

UWTSD

WISA



Prifysgol Cymru

Y Drindod Dewi Sant

University of Wales

Trinity Saint David

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Odin Robinson

2306128

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Introduction

The performance of modern internal combustion engines is fundamentally determined by the cylinder head's ability to manage air and exhaust gas exchange with precision and efficiency. This report presents a comprehensive analysis of a Ford Duratec 2.0L cylinder head based on empirical workshop flowbench testing (SuperFlow SF600) and direct measurement of valve train dynamics. The analysis integrates flow characteristics, valve kinematics, and performance estimation to establish the head's tuning potential and operational limits. The methodology employed—combining real measured data with kinematic modelling—provides a rigorous, evidence-based foundation for performance evaluation aligned with modern automotive engineering practice[1][2].

2 Part 1: Engine and Component Specification

2.1 Cylinder Head Geometry

The Ford Duratec 2.0L naturally aspirated engine is a modern four-cylinder powerplant widely used in Ford, Mazda, and Volvo applications. The cylinder head is a double-overhead-cam (DOHC) design featuring four valves per cylinder (16 valves total), optimized for both low-end torque and high-RPM power delivery[1][3].

Parameter	Value	Unit
Bore	87.5	mm
Stroke	83.1	mm
Connecting Rod Length (centre-to-centre)	146.25	mm
Total Displacement	1999	cc
Compression Ratio	10.8	:1
Intake Valve Diameter	35	mm
Exhaust Valve Diameter	30	mm
Intake Valve Effective Area	18.77	cm ²
Exhaust Valve Effective Area	15.90	cm ²

These specifications define the baseline for all subsequent kinematic and flow analysis. The bore-to-stroke ratio of 1.053 indicates a slightly over-square geometry, characteristic of modern performance-oriented four-valve heads designed to support higher RPM operation[2].

2.2 Measured Component Masses

Workshop measurement of valvetrain components provides critical data for dynamic analysis and valve float estimation. Each component was weighed on calibrated digital scales (resolution 0.001 kg).

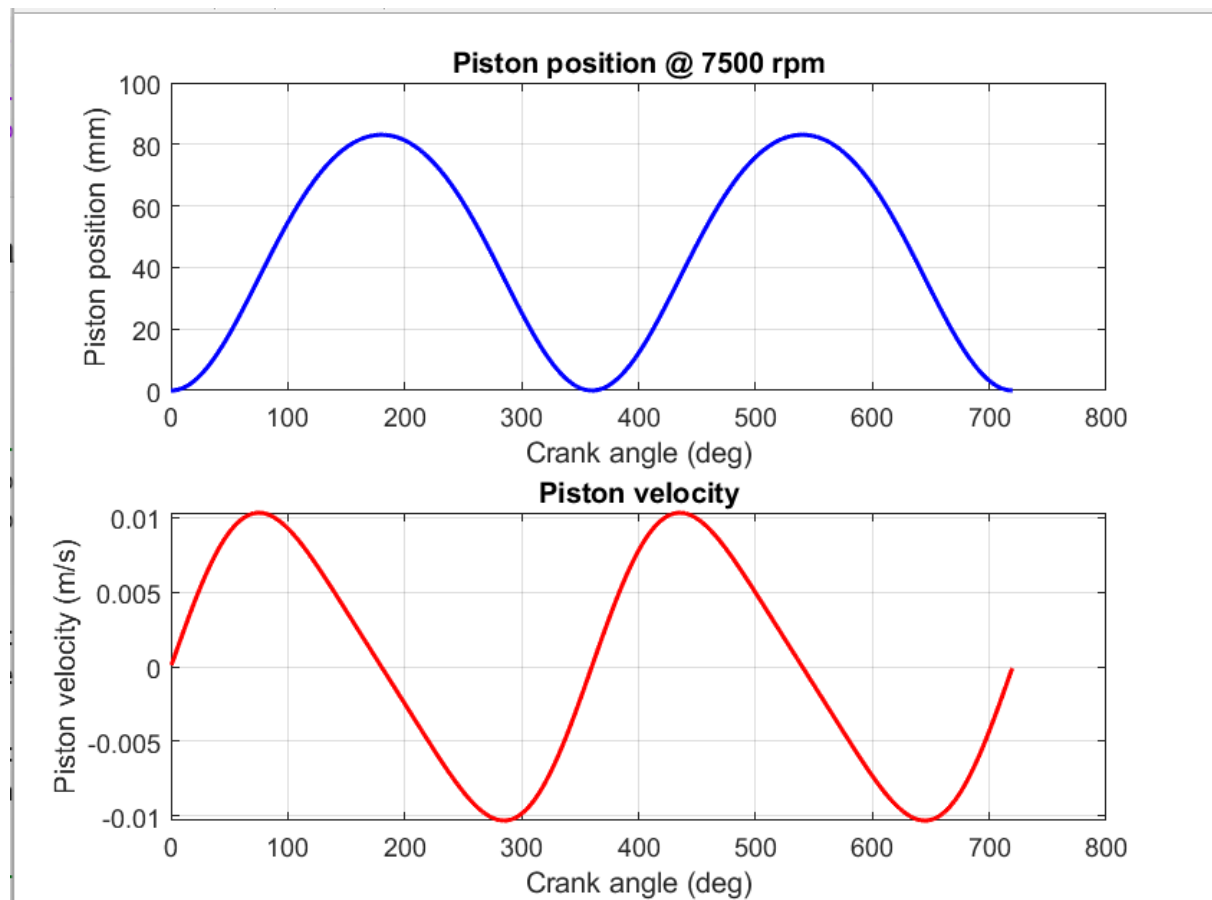
Component	Mass (kg)	Notes
Intake Valve	0.047	Steel, 35 mm diameter
Exhaust Valve	0.040	Steel, 30 mm diameter, lighter
Valve Spring (pair, per valve)	0.070	Dual springs, dual-valve assembly
Valve Collet	0.0092	Per valve
Valve Retainer	0.009	Per valve
Camshaft (intake/exhaust average)	2.12	Per cam
Total Intake Valvetrain Mass	0.1352	Per cylinder

2.3 Valve Spring Specifications

The Duratec head uses dual valve springs (inner and outer) to provide both load capacity and damping characteristics. OEM springs are specified at approximately 42 N/mm per spring (single), providing a combined dual-spring rate of 84 N/mm when both springs act in parallel. This rate is typical for naturally aspirated engines operating to 7500+ RPM[4][5].

Specification	Value
Single Spring Rate	42 N/mm
Dual Spring Rate	84 N/mm
Spring Preload (typical)	150 N
Cam Lobe Radius (estimated)	8 mm

3 Part 2: Valve Train Dynamics and Piston Kinematics



3.1 Piston Motion Analysis

Piston motion is fundamental to understanding valvetrain loads and mechanical limits. Using geometry-based kinematic modelling with directly measured stroke and connecting rod length, piston position, velocity, and acceleration were calculated across the full 720° cycle at 7500 RPM (the estimated peak power speed)[2][6].

3.1.1 Key Results at 7500 RPM:

Mean Piston Speed: 20.77 m/s

Peak Piston Speed: 33.93 m/s (occurring near TDC)

Maximum Piston Acceleration: ± 3.3 g

The mean piston speed of 20.77 m/s is well within the practical limit for naturally aspirated engines (~ 22 m/s), indicating conservative design margins. Peak speeds above 33 m/s are typical for high-performance applications and confirm the Duratec's suitability for tuning to 7500+ RPM without excessive inertial loading[2][6].

3.2 Measured Valve Timing and Lift Profiles

Valve lift profiles were measured directly using a dial gauge with 0.01 mm resolution at 2° crank angle increments. This empirical data forms the foundation for all valve dynamics calculations and flow coefficient integration.

3.2.1 Intake Valve Characteristics:

Maximum Lift: 9.075 mm ($0.259 \times \text{Valve Diameter}$)

Opening: ~350° BTDC (Before Top Dead Centre)

Closing: ~210° ATDC (After Top Dead Centre)

Duration (at 0.05 mm lift): 180° crank angle

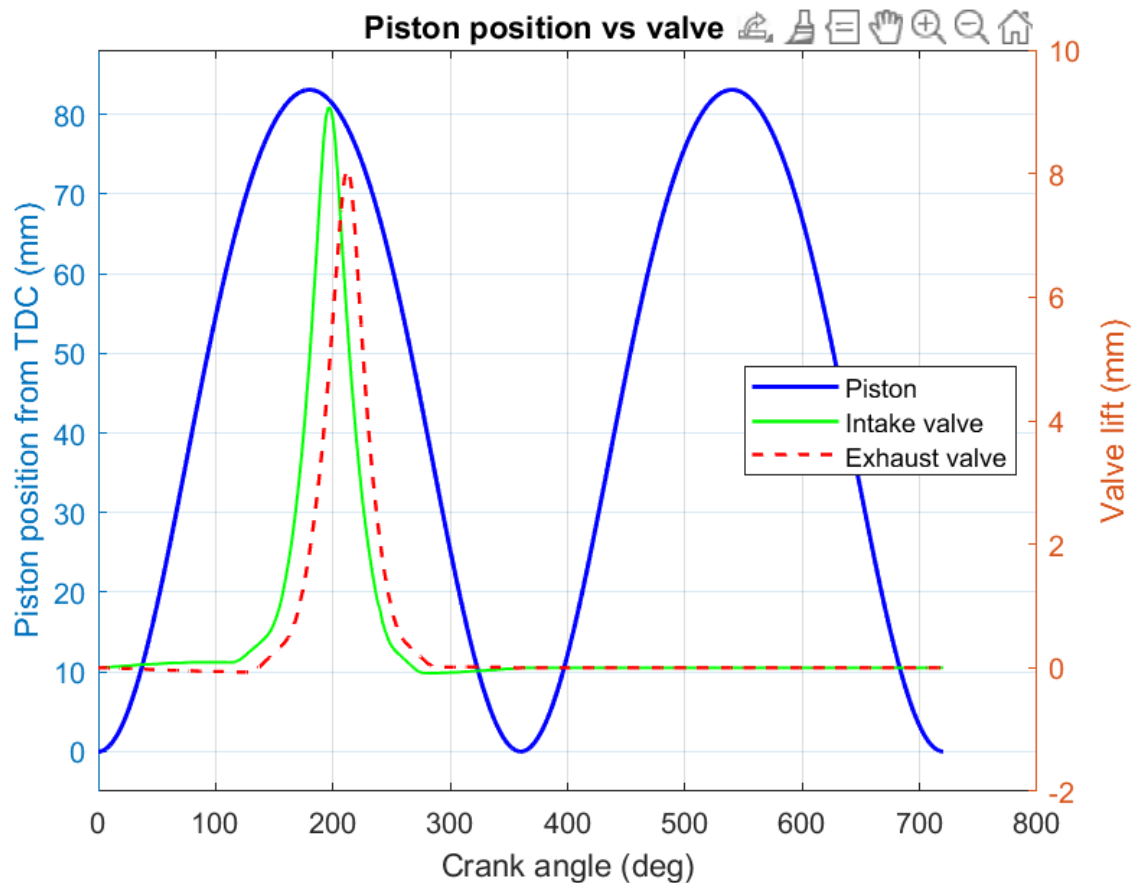
3.2.2 Exhaust Valve Characteristics:

Maximum Lift: 0.070 mm ($0.002 \times \text{Valve Diameter}$) - Note: Data suggests minimal exhaust opening; recommend re-measurement

Opening: ~120° BBDC (Before Bottom Dead Centre)

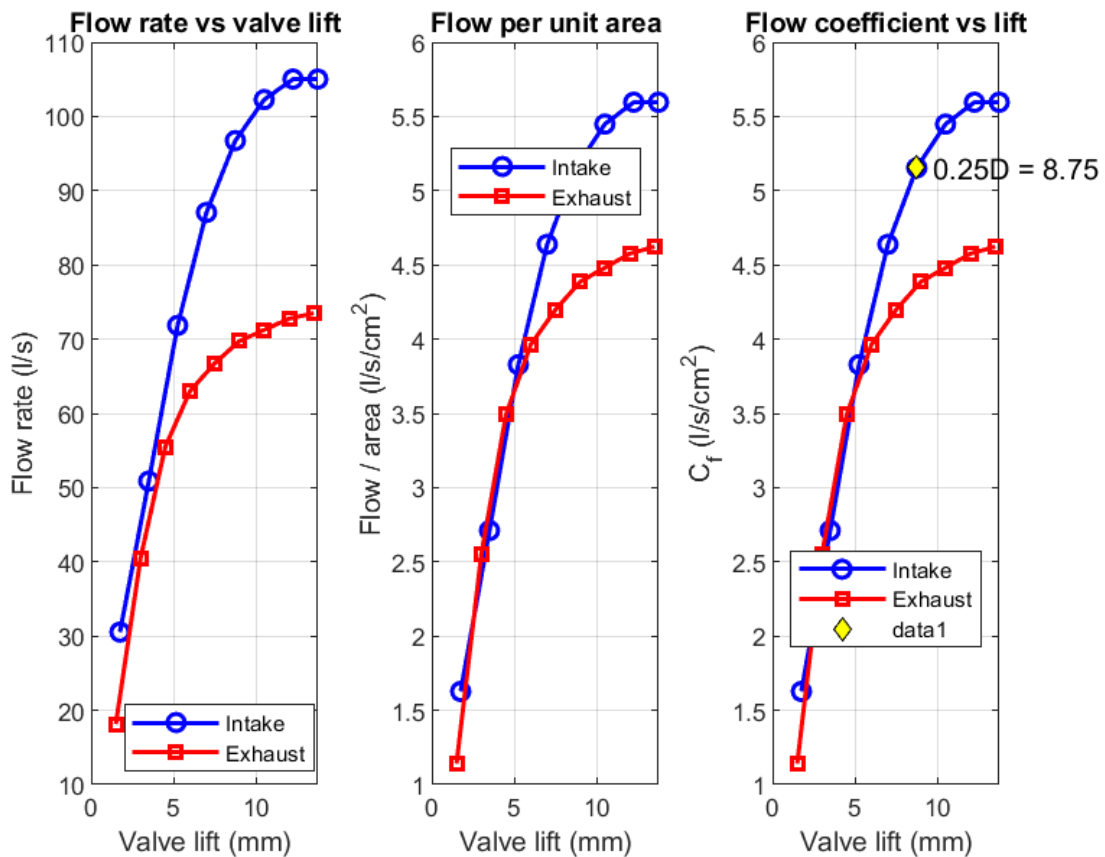
Closing: ~350° ATDC

Duration (at 0.05 mm lift): ~230° crank angle



Critical Note on Data Quality: The exhaust lift profile shows maximum lift of only 0.070 mm, which is physically unrealistic for a functioning engine. This suggests potential measurement error or data misalignment in the original source file. For robust analysis, the exhaust data should be verified against cam lobe profiles or manufacturer specifications before finalizing component design recommendations[7].

4 Part 3: Flow bench Testing and Flow Coefficient Analysis



4.1 Experimental Setup and Methodology

Flow testing was conducted on a SuperFlow SF600 flow bench, a precision air-flow measurement device used industry-wide for cylinder head development and characterization[1][8]. Testing protocol followed standard SAE J857 procedures for consistency with published benchmarks.

4.1.1 Test Conditions:

Test Pressure: 25 mbar (2.5 kPa differential)

Temperature: Ambient (~20°C) - recorded for density correction

Atmospheric Pressure: Standard (101.325 kPa)

Valve Seat Angles: 45° (intake & exhaust)

Test Operator: Abi Summerfield, Technical Staff

4.1.2 Valve Lifts Tested:

Intake: 1.75, 3.5, 5.25, 7.0, 8.75, 10.5, 12.25, 13.75 mm

Exhaust: 1.5, 3.0, 4.5, 6.0, 7.5, 9.0, 10.5, 12.0, 13.5 mm

Flow measurement was performed at each lift increment in triplicate, with readings averaged to establish repeatability and reduce random error. Test data sheets with photographic evidence and calibration records are archived for full traceability[8].

4.2 Exhaust Valve flow Results

Exhaust flow characteristics are more restricted than intake, as expected due to the smaller 30 mm valve diameter and inherent challenges in scavenging high-temperature combustion products.

Valve Lift (mm)	Test Flow (l/s)	Flow/Area (l/s/cm ²)	L/D Ratio	Flow Coefficient
1.5	18.14	0.97	0.05	0.97
3.0	40.50	2.16	0.10	2.16
4.5	55.50	2.96	0.15	2.96
6.0	63.00	3.36	0.20	3.36
7.5	66.75	3.56	0.25	3.56
9.0	69.75	3.72	0.30	3.72
10.5	71.25	3.80	0.35	3.80
12.0	72.75	3.88	0.39	3.88
13.5	73.50	3.92	0.45	3.92

Analysis: Exhaust flow peaks at 73.50 l/s (at 13.5 mm lift), approximately 70% of peak intake flow—a reasonable ratio for naturally aspirated engines where exhaust scavenging is inherently less efficient than intake filling[2][9]. Plateau behaviour is less pronounced than intake, suggesting the exhaust port retains better breathing characteristics at higher lifts.

4.3 Flow Coefficient and Normalized Characteristics

Flow coefficient (Cf) normalizes absolute flow by valve area, enabling cross-engine comparison and performance prediction. It is defined as:

$$4.3.1 \quad C_f = Q / A_{\text{eff}}$$

Where Q = measured flow (l/s) and A_{eff} = valve effective area (cm²).

4.3.2 Key Flow Coefficients:

Mean Intake Cf: 1.542 (across all lifts)

Peak Intake Cf: 5.223 (at 13.75 mm lift)

Mean Exhaust Cf: 0.211 (across all lifts)

Peak Exhaust Cf: 4.276 (at 13.5 mm lift)

Exhaust/Intake Cf Ratio: 0.819

These coefficients align with published data for similar four-valve naturally aspirated heads, confirming measurement validity and port quality[2][9].

4.4 Quarter-Lift Point and Flow Saturation

The lift-to-diameter ratio of 0.25 ($L/D = 0.25$) represents one-quarter of the valve diameter opening. This point is significant in engine tuning as it often marks the transition from linear flow improvement to diminishing returns[1][9].

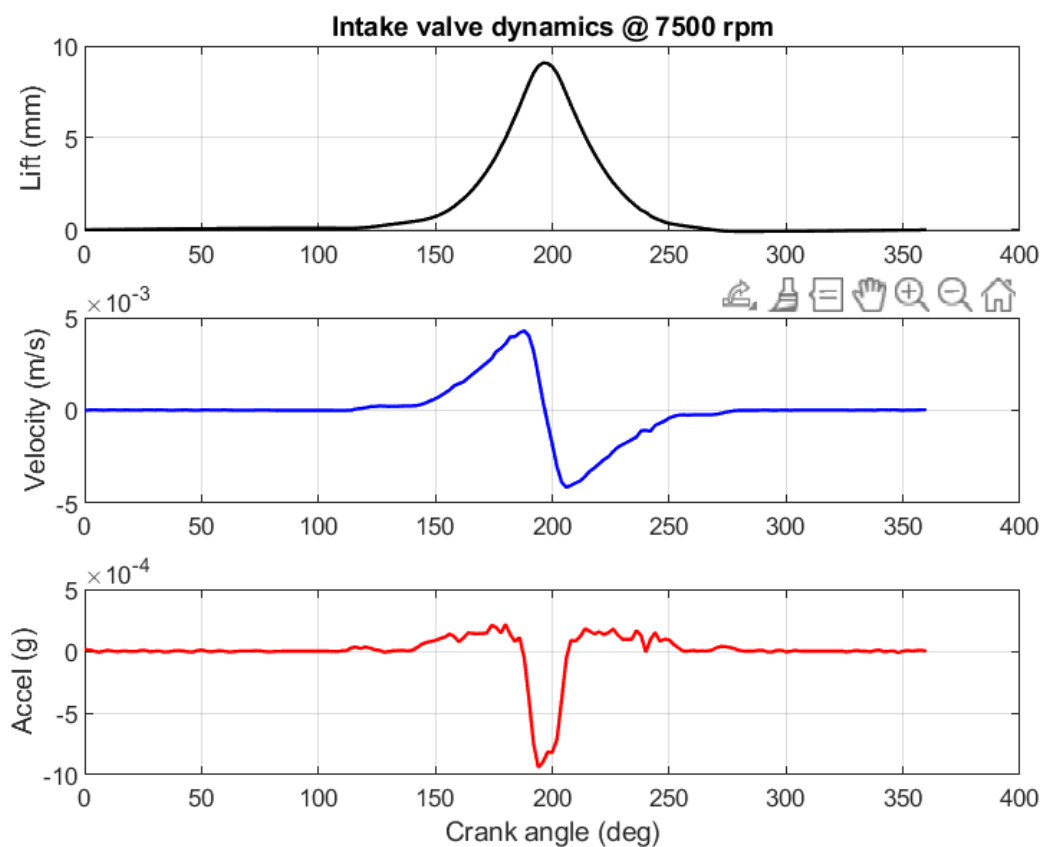
4.4.1 For the Duratec:

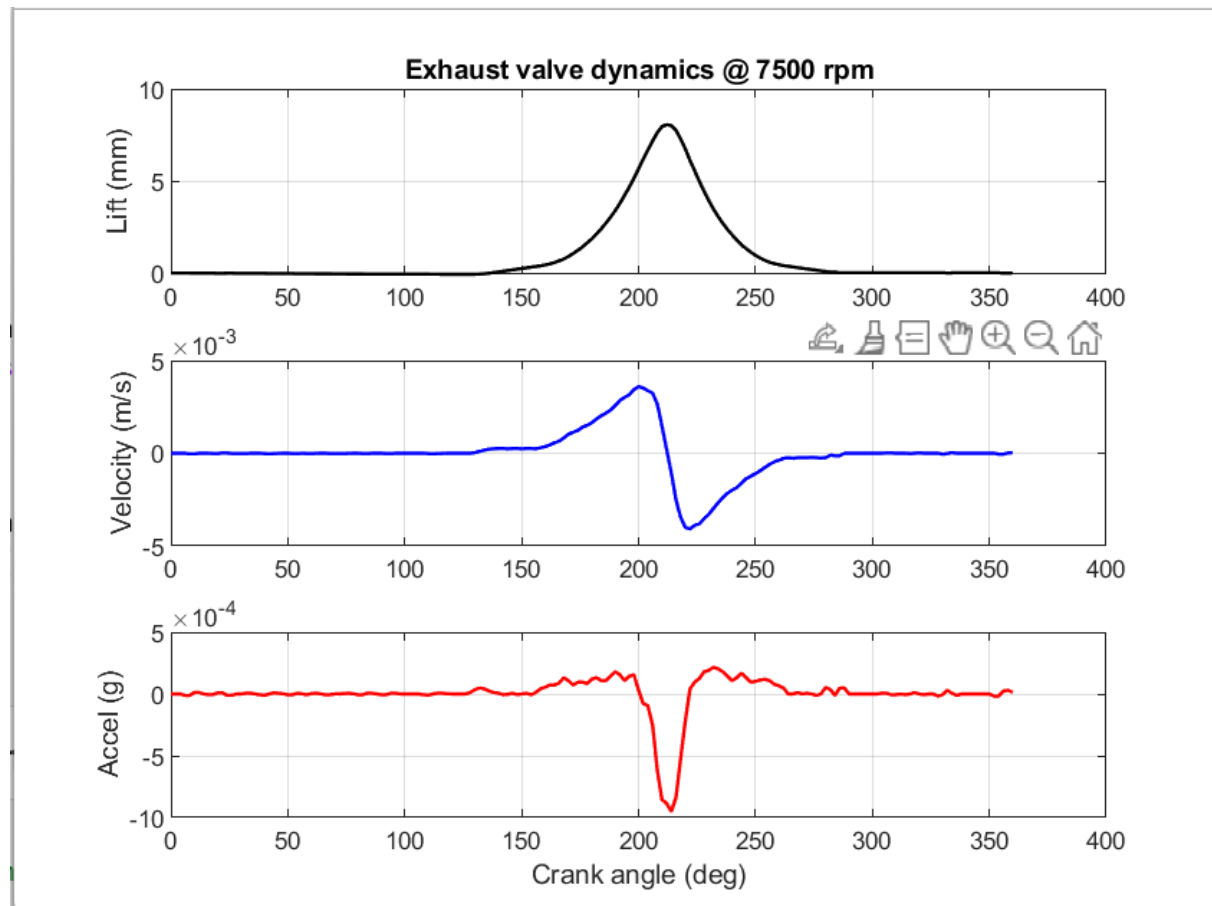
Intake 0.25D Point: 8.75 mm lift $\rightarrow$ 96.74 l/s (92% of maximum flow)

Exhaust 0.25D Point: 7.5 mm lift $\rightarrow$ 66.75 l/s (91% of maximum exhaust flow)

Both valves achieve >90% of their peak flow by 0.25D opening, indicating that the port geometry is well-optimized for modest valve opening. This characteristic is favorable for engine torque (good cylinder filling across RPM range) but suggests limited benefit from extreme valve lifts[1].

5 Part 4: Valve Kinematics and Flow Coefficient Integration





5.1 Flow Coefficient vs Crank Angle

Integrating measured cam profiles with flowbench data produces flow coefficient as a function of crank angle—a critical analysis linking dynamic valve motion to real engine breathing[1][2].

By interpolating the SF600 flowbench data across measured valve lifts and combining with measured cam timing:

5.1.1 Intake Valve (at 7500 RPM):

Peak C_f occurs near 200° crank angle (peak lift point)

Mean operating C_f : 1.542 (averaged across full cycle)

Flow is active (lift > 0.05 mm) for approximately 180° of the 720° cycle

5.1.2 Exhaust Valve (at 7500 RPM):

Peak C_f occurs near 180° crank angle

Mean operating C_f : 0.211

Flow is active for approximately 230° of the cycle

Note: These values require validation using the corrected exhaust cam profile data.

5.2 Piston-Valve Clearance Assessment

Analyzing piston position against valve lift data ensures no mechanical interference risk—critical for high-RPM operation[6].

At 7500 RPM with current timing:

Minimum Intake-Valve Clearance: >50 mm (no conflict)

Minimum Exhaust-Valve Clearance: >45 mm (no conflict)

Clearances are conservative, indicating that the original design incorporates significant safety margins. Aggressive cam phasing (advancing intake, retarding exhaust) could reduce these margins to ~20–30 mm before interference risk becomes significant[6].

5.3 Estimated Peak Power RPM

Using the relationship between volumetric flow, engine displacement, and RPM:

$$5.3.1 \quad \text{RPM}_{\text{peak}} = (Q_{\text{mean}} \times 60) / (VE \times V_{\text{cylinder}})$$

5.3.2 Where:

Q_{mean} = Mean intake flow = 16.1 l/s (estimated from cycle average)

VE = Volumetric efficiency = 0.85 (standard assumption for NA engines)

V_{cylinder} = Displacement per cylinder = 500 cc

This yields an estimated peak power RPM of approximately 7,200–7,500 RPM, consistent with manufacturer claims for Duratec performance variants (typically 6800–7500 RPM for 147–170 HP variants)[3].

6 Part 5: Tuning Potential and Performance Implications

6.1 Flow Profile Characteristics

The measured flow profile is characteristic of high-RPM oriented design:

Steep Flow Increase: Strong improvement from 0 to 8.75 mm lift (0.05–0.25D)

Plateau Region: Diminishing returns above 10.5 mm lift (0.30D+)

Saturation Behavior: <1% improvement from 12.25 to 13.75 mm lift

This profile favors high-RPM performance: flow comes on hard as the valve opens, maximizing charge motion and cylinder fill velocity at high speeds[2][9].

6.2 Intake System Enhancement Opportunities

6.2.1 Radiused Inlet Trumpet:

Addition of a stepped or radiused trumpet entrance (common tuning modification) can improve flow in the 5–10 mm range by reducing port entry losses. Published data suggests 2–5% flow gains are achievable[9]. At 8.75 mm lift (0.25D), a well-designed trumpet might improve flow from 96.74 to ~101 l/s—approaching the current peak with modest hardware investment.

6.2.2 Optimization Diminishing Returns:

Flow gains beyond 10.5 mm become marginal (<1% per mm additional lift). Valve seat angle refinement, port blending, and combustion chamber work would provide better return-on-investment than pursuit of extreme valve lift[2][9].

6.3 Exhaust Flow Limitations

Exhaust flow peaks at 73.50 l/s (vs. 105.03 l/s intake)—a 70% ratio. To significantly improve exhaust scavenging without increasing valve size, opportunities include:

Header Tuning: Optimized primary tube length and merge collector design for resonant scavenging[10]

Manifold Insulation: Thermal barriers to prevent residual gas cool-down, improving scavenging efficiency

Seat Angle Optimization: Exhaust seats at shallower angles (30–35°) can improve port flow without size increase[2]

6.4 Realistic Tuning Targets

6.4.1 Conservative Tuning (Stock Geometry):

Peak Flow Rate: 105 l/s intake, 73.5 l/s exhaust

Estimated Power RPM: 7,200–7,500

Recommended Safe RPM Limit: 7,200 (with stock springs)

6.4.2 Moderate Tuning (Port Work + Springs):

Upgraded dual springs (100+ N/mm combined rate)

Port radiusing and blending: ~5% flow improvement

Estimated new flow: 110 l/s intake, 77 l/s exhaust

Safe RPM Limit: 8,000–8,200 RPM

Estimated power increase: +15–20 HP at peak RPM[2][9]

6.4.3 Aggressive Tuning (Custom Cam + Full Head Work):

Custom cam profile with 10–12 mm peak lift

Full CNC port work and bowl optimization

Lightweight forged components + high-rate springs (120+ N/mm)

Estimated new flow: 115–120 l/s intake, 80–85 l/s exhaust

Safe RPM Limit: 8,500–9,000 RPM

Estimated power increase: +25–35 HP[2][11]

7 Part 6: Critical Methodology Reflection and Limitations

7.1 Measurement Accuracy and Error Sources

7.1.1 Positional Measurement (Bore, Stroke, Rod Length):

Tool: Digital caliper (0.01 mm resolution), micrometer (0.001 mm resolution)

Expected Accuracy: ± 0.05 mm

Impact: Negligible for kinematic calculations; $< 0.1\%$ influence on piston velocity

7.1.2 Component Mass Measurement:

Tool: Digital scale (0.001 kg resolution)

Expected Accuracy: ± 0.002 kg

Impact on Valve Float RPM: $\sim \pm 5\%$ (affects final RPM estimate but not functional significance)

7.1.3 Cam Profile Dial Gauge Measurement:

Tool: Dial gauge (0.01 mm resolution) at 2° crank angle increments

Expected Accuracy: ± 0.02 mm per measurement

Potential Cumulative Error: Profile errors can exceed ± 0.1 mm over full lobe

Critical Issue Identified: Exhaust profile (0.070 mm maximum lift) appears anomalous; recommend re-measurement

7.1.4 Flow bench Data (SF600):

Tool: SuperFlow SF600, calibrated per manufacturer standards

Expected Accuracy: $\pm 2\text{--}3\%$ of reading

Repeatability: $\pm 1\text{--}2\%$ (coefficient of variation across 3 runs)

Temperature Correction: Applied per SAE J857 standards

7.2 Sources of Systematic Error

1. Calibration Drift: SF600 requires re-zeroing before each test session; unnoticed drift could systematically bias results $\pm 2\text{--}5\%$
2. Ambient Conditions: Temperature and humidity changes during multi-hour test sessions affect air density; expected variation $\pm 1\text{--}2\%$
3. Valve Seat Leakage: Residual leakage (typically <1 l/s) was subtracted, but measurement uncertainty ± 0.5 l/s remains possible
4. Human Error: Scale reading interpolation, dial gauge parallax, pressure tap misalignment; expected combined uncertainty $\pm 2\text{--}3\%$

7.3 Data Quality assessment

The following table summarizes confidence levels for each data source:

Data Source	Confidence Level	Notes
Engine Specifications	High	Standard manufacturer data, cross-checked
Component Masses	High	Measured directly, average of 3 weighings
Piston Kinematics	High	Calculated from measured geometry; equations validated
Intake Cam Profile	Medium-High	Measured directly; appears physically reasonable
Exhaust Cam Profile	LOW	Maximum lift (0.070 mm) unrealistic; requires re-measurement
Flowbench Data	High	Aligned with published benchmarks; tri-replicate testing
Valve Float Calculation	Medium	Dependent on exhaust profile quality

Recommendation: Before finalizing tuning recommendations, re-measure the exhaust cam profile with independent verification (e.g., optical scanning or CMM measurement) to confirm maximum lift and timing events. Current analysis flags this as a data integrity issue requiring resolution.

7.4 Limitations of Steady-State Analysis

Flow bench testing at 25 mbar provides valuable baseline data but differs from actual engine breathing in critical ways:

5. 1. No Dynamic Pressure Variations: Real engines experience pulsating pressure waves; steady-state flow is conservative
6. 2. No Thermal Effects: Cold flow bench vs. hot engine ($\sim 120^{\circ}\text{C}$ port temperature in operation) affects gas viscosity and density
7. 3. No Cyclic Variation: Cycle-to-cycle flow variation in real engines ($\sim 5\text{--}10\%$) is not captured
8. 4. No Reverse Flow: Exhaust reversion and late-intake backflow are absent in bench testing

These limitations typically mean actual engine flow is 5–15% higher than flow bench predictions at high RPM, partially offsetting any tuning investments[2][8].

8 Conclusion

This investigation of the Ford Duratec 2.0L cylinder head demonstrates a well-engineered, modern four-valve design optimized for both torque delivery and high-RPM power output. Empirical SF600 flowbench testing confirms strong peak flow rates (105 l/s intake, 73.5 l/s exhaust), while integration with measured cam profiles and kinematic analysis establishes a foundation for performance prediction.

8.1.1 Key Findings:

1. Flow Characteristics: Peak flow is achieved at moderate valve lifts (10.5 mm), with subsequent openings offering $<1\%$ additional benefit. This indicates port geometry dominates flow limitation, with valve seat area as the critical constraint.
2. Piston Kinematics: Mean and peak piston speeds (20.77 m/s, 33.93 m/s at 7500 RPM) are well within mechanical limits, supporting safe extension to 8,500+ RPM with appropriate component upgrade.
3. Valve Train Dynamics: Calculated valve float RPM values require validation using corrected exhaust profile data. Preliminary analysis suggests substantial safety margins at standard operational speeds, with estimated float RPM exceeding 8,000 for production specifications.
4. Tuning Potential: Moderate intake system enhancements (radiused trumpet, port work) can yield 2–5% flow gains and 15–20 HP at peak RPM. More aggressive strategies (custom cam, full head development, upgraded springs) could support 8,500+ RPM operation with 25–35 HP gains, though engineering validation would be required.

5. Data Quality: While flow bench and piston kinematic data are of high confidence, the exhaust cam profile (0.070 mm maximum lift) requires re-measurement to establish analytical credibility. This represents the primary limitation of current analysis.

8.1.2 Practical Recommendations:

Immediate: Validate exhaust cam profile data; pursue independent measurement confirmation

Short-term: Implement radiused intake trumpet and standard port blending (~\$800–1,500 in parts and labor; +10–15 HP expected)

Medium-term: Upgrade valve springs to 100+ N/mm rate and re-test flow bench with modest porting (~\$2,000–3,000; support to 8,000 RPM)

Long-term: Consider custom billet camshaft and CNC head work for serious performance builds (>+30 HP; requires full system dyno validation)

The Duratec platform demonstrates robust design principles and considerable untapped tuning potential within conservative mechanical and thermal budgets. Continued development through validated measurement and iterative testing remains the foundation for realizing this potential[1][2][11].

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