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Effect of Manifold Inclination on an Unfired Engine Equipped with Flat Piston Using Non-Intrusive Technique–Experimental Flow Structure Analysis

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Abstract—*This paper mainly deals with experimental analysis of in-cylinder tumble flows in a single-cylinder four-stroke two-valve engine under motoring conditions with 0^0,30^0,60^0 and 90^0 intake manifold inclinations at an engine speed of 1000 rev/min., during suction and compression strokes using particle image velocimetry (PIV). Two-dimensional in-cylinder tumble flow measurements and analysis are carried out in the combustion space on a vertical plane passing through the cylinder axis. Ensemble average velocity vectors are used to analyze tumble flow structure. Tumble ratio (TR) and average turbulent kinetic energy (TKE) are evaluated and used to characterize tumble flows. From the results, it is observed that, at end of compression, 00 inclined manifold showed highest TR of 0.24 and TKE of 9.88 m2/s2 compared to other intake manifold inclinations considered in this study. The present study will be useful in understanding effect of intake manifold inclination on the nature of in-cylinder tumble flows under real engine conditions.*

Keywords*: In-cylinder flow, Intake manifold, Standard manifold, Velocity field, PIV.*

1. INTRODUCTION

In-cylinder flow of an internal combustion engine is directly related to engine performance characteristics (efficiency, combustion stability, knocking, emissions etc). Lean-burn combustion has become one of most promising concepts for improving fuel economy and reducing exhaust emissions in spark-ignition (SI) engines. Unfortunately, lean burning is associated with increased cycle-by-cycle combustion variations, due to reduced flame initiation and propagation rates and high hydrocarbon emissions. Engine stability under lean mixture conditions is improved when combustion variations are reduced and/or when combustion event is shortened. The most practical approach for improving engine stability under lean mixture conditions is to shorten combustion duration through enhanced mean flow and turbulence of mixture. There is recent evidence that formation of a tumbling vortex is an effective way to enhance preignition turbulence and promote faster burning rates. In-cylinder flow is unsteady and influenced by different designs of intake system, combustion chamber and wide range of engine operating conditions. Heywood (1988) reported that generating a significant vortex flows inside IC engine cylinder during intake process generates high turbulence intensity during later stages of compression stroke leading to fast burning rates.

Khalighi (1990), used flow visualization and particle tracking velocimetry (PTV) to study in cylinder flow field produced by a 4-valve engine head during intake process; reported that swirl and tumble flows should be maximized in order to maximize turbulence for achieving good combustion. Kent et al., (1989), Hill and Zhang, (1994) studied that intake-generated flow fields and subsequent combustion characteristics; reported that burn duration decreased with increases in tumble or swirl strength. Arocoumanis et al (1990), reported that generation of a strong tumbling motion means that port should be orientated as close as possible to plane passing through centers of valves and, therefore, there is less chance of any motion present in tangential plane surviving towards ignition. Stronger the tumbling motion, more turbulent kinetic energy is released during its breakdown and this release takes place later during compression relative to a weaker motion. Kurniawan et al., (2007), studied engine model for a single-cylinder of a CNG-DI engine; reported that combustion chamber shape of an engine is basically does not alter global in cylinder air motion but it is affect of velocity field close to piston top surface during later phase of compression stroke where fuel injection start to begin and spark plug is ready to burn air-fuel mixture to start off combustion process. Margary et al., (1990), investigated effect of intake duct length on volumetric efficiency and in-cylinder flow field by laser Doppler velocimetry (LDV); reported that turbulence intensity is shown to be less affected by inlet conditions. Kern et al., (1996), made an experimental study to provide better understanding of formation and decay mechanisms of tumble by LDV. Lee et al., (2001), reported that intake port height was dominantly affected on intake flow rate and tumble flow. Kim et al., (2000), made study on intake and compression flows; reported that tumble ratio and average fluctuation velocity remain approximately constant or rise slightly owing to spin-up phenomenon near top dead centre (TDC) after rapid decay of strong intake flow and turbulence in the compression stroke.

In the last decade, particle image velocimetry (PIV) has been increasingly applied to fluid flow measurements. The present study deals with study of in-cylinder tumble flow structures in a single-cylinder, two-valve, IC engine with different manifold inclinations under motoring conditions at an engine speed of 1000 rev/min., at various crank angle degrees (CADs) during suction and compression strokes using PIV. In this engine is equipped with flat piston for simplicity in all the cases of manifolds tested since combustion chamber shape of an IC Engine is basically does not alter the global in cylinder air motion but it is affect of velocity field close to piston top surface; during later phase of compression stroke where fuel injection start to begin and spark plug is ready to burn air-fuel mixture to start off combustion process (Kurniawan et al., 2007). In this paper, a detailed description of experimental set-up and measurement technique is given first which is followed by introduction. Finally, results based on PIV measurements presented and analyzed.

2. EXPERIMENTAL SETUP AND EXPERIMENTS

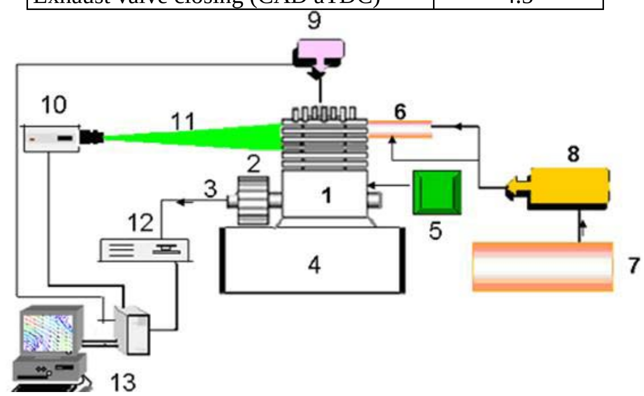
The specifications of a single-cylinder, four stroke, two-valve, air-cooled engine used in this study given in Table.1. This engine is coupled to an induction motor of 3.7 kW through an electronic speed controller. The maximum speed of motor is 1500 rev/min. In this study, motor along with engine is run at a speed of 1000 rev/min. In order to facilitate PIV measurements, an extension of cylinder liner is made using a transparent cylinder ring; to facilitate a field of view (FOV) (see Fig.2) by maintaining compression ratio of 10:1. The intake manifold of engine is connected to a plenum to mix and supply air and seeding particles with uniform mixing. The schematic view of the experimental setup is shown in Figs.1.

The PIV system consists of a double pulsed ND-YAG laser with 200 mJ/pulse energy at 532 nm wave length,

a CCD camera of resolution 2048x2048 pixels with a frame rate of 14 per second and a set of laser and camera controllers, and a data acquisition system and a software (Fig.1). The triggering signals for laser and camera are generated by a crank angle encoder mounted on engine crankshaft with a resolution of one CAD and were supplied to controllers via a signal modulator. A master signal of crank angle encoder is set to occur at suction top dead center (TDC) of engine (considered as a zero CAD). The triggering signals for laser and camera at required CAD can be set within the software.

Table 1: Specifications of the 4-stroke, 2-valve single cylinder engine

Bore x stroke (mm)	**87.5 x 110**
Compression ratio	10:1
Rated engine speed (rpm)	1500
Maximum valve lift (mm)	7.6
Intake/exhaust port diameter (mm)	28.5
Intake valve opening (CAD bTDC)	4.5
Intake valve closing (CAD aBDC)	35
Exhaust valve opening (CAD bBDC)	35
Exhaust valve closing (CAD aTDC)	4.5



1. Engine, 2. Motor, 3. Encoder, 4. Test bench, 5. Speed controller, 6. Intake plenum, 7. Air compressor, 8. Seeder, 9. Camera, 10. ND-YAG Laser, 11. Laser sheet, 12. Signal modulator, 13. Data acquisition system

Fig.1. Schematic diagram of experimental setup

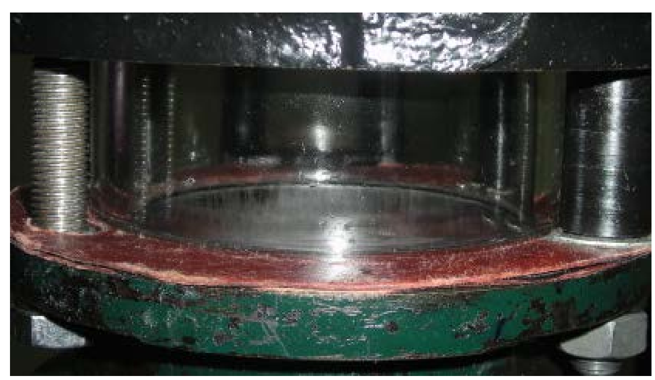
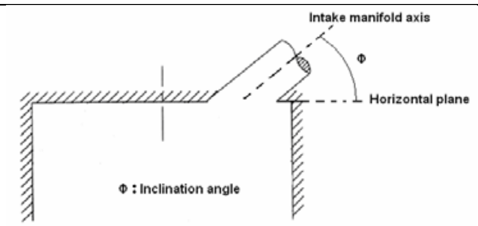


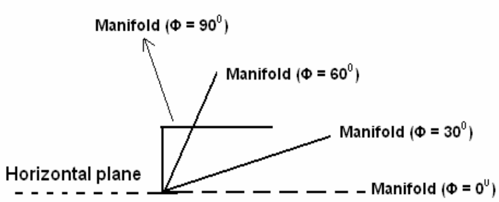
Fig. 2: Transparent cylinder liner - FOV

A seeding unit is used to generate fine particles of one micron size with di-ethyl-hexyl-sebacat (C26H50O4) as a seeding material. The seeding density is controlled accurately by varying pressure of air supplied to seeding unit. The laser sheet of 0.5 mm thickness is aligned with and camera is placed to view the FOV which is set on a vertical plane passing through the axis of cylinder.

In this study, in-cylinder tumble flow measurements have been done during suction (30 to 180 CADs) and compression (210 to 330 CADs) strokes in steps of 30 CAD and at every measuring point, 500 image pairs are recorded and stored. The time interval (Δt) between two images of an image pair is evaluated (6 µs for suction and 8 µs for compression strokes) based on pixel shift (< 5 pixel shift), FOV, maximum expected velocity of fluid flow in FOV and resolution of camera (LaVision, 2006 and Murali Krishna and Mallikarjuna 2008a-c). To minimize light reflections, a band-pass filter of central wavelength of 532 nm is mounted on the CCD camera. During PIV recording, camera focus is set to 3 to obtain sharp particle images. LaVision DAVIS (data acquisition and visualization software) is used for image acquisition and data post-processing. During post-processing, interrogation window size of 32x32 pixels with multi-pass cross-correlation algorithm is used (Raffel, 1998). Ensemble average velocity vectors are computed from 500 raw image pairs at required CAD.



a). Description of inclination



b). Definition of inclinations used

Fig. 3: Description of different manifold inclinations

The objective of study is to verify effect of manifold inclination on in-cylinder tumble flows. The tumble motion must be evaluated under transient conditions due to significant effect of piston and its motion on it unlike swirl (Khalighi, 1991). The different manifold inclinations used in this study are shown in Fig.3 with description of inclinations. Inclination angle (Φ) defined as angle between horizontal plane and axis of intake manifold. All the manifold inclinations tested at compression ratio of 10:1. It is observed that, at an engine speed of 1000 rev/min., maximum amplitude of vibration of cylinder liner at the point of measurement is equal to 0.0167 microns during a period of Δt, the separation time between two images, whose effect on error of measurement can be neglected. The calibration of in-cylinder environment as a whole is carried out along with plexiglass liner before PIV measurements.

3. RESULTS AND DISCUSSION

3.1 Characteristics of tumble flow

In-cylinder air motion before fuel injection process is most important to certify a proper air-fuel mixture (possible by turbulence) along with more tumble (to carry charge towards spark plug and to enhance turbulence at time of spark), finally affects on complete combustion in engine cylinder. This tumble distorted as piston moving near TDC of compression, later release its turbulent kinetic energy just before ignition. So that, this paper focused more towards end of compression stroke (330 CAD) even though study made during suction and compression. Ensemble average velocity vector plots of in-cylinder tumble flows with superimposed streamline patterns at 330 CAD are presented in the following Fig.4, which are obtained from instantaneous velocity vector fields of raw images. In all ensemble average velocity vectors, a constant length for velocity vectors is used with colour scale (right side of Fig.4) to represent their magnitudes.

3.1.1 In-cylinder air motion during suction

The combustion chamber shape of an engine is basically does not alter the global in cylinder air motion but it is affect of velocity field close to piston top surface, during later phase of compression stroke where the fuel injection start to begin and the spark plug is ready to burn the air-fuel mixture to start off the combustion process.

In all the cases of manifolds studied, where intake valve reaches to almost maximum lift (about 60 CAD), strong annular jet flows made a clockwise tumble vortex certainly with different in size depending on air entry inclination.

3.1.2 In-cylinder air motion during compression

During compression stroke, turbulence generated by annular jet flows during previous suction stroke decay quite quickly, may be due to that no fluid entry and reduced space between piston and cylinder head during compression stroke. In general, irrespective of formation of vortex and air flow movement at earlier stages of cycle, a favorable air flow pattern needs to occur at 330 CAD which is very much needed for stratified charged and direct injection SI engines. The air movement at this crank angle position plays a very vital role in mixture formation, ignition and flame propagation (Arocoumanis et al., 1990 and Khalighi, 1991). In all cases, it is seen that, vortices formed during intake stroke move towards exhaust valve side during compression stroke. But, effect of manifold inclinations on in-cylinder tumble flows can be better understood with the help of tumble ratio (TR) and average turbulent kinetic energy (TKE) of flow as discussed in following sections.

In case of 0^0 manifold

Fig. 4(a) shows that ensemble average velocity vector plot of in-cylinder tumble flows with superimposed streamline patterns for of 0^0 intake manifold at 330 CAD. The large tumble vortex formed during suction (not shown) due to deflection of intake flow air on cylinder wall after sliding along bottom of cylinder head. It may be due to less steep slope with this 0^0 intake manifold. It greatly contributed to retain tumbling flow during compression and towards end of compression (330 CAD) shown in Fig.4 (a).

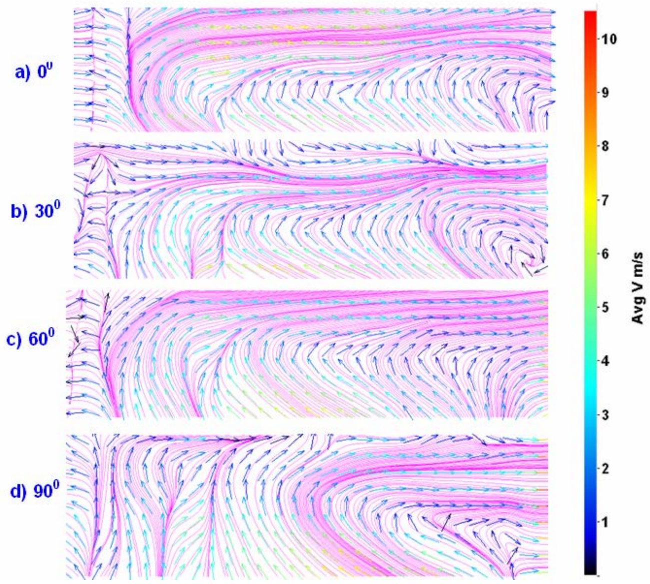


Fig. 4: Ensemble average velocity vectors of different manifold inclinations at 330 CAD

In case of 30_0 manifold

Fig. 4(b) shows that ensemble average velocity vector plot of in-cylinder tumble flows with superimposed streamline patterns for of 30^0 intake manifold at 330 CAD. The tumbling flow is formed by the air entering through intake manifold and deflected on cylinder wall with certain inclination angle, rather than flowing along cylinder head like previous case. Obviously, leads to generate slightly smaller vortex compared to previous case. But tumble generated during intake stroke still remains towards end of compression due to conserved angular momentum during compression stroke as it discussed in the previous case.

In case of 60^0 manifold:

Fig. 4(c) shows that ensemble average velocity vector plot of in-cylinder tumble flows with superimposed streamline patterns for of 60^0 intake manifold at 330 CAD. Tumbling flow is formed by the air entering through intake manifold and deflected on cylinder wall with certain inclination angle. Surprisingly tumble flow structure with this 60^0 manifold more similar to 0^0 manifold. Tumble generated during intake stroke still remains towards end of compression due to conserved angular momentum during compression stroke as it discussed in the previous case.

In case of 90^0 manifold

Fig. 4(d) shows that ensemble average velocity vector plot of in-cylinder tumble flows with superimposed streamline patterns for of 90^0 intake manifold at 330 CAD. The tumbling flow is formed by the air entering through intake manifold and deflected on cylinder wall with certain inclination angle. Tumble flow structure with 90^0 manifold more similar to previous manifolds tested but with reduced size in vortex. Tumble generated during intake stroke still remains towards end of compression due to conserved angular momentum during compression stroke.

3.2 Average turbulent kinetic energy (ATKE)

Fig. 5 shows variation of TKE with various CADs during suction and compression strokes; it is observed that TKE is gradually increasing up to 60 CAD and reaches peak in all the cases. Then it drops gradually towards 180 CAD, also in the beginning of compression stroke TKE trend continues to decreases may be due to the friction at cylinder wall, later becoming almost constant till end of the compression stroke.

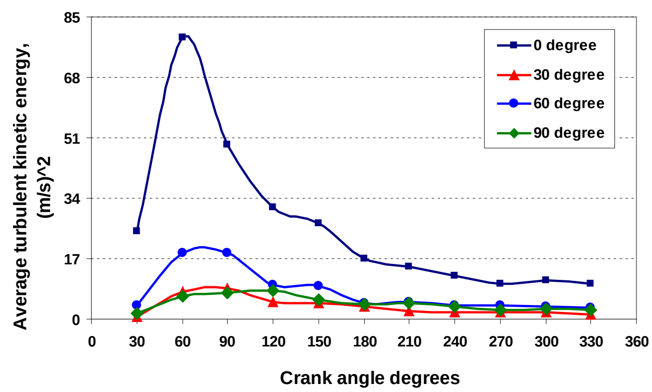


Fig. 5: TKE with CADs for various manifolds

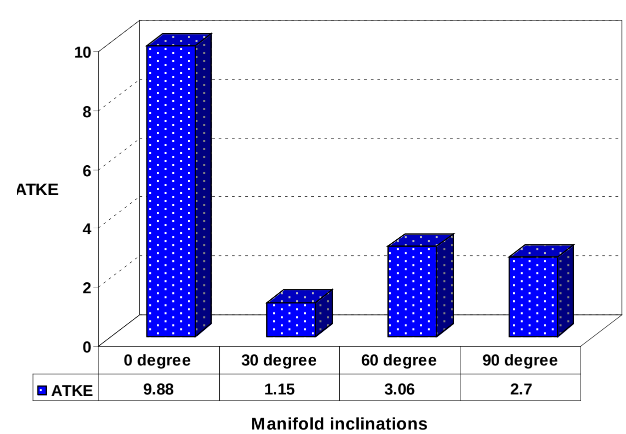


Fig. 6: TKE at 330CAD for various manifolds

The profiles of TKE obtained in this study are similar to that of Li et al., (2006).The 0^0 manifold with flat piston has an effect to incoming air as it is more easily allow fresh air into the combustion chamber and results in higher velocities around valve curtain area during maximum intake valve opening, therefore, higher turbulence generation rates existed compared to other manifolds.

3.3 Tumble ratio (TR)

Overall air movement at end of compression stroke gives a better idea to fix the position of the spark plug and fuel injector in modern SI engines. Pure tumble flow generates higher fuel concentrations in the vicinity of spark plug (Alger et al., 2000). Moreover, good charge stratification is crucial and it can be achieved with strong tumble flow (Li et al., 2006). In this study, quantitative analysis of tumble flows is done using TR as defined by Huang et al., (2005). The negative or positive value of TR indicates direction of overall in-cylinder tumble flows in a given plane as CW or CCW respectively. As piston approaches TDC, vortex is distorted considerably because it is forced into clearance between head and piston crown. Shear at this point is presumably very high, which makes large structures break down into small structure (Kern et al., 1996).

Fig. 7 shows the temporal variation of TR at different CADs during suction and compression strokes for different manifolds considered. From Fig.7, it is observed that TR ratio is changing from negative to positive value or vice versa indicating overall air movement changing from CCW to CW direction or vice versa. The reasons for this may be attributed to: (i) the overall air flow pattern due to low pressure and bifurcation zones, (ii) change in the piston speed with respect to CADs, and (iii) the direction of the piston movement during suction and compression strokes. Tumble ratio is initially increased by the strong intake flow and reaches a maximum at about 60 CAD. Then it decreases owing to a weak intake flow and down-ward motion of piston until intake valve close (IVC). The downward motion of piston increases moment of inertia, resulting in a decrease in TR. Also Fig.7 indirectly confirms that generation of a tumbling vortex towards end of suction stroke (180 CAD) with all manifolds, which later increases to a peak near about 240 to 270 CAD may be due to that flow associated with spinning-up process. The spin-up phenomenon is due to conservation of angular momentum and reduction in moment of inertia as piston moves upwards. It is to be noted that upto from 60 to 300 CAD, we can observe trend alone (limitation of FOV).The magnitudes of TR may be higher or lower magnitudes shown here within this CAD range. Fig. 8 shows the variation of the TR at 330 CAD for different manifolds considered. Stronger the tumble motion, more turbulent kinetic energy released during its breakdown at end of compression. It helps to have higher turbulence levels at the time of spark and ignition (Arocoumanis et al., 1990).

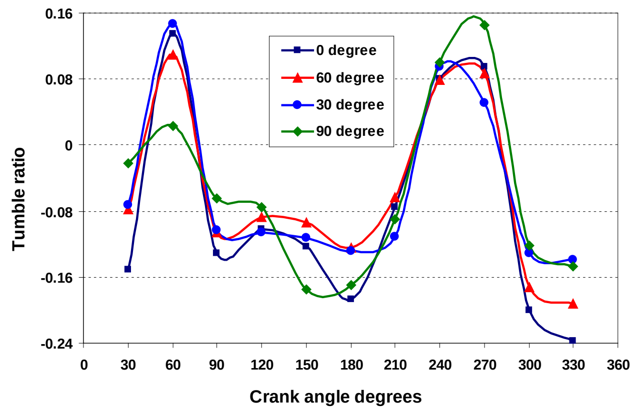
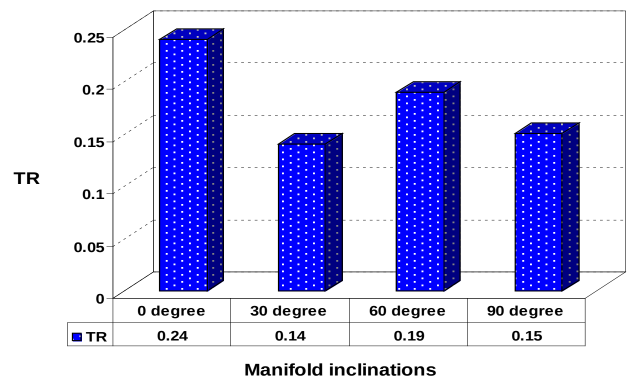


Fig. 7: TR with CA positions for various manifolds



	0 degree	30 degree	60 degree	90 degree
TR	0.24	0.14	0.19	0.15

Fig. 8: TR at 330 CAD for various manifolds

The 0^0 manifold was shown that highest TR of 0.24 compared with that of other manifolds tested at this 330 CAD. It is understand that 0^0 manifold release more turbulence as piston further approaching of TDC. Descriptions of TR behavior during latter stages of compression often refer to a period of vortex spin-up. This is a an increase in rotation rate owing to conservation of angular momentum as flow field is forced into reducing clearance volume near top dead centre (TDC). An increase in TR value during compression is cited as evidence for vortex ‘sign-up’ (Kurniawan et al., 2007). Kim et al., (2000) reported that tumble ratio and average fluctuation velocity remain approximately constant or rise slightly owing to spin-up phenomenon near top dead centre (TDC) after rapid decay of strong intake flow and turbulence in compression stroke. It is giving good evidence at 330 CAD for all the manifolds tested

4. CONCLUSIONS

From experimental study of tumble flows in a single-cylinder, two-valve motored IC engine using different manifold inclinations, at 330 CAD, 0^0 intake manifold shows highest tumble ratio of 0.24 compared to 30^0, 60^0 and 90^0intake manifolds; highest average turbulent kinetic energy of $9.9 m^2/s^2$ compared to 30^0, 60^0 and 90^0intake. This study shows that in cylinder flow structures are greatly affected by changes in intake fluid entry angle. So that it is suggested that, 0^0 intake manifold is the better choice especially for stratified combustion conditions.

5. ACKNOWLEDGEMENTS

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