A Review of Cavitation in the Cooling Fluid of an IC Diesel Engine Due to Forces Generated in the Piston Cylinder Assembly

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Abstract: The leaked water directly enters the cylinder for combustion, which brings great difficulty to troubleshooting. After disassembly and inspection, it was found that the exhaust valve seat was corroded and perforated, resulting in water leakage. Therefore, the cavitation of the valve seat directly affects the reliability and service life of the diesel engine. The data indicated that as the water depth decreases and the temperature increases, the weight loss rate increases, reaches a maximum, and then decreases again. Moreover, the weight loss rate increases linearly with increasing suppression pressure. The results indicate that the designer should design the engine with a larger gap between the cylinder liner and the jacket, the cooling liquid temperature value should be outside the extreme corrosion range and prevent high cooling water pressure to avoid severe corrosion.

Keywords: Cavitation, Cooling fluid, Internal Combustion, Diesel Engine, Ansys, Vibrations.

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1. INTRODUCTION

Cylinder liner and body cavitation is one of the main causes of failure. With the increasing power, high speed, and low weight of diesel engines, cylinder liner and body cavitation has become increasingly serious. Numerous researchers abroad have proposed the theory of cylinder liner cavitation and provided analysis methods and preventive measures. Zhou Yu-kang proposed that cylinder liner damage is primarily caused by liner cavitation. That is, the impact caused by bubble rupture has the greatest impact on cylinder liner damage. In 1998, Japanese researchers began studying diesel engine vibration and analyzed the mechanism of cavitation. They proposed formulas to calculate the variation in cooling water pressure and cylinder liner vibration velocity, and performed finite element analysis of the liner and piston. The phenomenon of cavitation erosion of wet diesel engine cylinder liners is a major problem for designers and users of high-speed, high-performance diesel engines. This phenomenon has been recognized for approximately 65 years. Cavitation erosion damage to cylinder liners results from the collapse of cavitation bubbles produced in the cooling water as a result of liner vibration. The pressure generated by the collapse of cavitation bubbles is often so severe that it causes erosion damage to the liners. Cylinder vibration is primarily due to the impact of the piston against the cylinder wall as a result of its lateral movement through the cylinder clearance. This is due to the reversal of the direction of the transverse force component of the connecting rod force, i.e., piston knock.

Figure 1. Cavitation of exhaust valve seat

2. LITERATURE REVIEW

Joyner [1], Clegg [2] and Brun [3] reported pitting erosion in cylinder liners due to the collapse of cavitation bubbles on their surface. Speller and La Que [4] were the first to understand that cylinder liner damage is exclusively due to the collapse of cavitation bubbles. Leith [5] stated that "the area with the greatest pitting is on the waterside of the liner, exactly where the piston 'side-kick' occurs during the power stroke." Tests by Leith [5] and Hobbs and Rachman [6] showed that cavitation damage can be reduced by the use of commercial coolant additives. Mahle GmbH [7] reported that two main factors control the cause of cavitation in cylinder liners: coolant flow conditions and cylinder wall vibrations.

Yu-Kang et al. [8] reviewed published research on the problem of cavitation erosion in wet cylinder liners of diesel engines. They discussed the conflicting findings in this research. When severe cavitation erosion of the cylinder liner occurs, complete penetration of the cylinder liner surface occurs, and engine oil will flow into the cooling water when the engine is running and the reverse will occur when the engine is stopped. This will reduce the engine life and reliability. Kessler et al. [9] performed a numerical study to analyze the water flow inside high-speed diesel engine, in order to determine possible cavitation regions, which may reduce the heat transfer efficiency. Based on their results, a modification in geometry leads to avoidance of cavitation occurrence in the water jacket regions.

Saleh et al. [10] have experimentally studied the effect of temperature on wear particles produced by vibratory cavitation erosion tests on Al99.92 in distilled water. Their results showed that the temperature of the test fluid affects both the erosion rate and the average particle size. Hattori and Tanaka [11] have experimentally studied the influence of temperature and air content on cavitation erosion using a vibratory apparatus. Their results indicated that erosion increases with increasing temperature, up to 50 °C, followed by a decrease with increasing temperature. Hattori et al. [12] and [13] studied the influence of liquid temperature on erosion and of liquid properties on cavitation erosion in liquid metal.

Chen and Leng [14] conducted ultrasonic vibration cavitation erosion tests to study the cavitation erosion protection performance of heavy-duty engine coolants. They concluded that increasing the ultrasonic vibration test time reduced the cavitation erosion protection performance in cast iron. Obviously, there is little published information on the various factors affecting cavitation erosion in cylinder liners. This is because much of the research has focused on the resistance of materials to cavitation erosion and its relationship to various physical and metallurgical properties.

Furthermore, it appears that most measurements were performed in vibratory setups with conditions very different from those of actual engine operation. Apparently, a thorough understanding of the factors, causes, and effects of cavitation erosion in cylinder liners is required to prevent serious damage to wet cylinder liners. Given this situation, the work, briefly presented here, aims to study the effects of the depth between the cylinder liner and the water jacket, as well as the static pressure and temperature of the cooling water, on cavitation erosion. Furthermore, the present study is carried out using a simple vibrating device under test conditions that practically simulate the actual operating conditions of wet cylinder liners in diesel engines.

3. CAUSES OF VALVE SEAT CAVITATION

Exhaust valve seat cavitation primarily manifests itself as the formation of needle-like holes on the back surface of the seat, in contact with the coolant. As gas dissolves in the coolant, when high-frequency vibration of the cylinder liner reduces the local coolant pressure to a critical value, the dissolved gas separates into bubbles, which flow toward the high-pressure zone. Collapse occurs when the pressure exceeds the bubble pressure. The bubbled gas redissolves in the coolant, and its volume suddenly decreases. The coolant moves toward the center of the bubble at high speed, producing a water hammer that generates a high impact force and high temperature, propagating at supersonic speeds in the form of pressure waves. When it acts on the exhaust valve seat, it produces high impact, compression, and high temperature. Under the repeated action of this force, the valve seat surface fatigues and gradually crumbles, presenting pits and pores, and gradually expanding as cavitation progresses. Factors affecting exhaust valve seat cavitation in diesel engine cooling water system include: cooling water temperature, cooling method, cooling water cavity structure and arrangement, and cooling water cavitation corrosion, etc., but the degree of influence is not the same.

3.1. The influence of cooling water temperature

The temperature of a diesel engine's coolant is closely related to the degree of cavitation. Each diesel engine has a specific temperature at which pitting is most likely to occur. Excessively high coolant temperatures will accelerate the corrosion process, but maintaining them too low for prolonged periods is also inappropriate. Too low a temperature will lead to negative consequences such as poor combustion, carbon deposits, increased wear, and higher fuel consumption. As the water temperature increases, cavitation damage decreases.

3.2. The influence of cooling method

There are two types of cooling methods for diesel engines: an open system and a closed system. The open system uses seawater directly as a coolant. To prevent salt buildup in the seawater due to heating, it is necessary to maintain the temperature of the cooling water, as this temperature promotes cavitation. Furthermore, cooling water, with its high salt content, is a strong electrolyte that increases electrochemical corrosion of the exhaust valve seat. Seawater also contains a large amount of gases and impurities that cause direct chemical corrosion of the exhaust valve seat. Therefore, with an open system, cavitation of the exhaust valve seat is more likely and develops rapidly. In a closed system, cooling water temperature and pressure can be increased and maintained high. With a closed system, softened and purified water can be used without requiring replacement for an extended period, and additives can be added to reduce pitting corrosion. Therefore, the closed method can effectively reduce the occurrence and development of cavitation on the exhaust valve seat.

3.3. The influence of cooling water cavity capacity and layout

The cooling water cavity channel is too narrow, increasing flow velocity and facilitating cavitation. Combined with the higher temperature and the repeated transmission of shock waves generated by bubble rupture, this will accelerate cavitation of the exhaust valve seat. Diesel engine design requires the water flow velocity in the cooling water cavity to be less than 2 m/s, the cavity width to be T=14%D or no less than 10 mm, and the water flow to be uniform. The water flow will not form stagnant water zones or vortices, which will help reduce cavitation erosion.

3.4. The influence of cavitation corrosion in cooling water cavity

Cavitation corrosion is characterized by clean surfaces on the valve seats and red pitting, common in internal combustion engines with closed-cycle freshwater-cooled systems. This corrosion is caused by cyclical pressure changes and high-frequency vibrations in the cylinder.

As the cooling water is compressed, the bubbles also compress. The water vapor present in the bubbles rapidly liquefies, and they burst. The surrounding water quickly disperses, generating a strong shock wave that acts on the surface of the valve seats. Although this impact force is small in time and space, it is generated continuously and repeatedly, acting on a very small area of the valve seat, causing plastic deformation and fatigue damage to the metal, which gradually decomposes, forming a hole. This cavitation corrosion develops slowly.

4. PATTERN OF VIBRATORY CAVITATION

Direct visual observations with the naked eye using strobe light through the transparent container indicated that a mass of bubbles (i.e., a cloud) appeared to radiate outward. Cavitation bubbles, which are thought to be produced radially, actually originate with a dispersed vertical distribution within a hemispherical space. At a depth of 2 cm, a cluster of bubbles appears in the center of the bottom of the container, which sometimes disappears but generally remains throughout the existence of the cloud.

5. EFFECT OF WATER DEPTH

This is because the bubbles collapse periodically and impact the sample surface at virtually the same point. The figure also shows that the maximum weight loss occurs at a depth of 1.1 cm. There are two possible explanations for this maximum erosion. First, the stress that creates cavities in a liquid attenuates with increasing distance from the vibrating end, so the number of cavitations would be expected to similarly decrease. However, the number of cavities formed, assuming a uniform distribution of nuclei, will depend on the volume of liquid between the sample and the vibrating end. Therefore, for small depth values, the number of nuclei in the volume of liquid between the vibrating end and the sample will restrict the total number of cavitations and, consequently, the erosion rate. Therefore, the maximum weight loss is expected to occur at a critical depth. In the second case, for cavitation to occur, liquid must re-enter the region between the vibrating end and the sample during each tension stroke of a vibration cycle. As the distance between the vibrating end and the sample decreases, the degree to which this occurs will decrease, and thus cavitation damage, as measured by sample weight loss, will be reduced.

7. CONCLUSIONS

Erosion tests indicated that weight loss increased with water depth, peaking and then decreasing. The rate of weight loss was also observed to increase and then decrease with increasing water temperature. The maximum damage temperature ranged from 50°C to 70°C, depending on the suppression pressure. Furthermore, the rate of weight loss increased linearly with increasing suppression pressure. The cavitation erosion results suggest that the designer should design the engine with a large depth between the liner and the jacket, that the engine coolant temperature should be outside the maximum erosion range, and that the use of high coolant temperatures should be avoided to prevent severe cavitation erosion.

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