Seoul 2000 FISITA World Automotive Congress
June 12-15, 2000, Seoul, Korea

F2000A135

A New Approach of Cavitation Criterion Analysis for Automotive Water Pumps

Ki-chan KIM[* 1)], Jae-joon Lee[2)], Mun-soo Chon[3)], Jeong-eui Yun[4)]
[1), 2), 3), 4)] Engine test team, Tech Center, Daewoo Motors Co.,
199 Chongchon-dong Pupyong-gu, Inchon, 403-714, South Korea

ABSTRACT Cavitation, represents one of the most important limitations of all types of hydraulic machinery so as to automotive water pump, is the result of a reduction of the local pressure in a disturbed or flowing liquid to a level at, or near to, its vapor pressure. This paper focused on the criterion for the generation and prevention the cavitation for automotive water pumps. The test was performed on a water pump motoring rig and mixture of 50% antifreeze, ethylene glycol, with 50% water were used for the coolant. The test was carried out for various system pressure and for various coolant temperature which were controlled. The present study shows that the cavitation of water pump is strongly depending on the vapor pressure of the coolant and coolant temperature as well. It has been proved that for above a certain value of system pressure, surge tank pressure there were no cavitation for all tested water pumps and the influence of cavitation for efficiency, flow-rate of water pump was investigated as well.

Keywords: Cavitation, automotive water pump, vapor pressure, coolant

INTRODUCTION

Cavitation, a dynamic and thermodynamic process and represents one of the most important limitations for all types of hydraulic machinery, is the result of a reduction of the local pressure in a disturbed or flowing liquid to a level at, near to, its vapor pressure.

Theoretically, cavitation occurs when the liquid reaches vapour pressure, the release of any dissolved gases present may cause cavitation at some higher pressure. Even if air (gas) bubbles are not visible, sub-microscopic gas bubbles may provide the nuclei which cause cavitation at pressure above vapour pressure.

Many researchers and investigators have investigated about the generation, the understanding of the mechanism, and the prevention of the generation of cavitation in various ways.

Hosny et al. investigated about cavitation intensity measurements for internal combustion engines (1) [**]. He recommended that in order to reduce engine cavitation, pressure caps should be maintained at all times to insure adequate block pressure, failed thermostats (hereafter refer as t/stat) should be replaced promptly and engines should be operated at the higher range of coolant temperatures.

Hosny researched a detection method based on the detection of the severity of cavitaton bubble collapse into micro-jets (2). He found that the cavitation intensity is not just affected by the pressure drop to reach vapour pressure of the fluid, but also, the bubble dynamics process which finally affects the severity of the generated micro-jets and subsequently damage potential.

Up to now, the causes of the generation of cavitation is known as below (3, 4);

(i) gas release
(ii) low pressure boiling
(iii) both gas release & low pressure boiling (in most cases)

And the aspects of cavitation are

(i) thermodynamic aspect
(ii) coolant composition
(iii) air content effects, i.e., much air content can generate easier cavitation
(iv) chemical aspect (corrosion effect) related to pump material

The damages of cavitation to hydraulic machinery are as below;

(i) erosion damage (the best known damage)
- mechanical attach characterized by high intensity, relatively infrequent blows due to impingement of either shock waves propagated in the liquid and/or liquid microjets
- chemical attach which is accelerated by both high pressures and high temperatures and often by the presence of free oxygen and water vapour
- the development of electrical potentials which may accelerate chemical attack
- a slight possibility of thermal attack, with some evidence of temperatures sufficiently high to cause microscopic melting

* Corresponding author. e-mail : kichan@dwmc.co.kr
** Numbers in parentheses designate references at the end of paper

(ii) loss of efficiency
(iii) vibration

The reduction of the local pressure which is the cause of cavitation is generated as below reasons.

(i) additional pressure loses in suction line or in pump impeller
(ii) increasing liquid velocity with increasing pump speed →can be easily understood by Bernoulli equation.
(iii) flow separation in pump impeller

The present study is focusing on the experimental approach of the prevention of the generation of cavitation which reduces the efficiency of automotive water pumps by understanding the factor of the control of the coolant vapour pressure and water pump inlet pressure.

Since the passage of the coolant of the present study was closed circuit, various system pressure, surge tank pressure, represents the value of water pump inlet pressure which is one of dominant factors of the generation of the cavitation for automotive water pump. And temperature variations of the coolant were investigated as well.

EXPERIMENTAL APPARATUS

Experimental apparatus which was used for the present investigation is shown in Figure 1. During the test, engine and all other cooling required parts for cooling were installed.

In the Fig. 1, the solid lines with arrow represent flow direction of the coolant and the dashed lines represent the signals from the flow-meters to the data bucket.

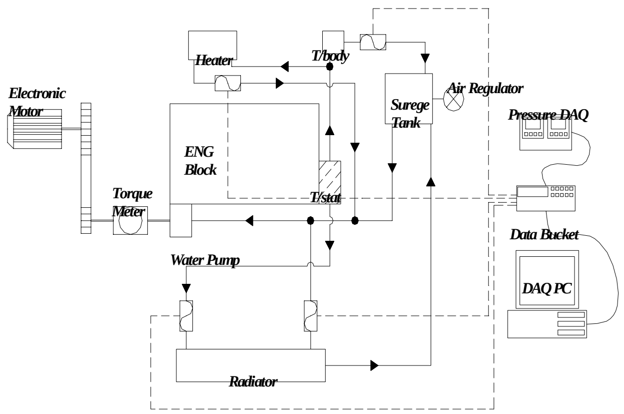

Figure 1 - Schematic diagram of test apparatus & DAQ system (for outlet temperature controlled type engine)

The tested water pump was driven by a electronic motor, which was controlled by a AC inverter, with flexible coupling after removal of the water pump pulley. A phase contrast type torque meter, which is better in precision to be compared with the well known strain gage type one, was installed to measure the driving torque of the water pump for further reasearch.

To modify the real combustion condition of engine, electronic heaters were installed into the each cylinder bore to heat the engine block to set the coolant temperature to the target or required value. The installed t/stat was adjusted for fully open to flow the coolant to radiator.

The flow-rate of water pump was measured by the sum of radiator flow, heater flow, throttle body flow, and the oil cooler flow (if any) with the conception of Eq. (1)

$$Q_{w/pump} = \sum(Q_{rad} + Q_{heater} + Q_{t/body} + Q_{oil\,cooler}) \qquad \text{Eq. (1)}$$

The pressure data acquisition from the engine parts were measured by pressure transducers (PDCR 912, Druck) and a data bucket (Hydra, Fluke), and analyzed in a DAQ PC.

Electromagnetic flow-meters (MAG-XE, Bailey Fischer & Porter) which use Faraday laws of induction were installed to prevent additional pressure drop of the coolant passage, i.e., the same diameter of the flow-meters were used with the coolant passage to desired positions, such as radiator, heater, t/body, and oil cooler (if any).

Eliminating of the generation of the air bubble in the coolant passage during the experiments, a new surge tank which was confirmed from a visualization test was manufactured by the author and installed for the test (5).

For the understanding of the generation of cavitation, system pressure which is represented by the pressure level of surge tank was controlled by using a 0 ~ 2.5 bar range air regulator (LRP-14/4, Festo) to pressurize and/or depressurize the system pressure. For this theory, raise of the system pressure means increment of the water pump inlet pressure.

The composition of the coolant for the test was Ethylene Glycol ($HOCH_2CH_2OH$, hereafter refer as EG) 50% with water 50% by volume like the general automotive engine coolant.

RESULTS AND DISCUSSION

PROPERTY OF COOLANT

Vapour pressure of liquid which is a dominant factor of cavitation has 4 aspects as mentioned earlier, such as thermodynamic aspect, coolant composition, air content effect, and chemical aspect.

The present study was concentrated on the effects of thermodynamic and coolant composition effect neglecting air content and chemical aspect. As a result, vapour pressure of the coolant for the present investigation can be as below;

$$p_{vapour} = f(temp,\ coolant\ composition) \qquad \text{Eq. (2)}$$

Figure 2 shows that the vapour pressure distribution of the coolant (EG) for various temperature and volume mixture ratio with water. It is clearly understood that cavitation is strongly affected by coolant temperature though in the same mixture.

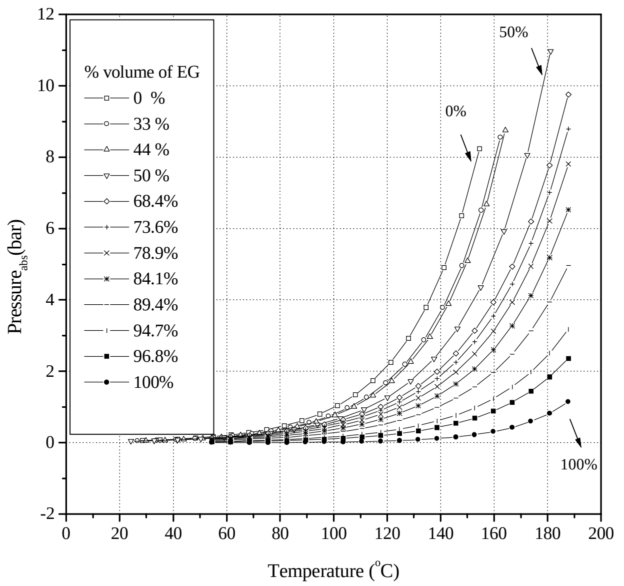

Figure 2 - Vapor pressure of coolant for various EG/Water % volume ratios and temperature

THE RELATION BETWEEN GENERATION OF WATER PUMP CAVITATION AND SYSTEM PRESSURE

For the experimental test, 4 types of engine were used, 1800, 2000, 2500, 3000cc, respectively. 1800 & 2000cc engines were the outlet temperature controlled type engine whereas 2500 & 3000cc engines were inlet controlled type.

In the outlet temperature controlled type engine, t/stat is installed at the exit where the heated coolant is flowing out to the engine block. The merit of this type is that the circuit is simple. While the demerits are that over/under shoot (hunting) can be easily generated, the expose temperature of t/stat is high, and the lack of durability of t/stat since the exit pressure of water pump is effecting in the opposite way to the t/stat. Figure 3, 4 show water pump flow-rate variation for the various system pressure of the 1800 & 2000cc engine, respectively.

The inlet temperature controlled type engine, 2500 & 3000cc, is that t/stat is installed at the inlet of the engine where the coolant flows into the engine block. This types of engine has the merits of less possibility of over/under shoot (hunting), low temperature of t/stat, and good durability of t/stat since the direction of t/stat opening is the same as the exit pressure of water pump. The demerits are complex coolant circuit and easy cavitation generation which is a result of pressure drop of water pump entry since the t/stat is positioned in the inlet way of coolant.

For those reasons it is clearly understood that the 1800 & 2000cc engines' water pump flow-rate, which are the outlet temperature controlled type, are linearly proportion to the speed of the engine at low system pressure to be compared with the inlet temperature controlled engines, 2500 & 3000cc.

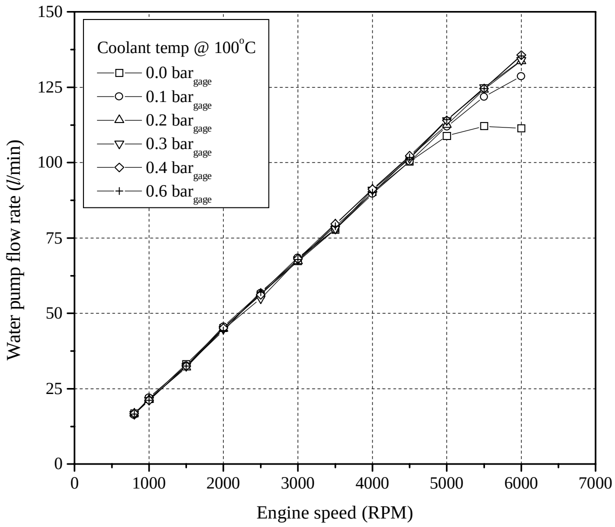

Figure 3 - Water pump cavitation criterion for various system pressure for constant coolant temperature (1800cc ENG)

The understanding of the generation of water pump cavitation is based on theoretical analysis of centrifugal pump. Flow-rate of automotive water pump is proportional to the speed of water pump from the theory of centrifugal pump velocity triangle. The assumption for the above theoretical analysis is that there is no flow separation through the coolant passage.

$$u_1 = \frac{\pi d_1 N}{60},\ u_2 = \frac{\pi d_2 N}{60} \text{ [m/sec]} \qquad \text{Eq. (3)}$$

(where, u_1 : impeller entry velocity,
u_2 : impeller exit velocity,
d_1 : impeller entry diameter,
d_2 : impeller exit diameter,
N : speed of water pump [rpm])

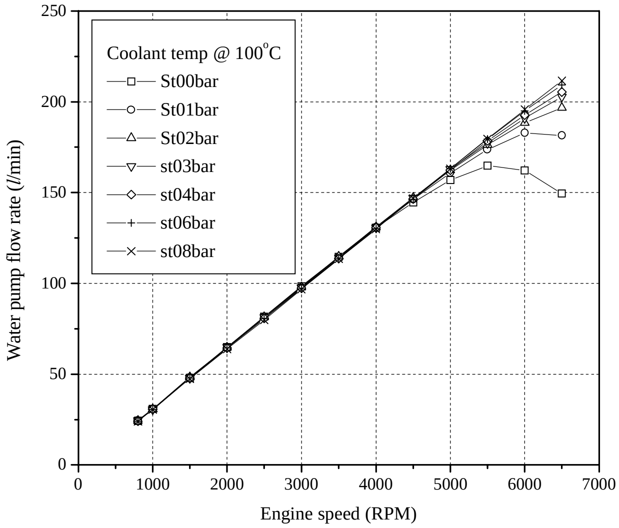

Figure 4 - Water pump cavitation criterion for various system pressure for constant coolant temperature (2000cc ENG)

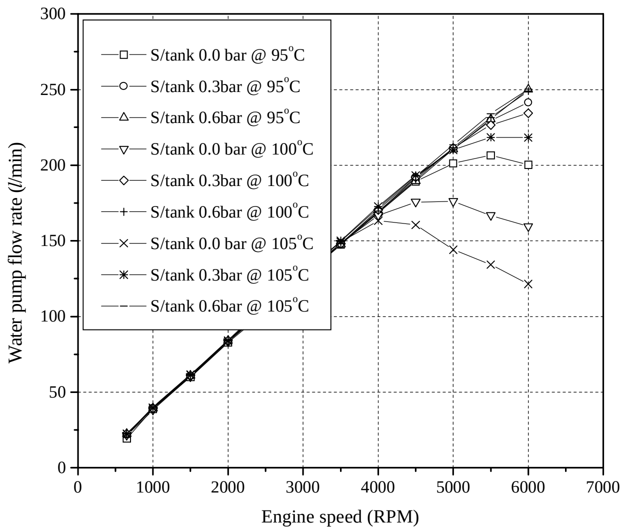

Figure 5 - Water pump cavitation criterion for various system pressure and various coolant temperature (for the 2500cc ENG))

The radian velocity of impeller entry is

$$c_{r1} = u_1 \tan \beta_1 \qquad \text{Eq. (4)}$$

(where, β_1 : impeller entry angle [deg])

From continuity Eq

$$Q = A_1 c_{r1} = A_2 c_{r2} \qquad \text{Eq. (5)}$$

(where, Q : water pump flow-rate
A_1 : pump inlet area,
A_2 : pump exit area)

i.e.,

$$Q_{water\ pump} \propto N_{water\ pump} \qquad \text{Eq. (6)}$$

Thus, under the assumption of no flow separation, one can define the generation of cavitation by the flow-rate of water pump.

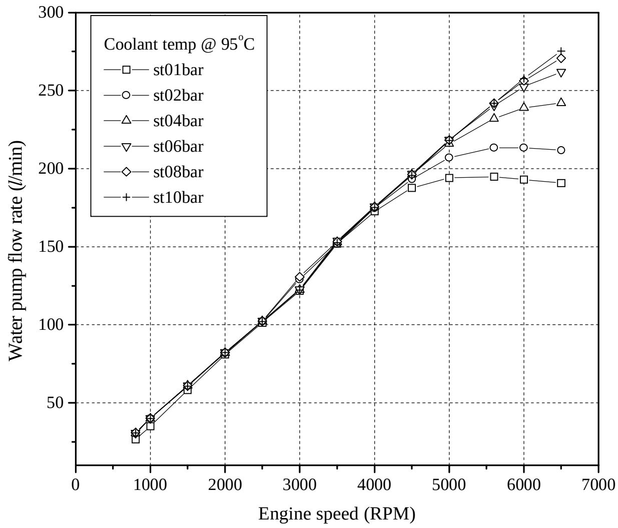

Figure 6 - Water pump cavitation criterion for various system pressure and constant coolant temperature (for the 3000cc ENG))

THE RELATIONSHIP BETWEEN THE CONDITION OF THE CAVITATION GENERATION FOR VARIOUS COOLANT TEMPERATURE

The vapour pressure of coolant depends on the mixture of antifreeze with water which is can be seen from Eq. (2). In the present study, constant volume mixture of coolant (EG 50% / water 50%) was used like general automotive coolant, and the experimental tests were carried out to figure out the relationship between the conditions of the caivtaion generation for various coolant temperature.

In the case of constant system pressure, water pump flow rates were varied with the change of the coolant temperature which can be seen Figure 7.

One can notice that the lower the system pressure, the easier cavitation inception state can be formed with the variation of the coolant temperature and this phenomenon can be found the variation of the coolant vapour as shown in Figure 2. As the coolant temperature goes high, the severe changes of the vapour pressure is occurred. The trends were shown through the investigation for all the tested engines regardless to the types of the temperature control way and the displacement of engine.

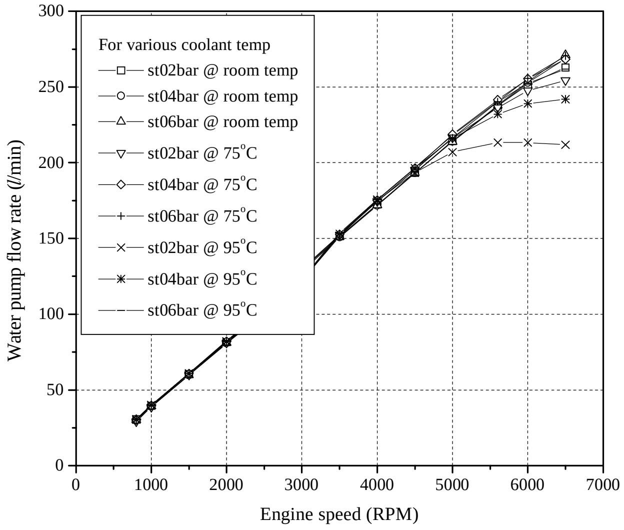

Figure 7 - Water pump cavitation criterion for various system pressure and various coolant temperature (for the 3000cc ENG))

COMPARISON OF WATER PUMP INLET PRESSURE AND VAPOUR PRESSURE OF THE COOLANT

As mentioned earlier, theoretically and generally it can be noticed that cavitation is generated when the liquid reaches vapour pressure as a result of local boiling of liquid. But practically, cavitation is generated at somewhat above the vapour pressure of the liquid.

Many dimensionless parameters are used to analyze cavitaion, such as Thoma sigma, NPSH, NPSE, suction specific speed, etc (5). NPSH, the available head and measured at the suction opening of the pump, is the most useful one.

Since one of the immediate visible effects of cavitation is loss of head, the minimum Net Positive Suction Head Required (NPSHR) to suppress cavitation was related to pump head at its design value.

And it is necessary to differentiate between NPSHA (NPSH available) and NPSHR (NPSH required). NPSHA, which is a characteristic of the system in which a centrifugal pump works, represents the difference between the existing absolute suction head and the vapour pressure at the prevailing temperature. NPSHR, which is a function of the pump design, represents the minimum required margin between the suction head and vapour pressure at a given capacity. From pump design, NPSH can be theoretically declared as below;

$$NPSH = (1.04 + \sigma_b)\frac{c_{mx}^2}{2g} + \sigma_b \frac{u_1^2}{2g} \quad \text{Eq. (7)}$$

(where, σ_b : vane cavitation factor,

$$\sigma_b = \frac{p_x - p_v}{\left(\dfrac{\gamma W_1^2}{2g}\right)}$$

c_{mx} : meridional component of absolute velocity at a variable point

p_x : pressure level at a variable point (critical point)

p_v : vapour pressure of the coolant

W_1 : relative velocity at pump blade entry)

Figure 8, 9, 10, and 11 show pump inlet (entry) pressure distributions for various system pressure. In the Figures, solid lines without symbols represent the vapour pressure of the coolant at test temperature.

Figure 8, connecting with Figure 4 the outlet controlled temperature type 2000cc engine, shows that above 0.3 bar, flow-rate of water pump is linearly proportional to the engine speed, i.e., cavitation was prevented as denoted in Eq. (6).

Figure 9, 10, and 11, connecting with Figure 5 the inlet controlled temperature type 2500cc engine, show the variation of water pump inlet pressure for various coolant vapour pressure which is dependent on coolant temperature.

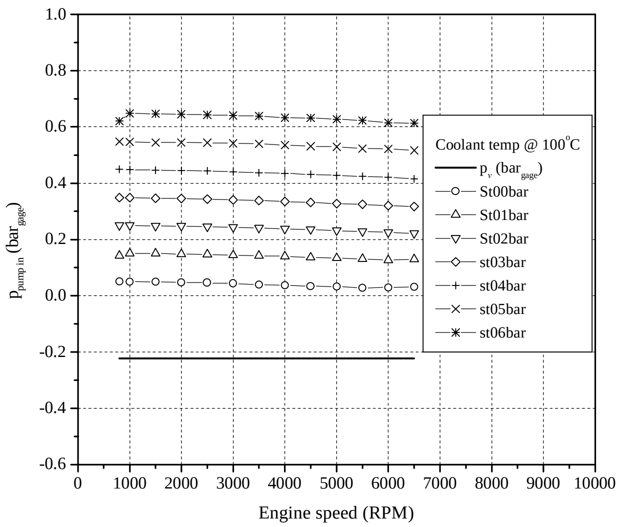

Figure 8 - Cavitation detection by using a pump inlet pressure & coolant vapour pressure (for 2000cc ENG)

Applying Eq. (7) to the result of Figure 8, 9, 10, and 11, one can analyze the reason of certain margin above the coolant vapour pressure. Calculating of the exact value of NPSH will remain for further investigation. When applying Eq. (7) to the result of the present study, one has to concern the coolant system layout so as to the possibility of bubble generation in the coolant flow circuit, separation for example.

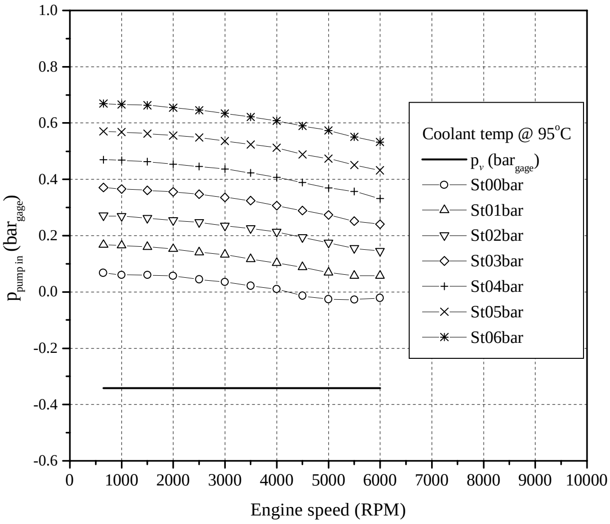

Figure 9 - Cavitation detection by using a pump inlet pressure & coolant vapour pressure (for 2500cc ENG)

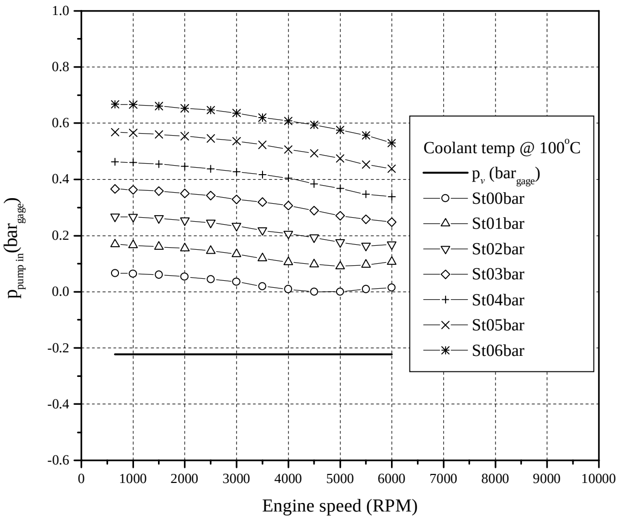

Figure 10 - Cavitation detection by using a pump inlet pressure & coolant vapour pressure (for 2500cc ENG)

CONCLUSION

The present study is focused on the effects of coolant vapour pressure and temperature to the generation of cavitation, which is a harmful limitation to water pump

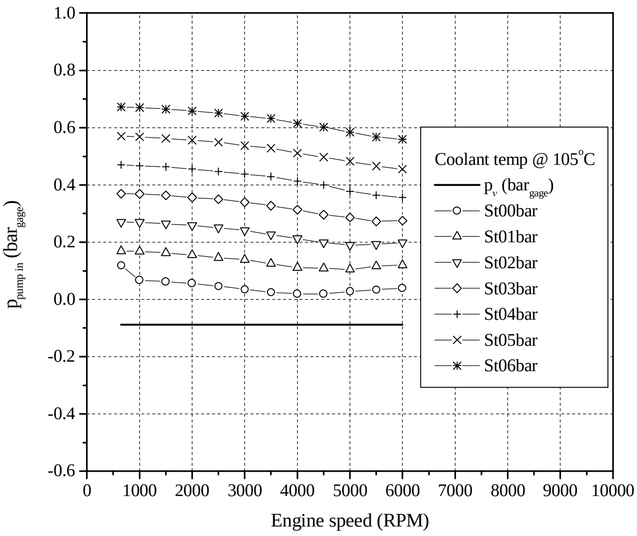

Figure. 11 - Cavitation detection by using a pump inlet pressure & coolant vapour pressure (for 2500cc ENG)

efficiency, and to the inlet pressure of the water pump for various engine displacements by experimental approaches.

The conclusions for the present investigation are as follow;

- Cavitation is strongly affected by coolant temperature and coolant compositions.
- Outlet temperature controlled type engines have somewhat strong resistance than inlet temperature one.
- The lower the system pressure, the easier cavitation inception state can be formed
- The generation of cavitation can be defined by the flow-rate of water pump under the theoretical analysis

REFERENCES

[1] "Cavitation intensity measurements for internal combustion engines", Diaa M. Hosny et al, 1996, SAE 960884

[2] "Real time cavitation detection method", Diaa M. Hosny, 1996, SAE 960878

[3] "Car cooling systems and their pumps", Farrokh Eimieh, M.A. Degree, 1975, University of Southampton

[4] "The effectiveness of degassing of surge tank by changing bypass ports positons", Kckim et al., 1998, Technical review '98, Daewoo Motors Co. Tech Center, 1998, pp. 277~282

[5] "The performance of water pumps for automotive cooling systems", Mahmoud Hadji-Sheikh, M.A degree, 1979, University of Southampton