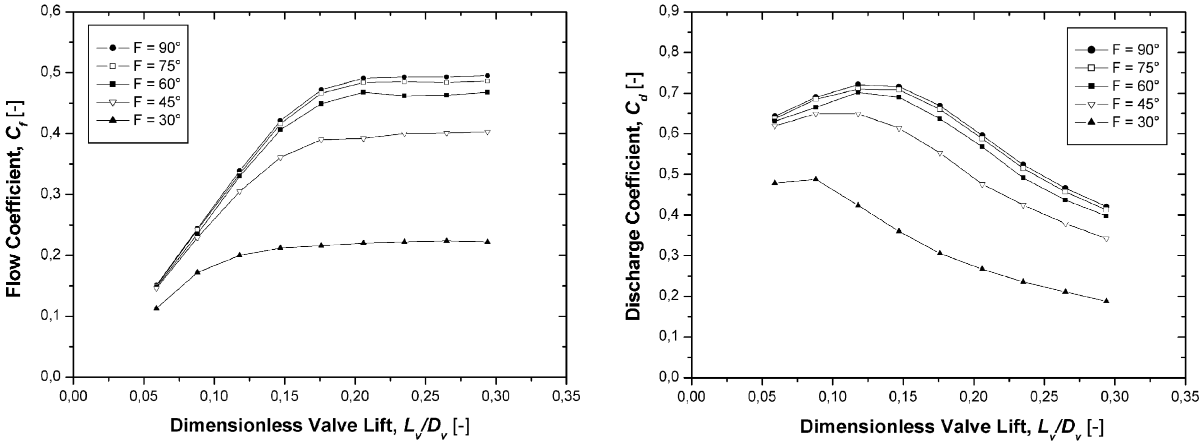
Fig. 3: Percentage difference in flow coefficients between WOT and throttled configurations. Standard configuration with both intake valves open

Table 3: Influence of the throttle angle on the absolute and mean flow coefficients. Standard configuration with the same valve lift for the two intake valves

Throttle angle, F	90°	75°	60°	45°	30°
Absolute flow coefficient, $C_{f\,Abs}$	0.395	0.380	0.350	0.250	0.114
Absolute discharge coefficient, $C_{d\,Abs}$	0.638	0.619	0.575	0.438	0.221
Mean flow coefficient, $C_{f\,Mean}$	0.422	0.404	0.372	0.262	0.117
Mean discharge coefficient, $C_{d\,Mean}$	0.633	0.613	0.569	0.425	0.206

Results confirm the presence of different flow regimes and the significant influence of the valve lift also when an inlet valve is deactivated. In addition, it is interesting to notice that the effect of the throttling process becomes noteworthy when the throttle angle is lower than 60°.

The comparison between the configurations with one and two intake valves open highlights that the standard arrangement with both the intake valves open guarantees better performances for $F \geq 75°$ while the deactivation strategy permits maintaining higher values of the head volumetric efficiency when $F < 60°$. In fact, at low and medium load, the absence of flow interactions between the two intake valves leads to a better filling of the cylinder when a single valve is open. Specifically, when $F = 60°$ the deactivation strategy guarantees a 3.9% and 2.5% increase in terms of absolute and mean dimensionless coefficients, respectively. The corresponding upsurges at $F = 30°$ are higher than 70%.

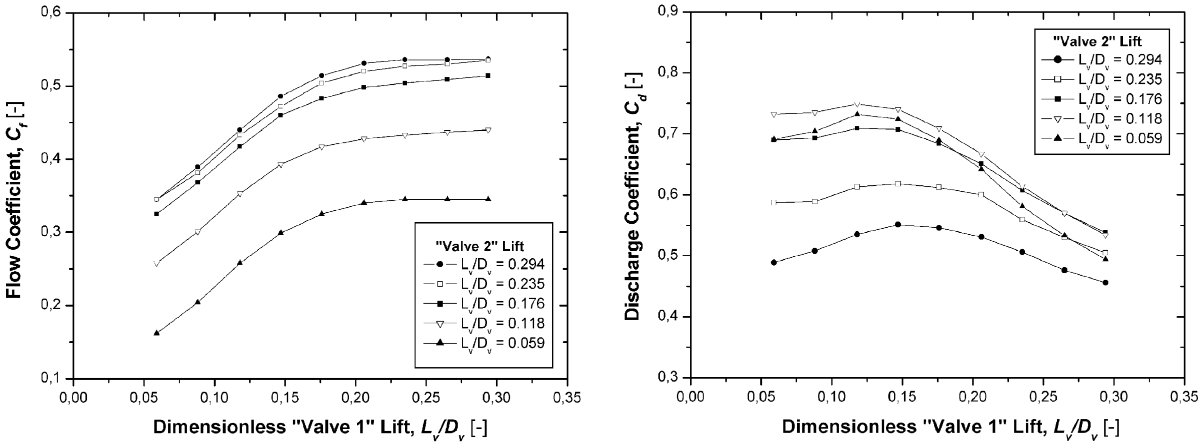


a) b)

Fig. 4: Influence of throttle angle on flow (a) and discharge (b) coefficient.
Valve deactivation strategy (only one valve open)

Table 4: Influence of the throttle angle on the absolute and mean flow coefficients.
Deactivated configuration with only one intake valve open

Throttle angle, F	90°	75°	60°	45°	30°
Absolute flow coefficient, $C_{f\,Abs}$	0.377	0.377	0.363	0.322	0.194
Absolute discharge coefficient, $C_{d\,Abs}$	0.609	0.612	0.593	0.539	0.345
Mean flow coefficient, $C_{f\,Mean}$	0.400	0.394	0.381	0.336	0.200
Mean discharge coefficient, $C_{d\,Mean}$	0.605	0.597	0.580	0.523	0.329



a) b)

Fig. 5: Effect of asymmetric valve lift strategy on engine permeability in terms of dimensionless flow (a) and discharge (b) coefficient

The previous behaviour is inverse at high engine load, probably due to significant irregularities that are generated in the flow at the bifurcation of the intake ducts when the mass flow rate raises and only one valve is open. In particular, for the wide-open throttle configuration, the system with both intake valves open assures higher absolute and mean flow coefficients (+4.6% and +5.3%, respectively).

Furthermore, different lifts between the two intake valves are imposed ("asymmetric lift condition") in the wide-open throttle (WOT) configuration in order to characterise in more detail the fluid dynamic behaviour of the intake system in "non-standard" configuration. The corresponding operating conditions are visible in Table 2 while Fig. 5 highlights the two dimensionless coefficients. As expected, the higher the valve lift, the higher the flow coefficient, due to the increase in the mass flow rate entering the cylinder. Furthermore, the plot illustrates that flow coefficients present a similar behaviour and the differences reduce with the second valve lift, with values lower than 2% when $L_v/D_v \geq 0.235$.

The analysis of the discharge coefficients puts in evidence that the higher values are registered for medium and low valve lift ($L_v/D_v \sim 0.118$). In fact, at low lift the flow remains attached to the valve head and seat and the entire curtain area is used, as already observed for the standard configuration.

The comparison between the different intake opening strategies (standard, deactivated, and asymmetric configurations) is proposed in Fig. 6 in terms of discharge coefficients and dimensionless mass flow rates. Specifically, the maximum mass flow rate - registered in the standard configuration (both intake valves open) at maximum valve lift and wide-open throttle condition - is assumed as a reference.

Experimental results show that the usual operating condition with both intake valves open guarantees the larger flexibility in the mass flow rate but, as the engine load reduces, the throttling process produces a significant decrease in the fluid dynamic efficiency. Specifically, a noticeable reduction in the discharge coefficient is registered when the throttle angle is lower than 60°.

The figure suggests the adoption of the asymmetric strategy when lower mass flow rate is requested. In fact, this strategy permits maintaining good engine permeability ($C_d \geq 0.450$) also at low and medium load, with large mass flow rate flexibility. At very low engine load the valve deactivation strategy is suggested. The mean discharge coefficient is always higher than 0.51 when the throttle angle is $F \geq 40°$ and it reaches $C_{d,\,Mean} = 0.327$ at $F = 30°$, with a 50.7% increase with respect to the corresponding value registered for the same mass flow rate in the standard configuration.

4 Conclusion

The work analysed the fluid dynamic behaviour of a multivalve internal combustion engine. In particular, the attention focused on a production spark-ignition engine during the intake phase. To this purpose, an experimental investigation was carried out at the steady flow rig and dimensionless discharge and flow coefficients were used to define the system permeability.

The research revealed the significant influence of the inlet valve opening on the fluid dynamic efficiency of the intake apparatus. Different flow regimes were observed and flow separation phenomena at the valve head and seat were noticed at medium and high valve lifts.

Furthermore, the effect of the throttling process on the engine breathability was studied. The investigation showed that the transition phenomena from a flow condition to another one is reached at lower valve lifts when the flow is throttled.

Moreover, experimental results highlighted that the power control based on the throttle valve guarantees a large flexibility, but a significant decrease in the fluid dynamic efficiency is produced as the engine load reduces. Particularly, a noticeable reduction in the discharge coefficient is registered when the throttle angle is lower than 60° and, moving from the wide-open throttle configuration to $F = 30°$, a percentage reduction in head permeability larger than 70.0% at high valve lifts is found.

To reduce the effect of the throttling process at partial load, alternative strategies were examined. Specifically, the fluid dynamic analysis was repeated both imposing different valve lifts between the two intake valves (asymmetric condition) and deactivating an intake valve (deactivation strategy).

The analysis shows that the adoption of the asymmetric lift strategy in the wide-open throttle (WOT) configuration permits high fluid dynamic efficiency to be maintained also when the mass flow rate is significantly reduced. In fact, the discharge coefficient remains always higher than 0.45 while the corresponding values for the standard strategy reach 0.25. At very low engine load the valve deactivation permits the range of the high efficiency operating conditions to be extended, owing to the absence of flow interference between the two intake valves and, as a consequence, to a better filling of the cylinder when only an inlet valve is open.

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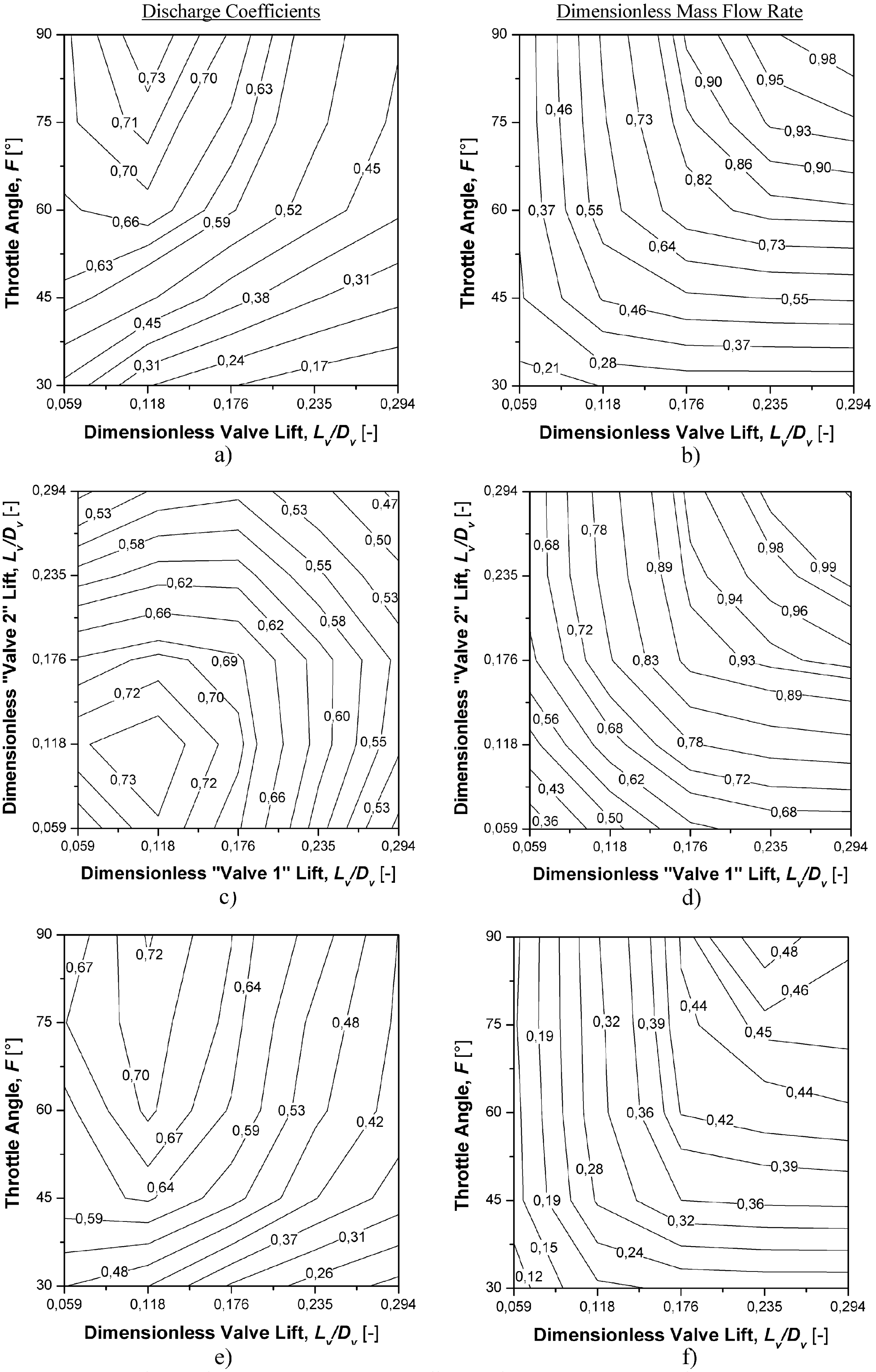

a)

b)

c)

d)

e)

f)

Fig. 6: Influence of intake strategy on discharge coefficient (left) and dimensionless mass flow rate (right). Standard (a-b), deactivated (c-d), and asymmetric (e-f) configurations

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