Wear 342-343 (2015) 117–128

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Effects of cylinder head temperature and coolant velocity on the erosion behavior of water jacket in a diesel engine

Donghoon Kim [a,1], Joonsik Hwang [b,1], Sangwook Han [b,1], Choongsik Bae [b,*]

[a] Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology (KAIST), 291 Deahak-ro, Yuseong-Gu, Daejeon 305-701, Republic of Korea
[b] Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology (KAIST), 291 Deahak-ro, Yuseong-Gu, Daejeon 305-701, Republic of Korea

ARTICLE INFO

Article history:
Received 9 June 2014
Received in revised form
26 June 2015
Accepted 29 June 2015
Available online 8 July 2015

Keywords:
Erosion
Boiling
Water jacket
Scanning electron microscope (SEM)
Energy dispersive spectroscopy (EDS)
Computational fluid dynamics (CFD)

ABSTRACT

Effects of surface temperatures and coolant velocities on the erosion behavior of the engine water jacket was investigated in a test bench, which was designed to provide similar conditions to the water jacket in an engine. Rectangular specimens were fabricated using the water jacket material (aluminum alloy A356T5), then installed in the test bench and heated using fire torches. To evaluate the effects of two parameters, high speed camera, scanning electron microscope (SEM), mass scale, energy dispersive spectroscopy (EDS) were used. If any pits appeared as a result of erosion, the pit size growth rates were calculated. In addition, the single bubble collapse pressure was calculated using an erosion model to quantify the interaction between the bubble and the solid surface. It was found that higher mass reduction and surface changes appear under the condition of the higher surface temperature and the faster coolant velocity. Surface temperature affected the bubble and pit formation, while, the coolant velocity influenced the overall trend of mass reduction. As a result of calculation, the single bubble collapse pressure was order of 10^9 Pa. Detailed effects of two parameters on erosion behavior are discussed.

1. Introduction

Erosion is one of the most serious problems in many industries, including the marine and automotive industries; [1], whereby interaction between bubbles and a solid surface is the main erosion mechanism. As the main sources of bubble formation, cavitation and nucleate boiling are two physical phenomena where the consideration of bubble dynamics is of significant interest.

Cavitation refers to the generation and collapse of vapor cavities or bubbles in a liquid due to the local pressure fluctuations in the liquid which results from high speed flow or vibration. If the pressure suddenly falls below the vapor pressure, bubbles will form and collapse in the liquid [1]. Cavitation occurs in most hydrodynamic systems and turbo-machines. In most cases, cavitation causes undesirable effects such as modification in the hydrodynamic properties of flow and breakdown in the performance of the systems, the generation of vibration and noise over a wide frequency spectrum, erosion and material damages. Erosion on the solid surface by cavitation-induced bubbles is known as cavitation erosion [1–6].

Over the past few decades, much attention has been given to the analysis of bubble-induced erosion in marine propellers, turbines, pumps, diesel engine cylinder liners, and inside injectors. Horseshoe-shaped pits were observed in a pump impeller of a cyclic cooling water system and material properties were investigated to provide better resistance to the erosion in the design of marine propeller blades [2,3]. Erosion in an automotive engine has also been investigated. Cavitation erosion in a diesel engine cylinder liner is caused by the vibration of the liner. Cavities or bubbles are formed when the pressure reaches below the vapor pressure of the coolant, and collapse of these cavities impact the cylinder liner. Cavitation erosion can cause pits on the cylinder liner that subsequently lead to perforations through the liner wall. This may induce the coolant to mix with the lubricant oil. It was observed that failure may occur after 48,000 km if tap water is used as a coolant and at 240,000 km if a poorly maintained mixture of antifreeze, water, and supplemental coolant additive is used [5–7].

Bubble formation is also caused by boiling. If the formation of bubbles is caused by an increasing fluid temperature at a constant

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[*] Corresponding author. Tel.: +82 42 350 3044; fax: +82 42 350 5044/8820.
E-mail addresses: kimmbs@kaist.ac.kr (D. Kim), ippo@kaist.ac.kr (J. Hwang), sangwookhan@kaist.ac.kr (S. Han), csbae@kaist.ac.kr (C. Bae).
[1] Tel.: +82 42 350 3063; fax: +82 42 350 5023.

http://dx.doi.org/10.1016/j.wear.2015.06.021

List of symbols

C_p	specific heat at constant pressure (J/kg K)
D	specimen length (m)
h	convective heat transfer coefficient (W/m^2 K)
H	distance from the surface to the bubble (m)
k	thermal conductivity (W/m K)
L	characteristic length (m)
Nu	Nusselt number
P	pressure (Pa)
q	heat transfer rate (W)
R	radius of the bubble (m)
Re	Reynolds number
T	temperature (K)
γ	distance ratio of H and R
μ	viscosity (kg/s m)
ρ	density (kg/m^3)
v	velocity (m/s)

Subscript

jet	micro-jet
l	liquid phase
v	vapor phase
Y	Yield stress

Table 1
Bubble collapse pressures.

	Investigators	Bubble types	Methods for calculation or measurement of collapse pressure	Results
Theory	Rayleigh [14]	Spherical empty bubble	Incompressible	1.26×10^8 Pa at the stage of 1/20 of initial radius
	Hickling and Plesset [15]	Spherical gas bubble; initial gas pressure : 10^2 Pa	Compressible	$< 2 \times 10^9$ Pa
	Ivany and Hammitt [16]	Spherical gas bubble; initial gas pressure : 10^2 and 10 Pa	Compressible	6.77×10^9 Pa 5.82×10^{10} Pa
	Plesset and Chapman [17,18]	Vapor bubble	Based on micro-jet velocity	2×10^8 Pa
Experiment: Single bubble	Jones and Edwards [19]	Spark-induced hemispherical bubble	Piezoelectric pressure-bar gauge	10^9 Pa
	Fujikawa and Akamatue [20]	H_2 gas in a water shock tube	Pressure gauge; holographic interferometry	Time duration: 2–3 μs 10^9–10^{10} Pa
	Tomita and Shima [21]	Spark-induced bubble	Pressure transducer; Photoelasticity	Several 10^7 Pa
Experiment: Repeated bubble	Sutton [22]	Acoustic	Photoelasticity	Collapse time 2 μs 1.35×10^9 Pa
	Endo and Nishimura [23]	Vibration	Observation of pit on steel surface	1.2–1.4×10^9 Pa
	Sanada et al. [24]	Vibration	Holographic interferometry	$> 1 \times 10^9$ Pa
	Kato et al. [25]	Hydrofoil	Pressure-detecting film	Max. 5.0×10^{10} Pa
		Model propeller		Max. 10^{10} Pa
	Okada et al. [12]	Vibration	Pressure-detecting film	Max. 1.5×10^{10} Pa

pressure as a result of vaporization, then the phenomenon can be termed nucleate boiling. Boiling-induced bubbles on the heated surface show that the initial bubble growth is very rapid, but as the size increases the growth rate slows and the bubble attains a maximum diameter. The nucleation and bubble growth from a given nucleating site is a periodic process [7]. Then, bubbles will be departed from the heated surface and start collapsing. When the fluid on the surface flows, due to the shearing flow near the surface, the shape of the bubble changes from hemispherical to oblate shape. Then the bubbles are detached from their nucleation site and start sliding (parallel detachment) [8,9]. The population of bubbles were greatly influenced by flow velocity and pressure [7–10]. These boiling-induced bubble behaviors have been studied by many researchers. However, research on erosion due to boiling has rarely been carried out.

Bubbles are formed in the liquid or on the surface in hydrodynamic systems as a result of cavitation and boiling. In previous research, it was found that the interaction between bubbles and the solid surface is the primary mechanism that erodes the surface [6,11–13]. The repetitive growth and collapse of cavities generate stress pulses directed towards the solid wall; these pulses have sufficient magnitude to induce plastic deformation. Finally, the materials are removed from the surface.

Two possible theories of bubble-induced erosion have been suggested: the action of a shock wave arising during the bubble collapse period and the impact of a micro-jet (also called ‘water hammer’) generated at the moment of asymmetrical bubble collapse near a solid wall [4,5]. Some researchers have also defined the ‘collapse pressure’ or ‘impulsive pressure’ that is generated when bubbles collapse [12,13]. Table 1 provides an overview of research carried out on bubble collapse pressure measurements and theories. It can be seen that the bubble collapse pressures range from 10^9 to 10^{11} Pa. Furthermore, the relationship between the bubble collapse and the impact on materials has been illuminated by theories presented since the 1940s. One theory proposed that a liquid jet created by bubble collapse impacts the specimen surface, i.e. the primary reason for the impact on the surface is the liquid jets produced by bubble collapse. An empirical equation based on this micro-jet theory was devised in order to calculate micro-jet velocity [17,18].

Recently, erosion problems of the water jacket in diesel engine cylinder heads have been reported [26]. These problems have undesirable effects on the cooling system and result in deterioration in performance, maintenance, and emissions. Most erosion was observed in the high temperature regions in the water jacket indicating that the problem is closely related to the boiling induced by high heat transfer. In contrast, the effect of cavitation on the erosion can be excluded because the coolant velocity is not sufficiently high to induce cavitation phenomena in automotive engines. However, the coolant velocity should be considered