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Thrust Augmentation of Single Cycle Pulse Detonation Engine using Nozzles

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ABSTRACT:
Pulse detonation propulsion systems have the potential to provide better performance with additional advantages such as considerably light in weight, cost effective and reduced complexity in comparison with other propulsion systems which are currently in use. These improvements are due to the high thermodynamic efficiency obtained because of constant-volume combustion. Pulse detonation cycle can be used for both air-breathing and rocket based systems. Present study investigates the effect of nozzles in various configurations. They are straight nozzle, conical and bell-shaped nozzles with varying length, divergent angles and area ratios on the thrust augmentation of Pulse Detonation Engine (PDE) test rig which was developed by research team at Punjab Engg. College (PEC), Chandigarh. It was found from the experiments that the conical nozzle with high divergent angle of 20° and high nozzle area ratio of around 23 increased the thrust to 14%. The bell shaped nozzle, with 20° angle of divergence and a nozzle area ratio of just around 7, produced 59.5% more thrust in comparison with baseline engine. The augmentation in thrust was found to be as high as 55% in comparison with straight nozzle. Divergent nozzles produced negative thrust with less divergent angle but gave an increment of 11.28% with high angle of divergence in comparison with a straight nozzle.

KEYWORDS:
Pulse detonation engine; Nozzle configuration; Thrust augmentation; Bell shaped nozzles, Area ratio

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1. Introduction

Pulse detonation propulsion systems have the potential to provide better performance with additional advantages of considerably light weight, cost effective and reduced complexity in comparison with other propulsion systems currently in use. These improvements are due to high thermodynamic efficiency and constant-volume combustion. Pulse detonation cycle can be used for both air-breathing and rocket-based systems. PDE is basically an internal combustion engine which works on constant volume cycle. The fuel and oxidizer mixture gets detonated, which leads to higher thermal efficiency and low weight to power ratio. They are currently of greatest interest for analytical and experimental investigations across the globe. PDE falls under the categories of unsteady flow device which has high performance potential but analysis of PDE is relatively difficult because of their non steady dynamic characteristics. The design principles which work for steady flow may not be applicable for PDEs.

The most important difference is the difficulty in matching exit conditions of PDE with those ambient conditions which is essential in rocket performance optimization. This criterion of matching the exit pressure and ambient pressure is not applicable in case of non-steady flow as the pressure field at PDE exit is not steady. Therefore optimization on exhaust nozzle is more difficult for PDEs and that may lead to loss in performance of the engine [1-3]. It was therefore desired to experimentally examine the effects of various nozzle configurations on the thrust produced by PDE. This paper presents experimental work done to analysing the effects of different nozzles on the single pulse operation of the PDE setup developed by research team at PEC, Chandigarh. In recent years, there have been many studies on the performance enhancement of PDE using different nozzles [4-17]. The analysis is very complex due to non-steady nature of the PDE. Till recent date, no theory has been developed for PDE regarding nozzle, and computational fluid dynamics has been the focus of all analytical studies.

In all the studies, the configurations used and fuel oxidizer used was different, it’s not possible to compare all of these studies. In some cases, combustible mixture filled both the main tube and nozzle, whilst in other cases filling was limited to tube only. How we initiate the detonation can also influence the results. In case of multi-cycle operation, additional parameters like chamber pressure, injection pressure and surrounding pressure considerably influence the performance of PDE. Cambier et al [4] made computational analysis on the efficiency of single pulse and multi cycle engine and predicted the performance variation using various diverging nozzles. They made the analysis by filling the tube and nozzle with a stochiometric mixture of hydrogen and air. The results indicated that nozzles were appreciably able to augment the thrust in single pulse operation. Due to outflow of boundary effects, results were noticeably different with single-pulse operation and multi-cycle operations.

Eidelman et al [5] numerically investigated various converging nozzles and diverging nozzles with fuel oxidizer combination of C_2H_2-air mixture. The analysis was done for single-pulse operation of PDE. In this case detonable mixture was filled in tube only. The results showed an increase in specific impulse in case of both the nozzle types i.e., convergent and divergent nozzles. It was also observed that using convergent nozzle leads to loss in cycle frequency of the engine, while the divergent nozzle maintained the cycle frequency. The highest performance of the engine was obtained using bell shaped nozzles using single-pulse operation in comparison with other nozzles. Mohanraj et al [6] studied a CFD model and investigated the multi cycle operation of some PDE nozzle combinations and predicted the performance enhancement of the engine. The stochiometric mixture of H_2-O_2 was filled both in tube and nozzle. The results obtained indicate, excluding case of low ambient pressure (pa < 0.2 atm.), a decrease in performance of PDE using a divergent nozzle with expansion ratio as 4. Yi et al [7] used numerical simulation on continuously rotating detonation engine to enhance the performance using various nozzles of different geometry. The observations were made for specific impulse and thrust with nozzles of four different configurations. Among all the nozzles used, divergent nozzle with a length of 4cm and 10 angle of divergence produced the greatest performance of the engine along with least loss in total pressure.

Yetao et al [8] numerically investigated the continuous detonation engine, using 3-D simulation, for its propulsive performance with various nozzles. The simulation was done using straight or constant area nozzle, divergent nozzle, convergent nozzle and C-D nozzle. The results were better in case of C-D nozzle in comparison with other nozzles and 1800 N of thrust was produced by it. Arian et al [9] numerically investigated the effect of angle and length of the nozzle on the performance parameters of pulse detonation engine mainly on frequency and impulse from perspective of gas dynamics. The equations were solved using quasi 1-D code. The main engine length used was 1m and a maximum temperature of 2500K was produced by the combustion product along with 10 to 20 bar variation in maximum pressure. The results indicated that impulse of the engine was improved using straight nozzle but cycle frequency improved with divergent nozzle and vice versa. The effect on thrust was reported positive with increased length of the straight nozzle and increased divergence angle in case of divergent nozzle. Amin et al [10] used CFD software to make investigation on the performance of a PDE by changing nozzle geometry. The simulation was done using different nozzle geometries and results indicated that highest performance of the engine can be obtained using an expanding nozzle with optimum area ratio.

Morris [11] numerically modeled the gas dynamics of Pulse Detonation Rocket Engine and used four different geometry combinations of the engine to predict the performance. The combinations used were base-line engine, then extended the tube length and in next combination they used two types of converging diverging nozzles. The convergent-divergent nozzles at high pressure ratios proved to be more efficient than other geometries used. Rouf [12] did a parametric study using numerical simulation to optimize the performance of PDE. It was found that the performance of the engine got affected by use of nozzle. The impulse produced by the engine was found to be significantly more in case of divergent nozzle while the convergent nozzle and straight nozzle produced lower impulse. It was also observed that engine cycle time also gets affected by nozzle geometry. Variable geometry nozzles were suggested to be the best for performance optimization. Wenjuan et al [13] experimentally investigated the improvement in thrust and inlet pressure of Air-breathing Pulse Detonation Engine (APDE) by using nozzles. For this they used 2050mm length and 68mm diameter detonation tube along with fuel oxidizer combination of gasoline and air. The improvement in thrust was reported in case of straight, diverging and converging-diverging nozzles. Divergent nozzle with greater value of exit area and C-D nozzle having big throat area resulted in maximum enhancement of thrust, in the range of 20% to 40%.

Daniau et al [14] investigated the effects of diverse shapes and lengths of cylindrical and diverging nozzles on the performance of a PDE. The experiments were performed for single-pulsed PDE and tube alone was allowed to be filled with fuel oxidizer mixture of acetylene and oxygen. Results illustrated that performance of the engine was appreciably affected by the use of the nozzle. In all the conducted tests, specific impulse was reportedly improved significantly but in some cases this improved impulse resulted in decrease in cycle frequency.However, diverging nozzle configurations indicated unchanged thrust value but obtained maximum cycle frequency. The average thrust can be improved using those divergent nozzles along with increase in specific impulse. Cooper et al [15] conducted experiments on a single-pulse detonation engine having tube length of 1m. They measured the impulse of the engine with and without a nozzle. The nozzle used was divergent nozzle of length 0.3m and divergence angle as 8°. They used the combination of ethylene-oxygen-nitrogen mixture as fuel-oxidizer and purge gas. It was observed that specific impulse of the engine didn't show any noticeable improvement with use of the nozzle.

Yan et al [16] conducted experiments on Pulse Detonation Rocket Engine (PDRE) to improve its performance by using various geometries of bell-shaped C-D nozzles. The highest thrust increase was observed by the nozzle with 5.325 as inlet and throat area ratio and 12 as throat and exit area ratio, nearly 21% increment in thrust was observed. Stuessy et al [17] conducted experiments using annular conical nozzles with divergence angle of 9.52° and 14.24° respectively. The augmentation in was found to be maximum using the nozzle of 14.24° divergence angle. The contradictory conclusions in these studies indicate that the effect of nozzle configuration may depend on several parameters of the PDE like its tube diameter, fuel-oxidizer used and the dimensions of schelkin spiral etc. The performance of the engine can be enhanced using a particular configuration of nozzle. This paper investigates the effect of some nozzle geometry on the PDE as developed by Punjab Engineering College's research team. It was done by fixing all other parameters of the engine.

2. Pulse detonation engine-test facility

The research team developed a single tube valveless PDE for conducting research in various field of interests. The engine basically consists of combustion tube, a schelkin spiral, fuel injection system and spark plug as ignition system. The detonation in the engine is produced using fuel oxidizer mixture of either acetylene-oxygen or acetylene-air. A schelkin spiral is integrated as deflagration to detonation transition (DDT) device. A thrust stand was built and a load cell was attached at the front end of it to measure the axial thrust to collect the data. A data acquisition software (DAQ) was created and used. The basic constructional details of the engine are given in simplified layout of PDE system as shown in Fig. 1 [15-17]. The basic structure of the engine consists of combustion tubes resting on middle support bar. To reduce the friction a curved wedge integrated with a slider is provided to combustion tube. When measured the friction in complete system having a tube length of 80cm was found to be 35N including vibration of stand. Impact sensors are designed to measure compression and impact forces from a fraction of l b (4N) to 50,000 lbs (to 22.4 kN). The flat sensing surface located on the top of the sensor is designed to measure a dynamic force quickly applied axially to the sensor.

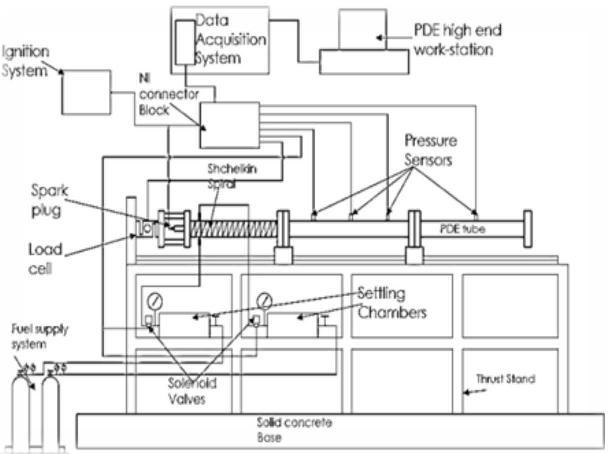

Fig. 1: Simplified schematic layout of PDE system [18]

To collect the high-speed data, an amil make DAQ hardware system was used. The DAQ unit was used with three input-output boards, a low resistance 6m cable along with some pressure sensors and a load cell (PCB make). To support the engine a stand for the test rig is fabricated. Fig. 2 shows the experimental setup with attached nozzle. The engine stand is 365cm long, 91cm wide and 184cm high in dimensions. In addition to that it has a curved cowl covering of 35cm height over it, to provide safety to the people working on the engine. The fuel air mixture that is supplied to the combustor is controlled by fuel injection-delivery system, shown in Fig. 3, which is designed to provide the stochiometric ratio of the fuel/air mixture. A valve-less air delivery supply system was designed to provide a constant flow of air to the engine. The fuel supply was controlled by changing the pressure of the fuel injected. The supply of air/oxygen was delivered from air/oxygen cylinder at varying mass flow rates with respect to pressure in pipe line controlled by the valves in line. The supply was controlled by flow controller & electronic microcontroller-based system. For supplying acetylene to detonation tube a self-sufficient injector system of Danfoss make was used. It's a high frequency electrically controlled system. The acetylene is mixed with oxygen before entering into the detonation tube.

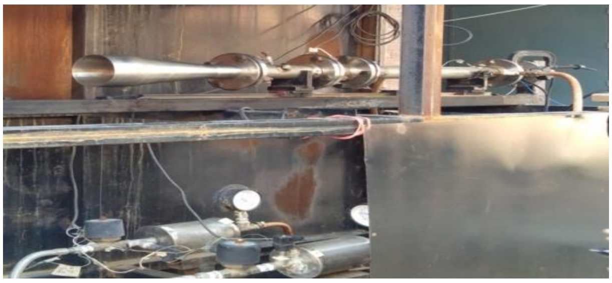

Fig. 2: Experimental setup with nozzle attached

Fig. 3: Fuel injection/ air delivery system

For ignition, a spark plug with a 12V DC supply was provided in flow control circuit, it has the control of the spark plug ignition. A mobile application is created to command the spark plug when the tube is filled with fuel and oxidizer mixture in required ratio and time. The fuel and oxidizer inlets are situated close to the spark plug, enabling it to start the combustion easily by spark created by high voltage in the plug. The detonation tube is a hollow stainless steel (Grade 304) tube with 48mm of internal diameter and 6mm thickness. This tube is capable to withstand a high pressure waves created by the detonation inside it. The basic length of the combustion tubes is 80cm.

3. Nozzle used for thrust augmentation

Due to detonation in tube, a high intensity pressure wave is created and it travels through the tube at very high speed, the gas at the exit of tube expands to the atmosphere. The purpose of using a nozzle at the end of the detonation tube is to use the kinetic energy of exhaust gas for the production of additional thrust. Various nozzles configurations were tested, i.e., type of nozzle, various angles of divergence/expansion and lengths. Using single-pulse operation, apart from straight extension, eight different nozzle geometries were tested. The primary engine consists of detonation tube of 80cm alone. The next configuration was extending the tube to 100cm. A straight nozzle of 20cm was attached to the tube further configurations include four conical nozzles of increasing lengths and divergent angles resulting in increased area ratios as shown from Fig. 4 to Fig. 7. The subsequent geometries include bell shaped nozzles with small length but large divergence angle, long length with small divergence angle and medium length with medium angle of divergence as shown from Fig. 8 to Fig. 12. The area ratios of the nozzles may vary accordingly. These nozzles were attached at the end of the detonation tube and it was open to the atmosphere.

Fig. 4: Divergent nozzle configuration - 1

Fig. 5: Divergent nozzle configuration - 2

Fig. 6: Divergent nozzle configuration - 3

Fig. 7: Divergent nozzle configuration - 4

Fig. 8: Bell shaped nozzle configuration - 1

Fig. 9: Bell shaped nozzle configuration - 2

Fig. 10: Bell shaped nozzle configuration - 3

Fig. 11: Bell shaped nozzle configuration - 4

4. Results and discussions

The baseline engine configuration had a detonation tube of 80cm length. It was incorporated with a Schelkin spiral of 24cm having a pitch of 1.7cm and wire thickness 0.8cm. The fill pressure for acetylene and oxygen were kept constant at 40 and 70 psi respectively. The ignition was initiated with spark plug which was being operated using the mobile application. The detonation tube with 80cm length produced 657 N of peak thrust and peak pressure of 17.5 bar was recorded in the tube. When the detonation tube was attached with straight nozzle, of 20cm length, the thrust increased slightly to 674N or 2.3% in comparison with baseline engine but there was a drop in peak pressure to 16.8 bar.

4.1. Divergent nozzles

Divergent conical nozzles of increasing length, divergent angle and hence the increased area ratios were bolted to the tube. The peak pressure and thrust variations are presented from Fig. 12 to Fig. 15. When compared with straight nozzle there was decrease in thrust when divergent nozzle with divergence angle of 5°and 100mm length was attached to detonation tube. The decrement reported was 3.2% in comparison with no nozzle and 5.64% in comparison with straight nozzle. Further the maximum pressure recorded in the tube was 1.1 bar less in comparison to no-nozzle case. The peak thrust increased about 8% and 5% in case of divergent nozzle of 150mm length and 10° divergence angle and maximum pressure in tube was recorded as 17 bar, which is 0.5 bar less than maximum pressure with no-nozzle. The divergent nozzle having 15° divergence angle and 200mm length produced 8.219% and 5.49% more peak thrust as compared with no-nozzle and straight nozzle respectively. The maximum pressure obtained was 15.6 bar, which is 1.9 bar less than pressure obtained with no-nozzle configuration. The peak thrust increased to 14% and 11% in case of nozzle with 20° divergence angle and 250mm length with same peak tube pressure as in case of divergent nozzle of 15°, i.e., 15.6 bar.

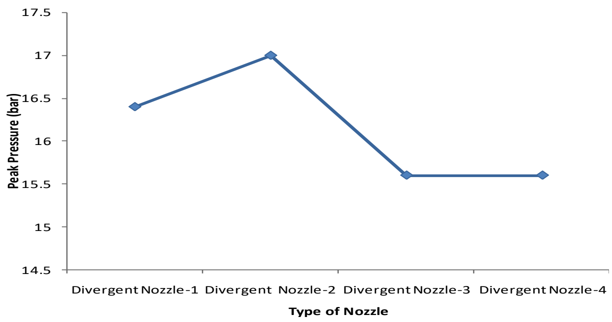

Fig. 12: Variation of peak pressure with divergent conical nozzle

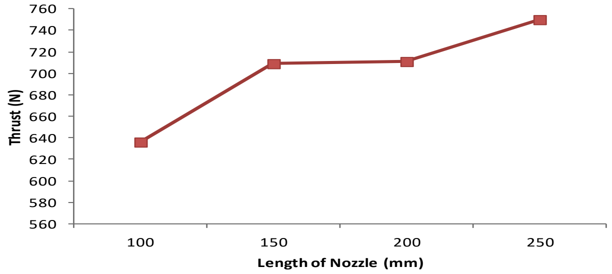

Fig. 13: Variation of thrust with length of divergent conical nozzle

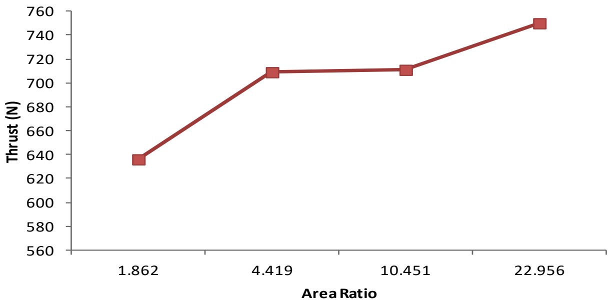

Fig. 14: Variation of thrust with area ratio of conical nozzle

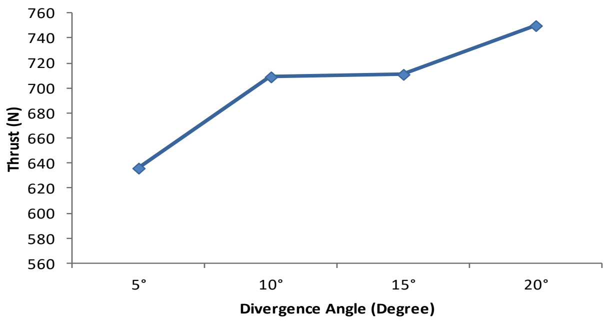

Fig. 15: Variation of thrust with divergence angle of conical nozzle

4.2. Bell shaped nozzles

The variation of peak pressure in tube and maximum thrust obtained for various bell-shaped nozzles are depicted in Fig. 16 to Fig. 19. The bell shaped nozzle with 5° expansion angle and 200mm length increased the thrust to 920 N. There was around 40% increase as compared to no nozzle and 36.5% in comparison with straight nozzle. The peak pressure obtained in the tube was found to be 28.4 bar. Using 15° as expansion angle and 100mm length of bell-shaped configuration, the increase in thrust reported to be 938 N or 42.7% and 39% along with peak pressure of 17.2 bar. Next bell-shaped nozzle of 10° expansion angle and 250 mm length further increased the thrust to 960 N or 46% and 42.4%, but recorded rise in peak pressure to 27 bar. Maximum increment in thrust was obtained with bell shaped configuration of 20° expansion angle and 150mm length. The augmentation value of thrust reported was 1048N or 59.5% and 55.5% respectively in comparison with no-nozzle and straight nozzle, but a sharp decrease in peak pressure was observed. The peak pressure in the tube was obtained as 18 bar.

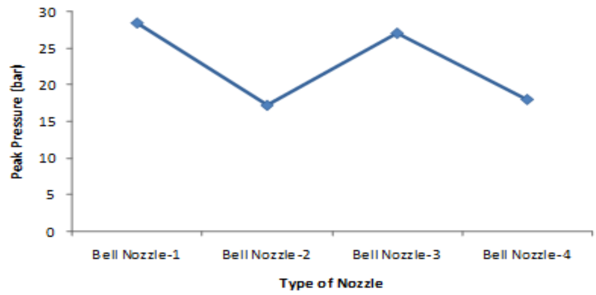

Fig. 16: Variation of peak pressure for bell-shaped nozzles

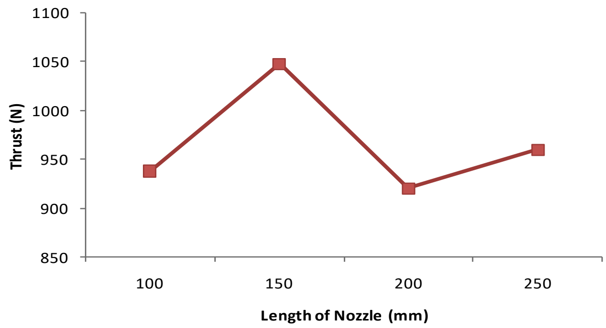

Fig. 17: Variation of thrust with length of bell-shaped nozzle

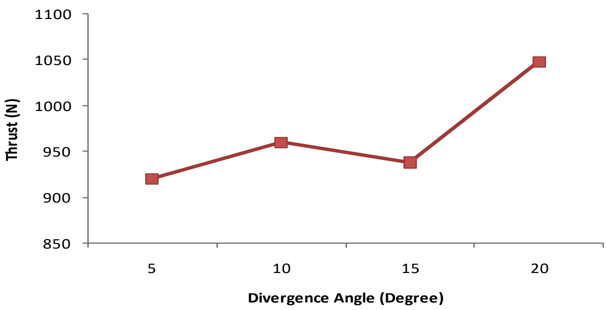

Fig. 18: Variation of thrust with divergence angle of bell-shaped nozzle

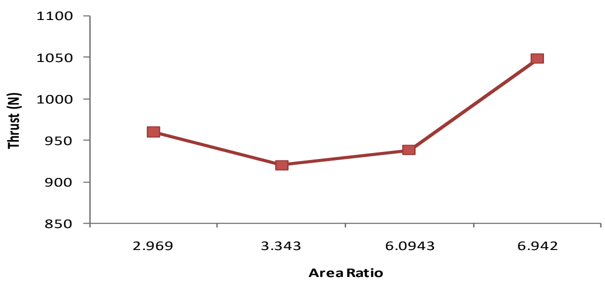

Fig. 19: Variation of thrust with area ratio of bell-shaped nozzle

5. Conclusion

The effects of different nozzle configurations on the thrust produced by single-cycle detonation engine were investigated experimentally with acetylene-oxygen mixture using PDE facility available at Punjab Engineering College. Various nozzle configurations including straight nozzle, bell shaped nozzle and divergent nozzle were used. The bell shaped and divergent nozzles were tested with variation in length and angle of divergence and hence nozzle area ratios. The maximum augmentation in thrust was obtained in the bell-shaped nozzle with a 20° divergence angle, 150mm length and area ratio of 6.942. The thrust augmentation obtained was 59.5 % more as compared to no-nozzle and 55.45 % against straight nozzle of 200mm length. The thrust value obtained for other bell-shaped nozzle varied from 46% to 40% for divergent angle 15° to 5° and for various lengths and area ratios. On the other hand, divergent nozzles with various divergent angles (5° to 20°) were found to be less effective as compared to bell shaped nozzle. The peak thrust value obtained was varying from negative thrust (-5.64%) to around 11.28% more in comparison with straight nozzle. In conclusion, the bell-shaped nozzles of high divergence angle and high area ratio was found to be more effective for thrust augmentation of PDE (as high as 59%) as compared to no nozzle, straight nozzle and divergent nozzle. The divergent nozzles with high divergence angle and high area ratio could obtain an increase of 11.28% in thrust as compared to straight nozzle.

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