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CFD Analysis of Pulse Detonation Engine-A Review

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Abstract—*Pulse detonation engine (PDE) is a revolutionary propulsive system that uses detonation wave to combust the fuel and oxidizer mixture and produce high thrust efficiency (simplicity and thermodynamic) than current engine systems. The engine is pulsed because the mixture must be renewed in the combustion chamber between each detonation wave.PDE produces a higher specific thrust than ramjet engines at speeds of Mach 2.3. PDE can operate from subsonic up to a hypersonic flight speed (Mach 5). To improve the performance of the engine, it is imperative to develop an effective deflagration to detonation transition enhancement device with minimum flow loss and higher survival in uncongenial detonation tube. These methods include inserting regular or irregular obstacles like spiral different spiral grooves or using divergent-convergent sections in the detonation tube, or designing shock-focusing end-walls. PDE is suitable for multi-stage propulsive systems. The PDE can provide static thrust for a scramjet or operate in combination with turbofan systems. The PDE can be used in many sectors of the aerospace, aeronautic and military application. To date, no practical application run PDE technique, but several test bed engines have been built and tested. Current methods for initiating the detonation process need refinement. Nickel based super- alloys used in jet engines are inadequate to withstand the extreme heat and pressure generated by detonation.*

Keywords*: Pulse detonation, spiral grooves, Mach number, specific thrust, deflagration, hypersonic*

1. INTRODUCTION

A pulse detonation engine is a new-concept propulsive system utilizing repetitive detonation to produce thrust or power. In present days researchers from all over the world in propulsion field has interested towards the historical background, thermodynamics analysis, detonation initiation and deflagration to detonation transition (DDT) device of pulse detonation engine in detonation combustion area. Researcher from the United States, Russia, Japan, China, Germany and Malaysia are interested in this field. In combustion chamber shock wave was generated that is followed by combustion wave. In 1993, Pratt and Whitney began to develop the pulse detonation engine. Their research work was to study the DDT through the pulse detonation engine. Nicholls and their fellow conducted a study to investigate the thrust, fuel flow, air flow, and temperature over the range of operating conditions. Recently many researchers contribute to research of multimode combined detonation engine in hypersonic aircrafts propulsion. Kailasanath studied the development of pulse detonation engine and derived the detonation combustion parameters such as Chapman velocity and pressure. Wilson and Lu integrated studies for both PDE and RDE based propulsion system. They studies on detonation wave to hypersonic flow simulation and power generation.

2. LITERATUREREVIEW

Yuhui Wang and Jianping Wang [1] studied the experimental and numerical analysis of rotating detonation waves in hydrogen-oxygen mixture. The result shows that the velocity of the rotating detonation wave increases first, and then decreases with increasing the equivalent ratio. According to Previous study the velocity of the detonation wave decreases monotonously with increasing the equivalence ratio. RDEs (rotating detonation engine) may have 20% higher thermal efficiency than deflagration engine. RDE model based on hydrogen-air fuel can be specific impulse 5500s with a pressure ratio of 20. Song-Bai Yao et al. [2] Studied the effect of number of detonation waves and inlet totapressure of rotating detonation engine (RDE), using a three-dimensional numerical model method. In this paper

Premixed hydrogen-air fuel Arrhenius one step chemistry model is used .They found that the number of detonation wave effect the required time to reach stable detonation condition, but negligible effect on the thrust, the specific impulse and the outlet flow under same inlet total pressure.The energy of the detonation waves depends on the inlet total pressure, lower inlet total pressure developed unstable combustion phenomenally. To accelerate the stability of detonation waves, the inlet pressure should be same with ignition for fuel injection. Liu Yu-Si et al. [3] Studied with the effect of reflected shock wave on Continuously Rotating Detonation Engine (CRDE). Experiments are carried out with hydrogen-oxygen premixed fuel. Experimental results show that small grooves and indentations (unsmooth surface) on the wall of combustor does not affect too much on Continuously Rotating Detonation waves (CRDW). But the obstacles in downstream of the combustor may cause strong reflected shock wave and leads to killing the CRDW. For sustaining of Continuous Rotating Detonation waves, continuous supply of fresh reactants injection on the head wall is required.Experimental studies have been carried outbyLiu Yusi et al. [4] To investigate Spectral analysis and self-adjusting mechanism for an oscillation phenomenon in hydrogen-oxygen continuously rotating detonation engine (CRDE). The results of this experiment show that CRD waves stabled when feeding pressures for fuel and oxidizer are higher than 0.5 MPa, respectively, hydrogen-oxygen is used for combustion gas and the supply of fresh gas maintains. The result shows that splitting of CRDW and repeatability of pressure pick, which indicates thedetonation velocity in hydrogen–oxygen CRD and formation of the stable CRD in the annular chamber. Spectrum of pressure history shows multi-wave phenomena and only one quasi-steady CRDW is rotating in the annulus. CREW splits into primary (main) and secondary (two, three or four) detonation waves. Peak of Spectrum of pressure history indicates a self-adjusting mechanism for an oscillation phenomenon in hydrogen-oxygen CRDE.Lu Jie et al. [5] did an analytical study on liquid-fuel pulse detonation engine and different thrust measuring method. Average thrust of PDE is measured by the direct thrust measurement method with a force transducer, indirect measurement method with an eddy current displacement sensor (ECDS) or a linear variable differential transducer (LVDT) and ballistic pendulum method. The ballistic pendulum method gives better accuracy limited to a single impulse measurement. Data obtained from the different measurement method are compared with each other to verify the accuracy and feasibility of the thrust. Results show that average thrust data obtained from the impulse measurement system is slightly lower than the data of the force transducer method due to the axial momentum losses of the detonation jet. Results also show that thrust data of direct thrust measurement and indirect thrust measurement method are within range of measurement error. The impulse measurement method is used for measurement of average thrust of PDE. In this paper Analytical model (updated numerical analysis method) is used to obtain the thrust of PDE. Data of analytical model shows that the analytical thrust is higher (24.7%) than the experimental thrust data due to the losses during the DDT (deflagration to detonation transition) process. An analytical model is used to analyze the effect of the equivalence ratio on the thrust performance of liquid-fueled PDE. Maximum thrust obtained as the equivalence ratio of about 1.1. Navid Mehrajoo et al. [6] studied on a method of detonation transmission from a small tube to a large area of the pulse detonation engine. In this method an obstacle created at the exit of the small tube before the planer detonation takes place into large place. Obstacles created by small blockage generating flow instability which promote the detonation transmission. In this paper investigate the effect of small perturbations with a varying blockage ratio of the critical tube diameter with two unstable undiluted stoichiometry mixtures of acetylene-oxygen and acetylene-nitrous oxide. An irregular cellular pattern found in most hydrocarbon mixtures is used in practical aerospace applications. Result shown that the optimal blockage ratio (8%to10%) created the obstacles is varied systematically to identify the optimal condition under which a reduction in critical pressure for transmission can be obtained. The optimal blockage ratio is independent of the obstacle geometry for the irregular fuel mixtures. These results provide useful information to design of PDE for the power system and aerospace propulsion. Zhiwu Wang et al. [7] designed and tested a four-tube two-phase gasoline/air valve less air-breathing pulse detonation engine (PDE) to find out the operational characteristics of PDE. In this experiment gasoline and air were used as fuel and oxidizer respectively. The PDE was worked under the minimum and maximum frequency of 30 Hz and 120 Hz respectively. Four different firing patterns: single tube firing, dual tube firing, three tube firing and all four tubes firing simultaneously were carried out. Detonation wave and back-pressure wave created by multi-tube firing pattern was measured and compared. In comparison, of data, of detonation waves showed that four tube PDE worked successfully under four tube firing pattern and could transfer from one firing pattern to another. A wide range of thrust frequency could be obtained by changing the number of firing tubes. In all multi-tube firing patterns, times of arrival of detonation waves were different which creates differences of back-propagation pressure waves. Only for dual tube firing system, time interval decreased with increasing frequency. In comparison, of the average peak values of back-pressure waves in the air plenum chamber and results showed that the maximum peak pressure value was 0.22 Mpa in single tube inlet for single tube firing pattern. Peak pressure was reduced to 0.064 Mpa when the pressure propagated into the air plenum chamber. At the same time, detonation waves and back-pressure waves are closely related to each other. Pattern of average peak pressure is similar to the multi-tubes firing patterns. Pressure peak increase with increasing fired tubes. Zhiwu Wang et al. [8] did an experiment studied to find-out the total pressure recovery coefficient, flow coefficient, multi-cycle back-propagated pressure characteristics and intake resistance of a valve less pulse detonation engine (PDE). They conducted whole PDE mock-up tests like the air flow test, the multi-cycle detonation test and the thrust measurement test with five different combination induction systems at semi-free-jet. Experiments were carried out successfully with liquid gasoline-air mixture and low-energy ignition system (total stored energy less than 50 mJ). Results of experiment provided important theoretical and experimental basis for the future design and application of PDE. The induction system 1 showed higher total pressure recovery and flow coefficient and easily operated than others at high frequency. At higher operating frequencies PDE (25 Hz), induction system 1 had highest average thrust. But induction system 4 had highest average thrust at operating frequencies of 10 Hz and 15 Hz. At the frequency range of 0 Hz to 25 Hz, PDE mock-up worked steadily. The operating frequency of PDE could improve to 35 Hz when induction system 1 and 3 were used. Initial pressure perturbation had propagated to the PDE import before detonation generated in the PDE mock-up when combination of four induction system used with the shorter conical inner body. Detonation initiated in the PDE mock-up before initial pressure perturbation propagated to the import of air inlet when the induction system 5 in the long conical inner body was utilized. The time interval between the time of backward pressure perturbation propagating to the PDE inlet and time of detonation ignition decreased gradually in increasing frequency. At an operating frequency of 35 Hz, initial pressure perturbation and detonation occurred at the same time. Yu Yan et al. [9] conducted an experiment on pulse detonation rocket engine (PDRE) with various injectors and nozzles. Liquid kerosene, gaseous oxygen and nitrogen were used in PDRE (30 mm in inner diameter and 860 mm in length) as fuel, oxidizer and purge gas, respectively. Four different geometrical shaped injectors were tested in this experiment to improve the atomization of liquid fuel and reactant mixture. In order to find out the effect of different injector configuration on PDRE performance, the injector can replace or remove from PDRE. The results show that PDRE performed with all injector except injector A and injector B performed better. Small fuel exit area and large gas exit area of injector gave better atomization of liquid fuel and reactants mixing process. Oxygen play important role in atomization and mixing process. In this experiment, optimized the nozzle configuration and investigated the effect of various bell-shaped converging– diverging nozzles of PDRE. It was found that high expansion and contraction ratio of nozzle generated highest thrust augmentation of 27.3%. Length and the half angle of a nozzle also play a major role. Ke Wang et al. [10] did an experiment studied to investigate the effect of wall temperature on the performance of a pulse detonation rocket engine (PDRE). Long durational experiments carried out with an internally grooved semi-circle spiral in the place of the traditional Shchelk in spiral to facilitate the deflagration to detonation transition (DDT) process. K type thermocouple and four pressure transducers were used to measure data. Three different frequencies such as 10 Hz, 20 Hz and 30 Hz were used in this experiment. Collected data indicate that the rate of increment in wall-temperature with a faster rate of higher operating frequency and a maximum wall-temperature of 770°C was obtained at 30 Hz after 90s of run-time. The results show that DDT distance and DDT time both decreased with increasing of wall temperature due to hot tube wall vaporized fuel particles. Also found that the wall - temperature was closely related to detonation pressure. First detonation pressure increased sharply with wall-temperature and decrease slowly after certain wall-temperature due to vaporization of fuel on hot-wall and reactants temperature. The high wall – temperature would cause pre-ignition of fuel-oxidizer mixture and this resulted in unsteady operations of PDRE. WANG Ke et al. [11] conducted an experiment to investigate operation of PDRE using a customized rotary-valve supply system. An experiment conducted at different range of operating frequency to find out the pressure profile by changing the initiation phase of ignition signal. Oxygen used as oxidizer and liquid aviation kerosene used as fuel to conduct this experiment. Low ignition energy (50 mJ) is used to initiate detonation using an automobile spark plug. The results show that steady operation of PDRE is obtained with operating frequency ranging from 1 Hz to 10 Hz. Results showed that experimentally measured pressure value is lower than the theoretical value by 13% at 1 Hz and 37% at 10 Hz and shows a velocity deficit at different operating frequencies. Velocity deficits and lower pressure value may have occurred due to atomization and vaporization of droplet size of liquid fuel. Yuhui Wang et al. [12] conducted an experiment with tangential flow hydrogen-oxygen mixture of multiple rotating detonation waves. In this experiment, single detonation wave or multiple detonation waves were used to run Rotating detonation engine (RDE). Pressure sensors and gas flow controller were used to measure the pressure of rotating detonation waves and control the flow rate of reactants. Multiple RDWs form when axial flow from the head of the combustor and tangential flow from the pre-detonation of reactants takes place after a DDT. The tangential flow induces new RDWs which move in upstream direction. The intensity of multiple RDWs is different from each other. The detonation wavelets are detonated at much lower velocity of the main detonation wave than of the single RDW. In the case of multiple RDWs with constant flow rate, RDWs fluctuates in a small range. If the number of fluctuation of RDWs is too small then the new detonation wave will be induced by the shock waves. Induction of single or multiple RDWs in combustor depends on the flow path of reactants. Changxin Peng et al. [13] conducted a series of experiment on valve less air-breathing dual-tube pulse detonation engines to improve the understanding of the characteristics. To conduct this experiment, gasoline and air were used as fuel and oxidizer respectively. Operating frequency varied from 4 Hz to 12 Hz. Simultaneous and single-tube firing is two different operations were successfully performed. The synchronicity of detonation waves was quantitatively evaluated in two tubes. The results show that the time interval was less than 1 ms and inversely proportional to the operating frequency. A degree of randomness had found in detonation wave that arrived firstly. In the experiment, the situation that the detonation wave always kept ahead never happening in certain tube. Ahead time of detonation wave little changed with the frequency. It was found that the back-propagation pressure wave was not synchronous in the upstream single-tube air inlet. Its synchronicity was a little lower in position than the detonation wave's and improving characteristic with increasing frequency. Back-pressure waves increased the period of pressure oscillation in the common air inlet and pressure rise occurred twice in this period. The single tube firing system showed that the flow field in the non-detonation chamber was the influence of the diffracted wave and the upstream-propagating pressure wave. In comparison with the dual-tube firing system, the single tube firing system is more effective to reduce the pressure disturbance in the common air inlet. Chao

Wang et al. [14] conducted an experiment on continuous rotating detonation (CRD) using room-temperature hydrogen and vitiated air as reactants. Based on high frequency pressure from PCB sensors, analyzed the propagation mode, velocity and propagation direction of detonation wave. They were found two types of detonation, continuous rotating detonation wave (CRDW) and detonation wave (DW). CRDW and DW were traveling azimuthally and axial direction within annual combustor. These waves could be sustained under a high total temperature of air. Four different combustion patterns existed in CRDW, namely, one wave in homo-rotating mode, two waves in homo-rotating mode, one couple in hetero-rotating mode and two couples in hetero-rotating mode. DW propagated axially like pulse detonation engine (PDE) and do not require repeated ignition. Three out of five combustion patterns, are similar to room-temperature oxidizer, other two are different (the two couples in hetero-rotating mode and downstream started pulse detonation). DW propagated axially upstream with high velocity, and worked with higher frequency than PDE, but lower than CRDW. The results also showed that DW could be sustained steadily and continuously in all five patterns within the annular combustor without repeated ignition. Lu Jie et al. [15] conducted a series of experiment to find out the feasibility of a pulse detonation turbine engine with a pulse detonation combustor (PDC). Gasoline and air used as fuel and oxidizer respectively to investigate back pressure waves and the operating characteristics of a four-tube two phase PDC. Under different firing patterns, a four-tube two phases PDC was examined successfully. In this experiment, two different firing patterns, namely, all tubes firing sequentially and all tubes firing simultaneously were conducted under frequencies range from 5 Hz to 25 Hz. The results showed that at all ranges of firing frequency, the average peak pressure under the sequential firing pattern were much lower (half) than under the simultaneous firing pattern. The operating frequency was increased, the peak value under the sequential firing pattern and the average peak pressure under the simultaneous firing pattern both increased. In general, the operating frequency increased then the percentage of relative peak pressure tends to reduce. Tube-to-tube investigation showed that under the sequential firing pattern, the back-propagated pressure waves propagated upstream and diffracted into the adjacent tubes. In tube 1, average peak pressure and percentage of the relative peak pressure of the diffracted waves increased with an increase in frequency. The maximum and minimum percentage of relative peak pressure in tube 1 was 23.7% (20 Hz) and 7.8% (25 Hz) respectively. The diffracted waves at a higher operating frequency worked adversely of the adjacent tubes. Peng Changxin et al. [16] conducted a series of experiment to better understanding of the performance of PDE-ejector with converging nozzle. A gasoline-air PDE-ejector was quantified by thrust measurements at four different frequencies of 8 Hz, 10 Hz, 12 Hz and 15Hz. In this experiment,they investigate the effect of single ejector length and axial location on thrust augmentation. The results show the largest thrust augmentation was up to 1.8 and the single ejector with L/D of 2 shows the maximum thrust augmentation occurred at a downstream placement of +1 tube diameter. The results also indicated the single ejector was very sensitive to axial placement. Two-stage and three-stage ejectors were also investigated and results indicated that flow area between two stages and overlap ratio should not be too large. Two-stage ejector was not as sensitive as single-stage ejector to axial placement. Performance of three-stage ejector was better than two-stage ejector, but worse than single-stage ejector in same working conditions.Li Xiaofeng et al. [18] did the experimental work to investigate the key factors on the powerful extraction of a turbo charger turbine driven by a pulse detonation combustor (PDC). Gasoline-air mixtures used to operate PDC-turbine hybrid engine. Turbocharger turbine had a nominal mass flow rate of 0.6 kg/s and 50000r/min. The results show that the optimal equivalence ratio of air and fuel mixtures is 1.0168, maximum speed of engine turbine and the highest flow rate of the compressor of the engine ignition frequency of 5 Hz. The momentum difference per unit area between the turbine inlet and outlet, and the velocity of the gas at the turbine inlet played an important role in the power extraction and the speed of the turbine, while little effect of peak pressure detonation. Equivalence ratio and the transition structure between PDC and turbine also play an important role for power extraction. The equivalence ratio affects the velocity, intensity and stability of detonation wave and the transition structure changed the pressure curve of the detonation wave. This experimental work showed that performance of PDC-turbine hybrid engine can be enhanced by enlarging the momentum difference per unit area through designing an appropriate transition structure.Quan ZHENG et al. [19] did an experimental research to study the propagation mechanism of continuous rotating detonation wave. An experiment was conducted with tangentially installed hydrogen/oxygen pre-detonation tube using a tilt slot injector structure. Collecting and analyzing the pressure curve and propagation mechanism of rotating detonation wave. Experimental results show that the experiment was successfully conducted and achieved the stable rotating detonation wave in CRDE with the equivalent ratio of 0.93. The range of the propagation frequency of the rotating detonation wave and corresponding velocity were 5200 Hz to 5500 Hz and 1518.5 m/s to 1606.1 m/s, which is closer to the theoretical value. An exit detonation flame appeared light blue and shorter than the deflagration flame with unpleasant sound. In this experiment, different process such as the initiating process, the shutdown process, and the detonation wave propagation process was analyzed and grouped into three propagation modes: rotation, reversal and bifurcation.CHEN Wenjuan et al. [20] investigated a series of experiment to find out the effect of nozzle on the thrust and inlet pressure of a multi-cycle air-breathing pulse detonation engine (APDE). The gasoline - air mixture was used in an APDE with 68 mm in diameter and 2050 mm in length. Different type of nozzles like Straight nozzle, converging nozzle, converging-diverging nozzle and diverging nozzle were used to conduct this experiment. The results show that diverging nozzle and converging-diverging nozzle gave better thrust augmentation than other nozzles. The larger expansion ratio of diverging nozzle and larger throat area of converging-diverging nozzle have the largest thrust augmentations on the range of 20% to 40% of testing frequencies. The mass flow rate of inlet air increased with the increasing frequencies. At each operating frequency, filling pressures and average peak pressures of an inlet of diverging nozzle and conversing-diverging nozzle with the larger throat cross-section area are higher than other two nozzles. It also indicates that near the thrust wall, the pressure increases with increasing in an order from without nozzle, diverging nozzle, straight nozzle, converging-diverging nozzle to converging nozzle. Y. H. Wang et al. [21] did an experimental studied to find-out the breathing phenomenon in continuous rotating detonation engine (CRDE). Hydrogen and oxygen are used as fuel and oxidizer in CRDE and tested in the exhausting system of length 2m, inner diameter 78mm and a vacuum tank of 1.36 m3. In this experiment, they found two types of breathing phenomenon, Low Breathing and Deep Breathing. Changing the breathing phenomenon caused by the mass flux of working medium which created pressure change in the combustor. Low Breathing created weaker detonation with low velocity and smaller number of rotating detonation waves than the number of steady detonation waves. Deep Breathing created reverse DDT with a subsonic velocity. The closed loop system can reduce the breathing phenomenon, if the pressure changes in the combustor could be fed upriver to change the mass flux of working medium quickly. RDE creates strong thrust with high efficiency, used in the Aerospace industry. Zhen-Cen Fan et al. [22] conducted a series of multi-cycle experiments to study the beneficial effect of preheating and adding additives in liquid kerosene-oxygen pulse detonation rocket engines (PDREs). To determine the geometrical effect on the heating efficiency, examined five concentric –counter –flow heat exchangers based on active cooling. The results show that the efficiency of heat exchanger was remarkable to utilize the waste heat of the engine. The optimum length and annular thickness of heat exchanger were 300 mm and 5 mm respectively. During preheating of heat exchanger, the kerosene temperature rose from 25°C to 250°C in 140 sec and also improves the evaporation process. PDRE with heat exchanger worked without fuel injector and operation life of detonation tube was extended due to the active cooling. The results show that the aid of kerosene preheater reduced the detonation initiation time and a fully-developed detonation wave achieved at 250 mm away from the thrust wall. By adding additives to liquid kerosene also reduced the detonation initiation time from 0.75 ms to 0.34 ms and improve fuel detonation. For further improvement of PDRE, advance material and more additives can be tested to increase the PDRE operation life and to decrease coke deposition respectively.Xing-tao Wang et al. [23] did an experimental research on the temperature distribution along the combustor and the effect of natural cooling and jet impinging cooling in an air-breathing kerosene/air detonation combustor. The experiment conducted at various operating frequencies range from 10 Hz to 50 Hz. The results show that the temperature distribution under natural cooling condition is non-uniform and the hottest region of combustor appears where transition (deflagration to detonation) takes place. The number of detonation waves increased with increasing frequency, which raised the temperature inside the combustor liner. Increment in temperature at higher frequency is lower than that at lower operating frequency. If the coolant flow rate increased, the maximum temperature on detonation combustor liner is decreased. The impinging distance between the jet orifice tube and circular liner plays an important role in temperature distribution.Jian-Ling Li et al. [24] did a series of multi-cycle detonation experiment to improve the performance of the pulse detonation rocket engine (PDRE). Liquid kerosene, oxygen and nitrogen were used as fuel, oxidizer and purge gas respectively. Three spiraling internal grooves: semicircle, square and inverted-triangle grooves were tested. The experimental results show that spiraling grooves increase the efficiency of DDT and operation time of PDRE. Under all tested frequencies spiraling semicircle groove increases the thrust performance. The flow loss can be minimized by shortening the spiraling groove length. It shows lower flow loss and better thrust performance than Shchelkin spiral. Aiding of preheated kerosene can reduce the detonation initiation time for liquid kerosene and achieve a fully-developed detonation wave away from igniter 4.67 times the diameter of the detonation tube. The detonation initiation time also decreased by adding additives to liquid kerosene from 0.75 ms to 0.34 ms.The detonation pressure decreases to certain value and the plumb temperature rises with increasing of operating frequency. The fill fraction can enhance the specific impulse of PDRE.

3. SCOPE OF FUTURE RESEARCH

1. The detonation combustion wave can be using orifice plates and multiple reflections in detonation tube.

2. Using multi-injector system, detonation wave can be simulated.

3. At different frequency of detonation wave, heat transfer can be analyzed in detonation tube.

4. To improve the propulsion performance of pulse detonation engine, optimizing the detonation parameter such as detonation wave pressure, temperature, density, and species mass fraction by using different optimization technique.

5. The detonation combustion can undergo experimental approach with different fuel utilization in pulse detonation engine.

6. To analyze the effect of different internal grooves on detonation wave characteristics.

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