An Experimental Investigation on the Contamination Sensitivity of an Automotive Fuel Pump

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This study addresses the contamination sensitivity test of a typical fuel pump for an automotive vehicle. The objective of the study is to find the contamination sensitivity coefficient of a fuel pump on specific contaminant particle sizes so that an optimal fuel filter could be selected. To achieve the objective, the degradation of discharge flow rate of the fuel pump is measured under the experiments of various contaminants size ranges of ISO test dust up to 80 μm. The fundamental theory of contamination sensitivity is introduced and the contamination sensitivity coefficients are estimated using the experimental data. Maximum contamination sensitivity coefficient of 5 x 10^{-6} L/min · Ea is found in the contaminant size range of 40 μm ~ 50 μm. The magnified picture of the surface of vane disc reveals that the abrasive wear is the principal cause of discharge flow rate degradation. Hence, this study reveals that a high efficiency filter for contaminant particles especially in the size range of 30 μm ~ 70 μm especially should be used to maintain the service life of the fuel filter.

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1. Introduction

The tribological lifespan of a hydraulic pump is influenced by the design parameters, operational parameters, the oil parameters, and the degree of oil contamination. The design parameters include such things as the pump structure, specifications and tolerances. The operational parameters include pressure, flow rate, and temperature. Stability against oxidation and corrosion, and resistance to wear are the parameters of the oil. In addition oil contamination affects the useful life of a hydraulic pump.

As it can be observed in Fig. 1, the performance of the pump due to the contaminants is determined by the oil contamination level and the contamination tolerance which represents the characteristics of the pump.[1] The contamination level is represented by the number of contamination particles of each size in a unit volume of oil which is the contamination concentration, and the contamination tolerance can be verified through experiments testing the contamination sensitivity.

Contamination sensitivity refers to the decrease in the function of a mechanical part when it is exposed to a specifically contaminated environment. The amount of functional loss due to a specific unit contaminant is called the contamination sensitivity coefficient.[1] In the 1970's the hydraulic and pneumatic research lab at Oklahoma State University conducted most of the research related to the general contamination sensitivity of oil pumps.[2,3,4]

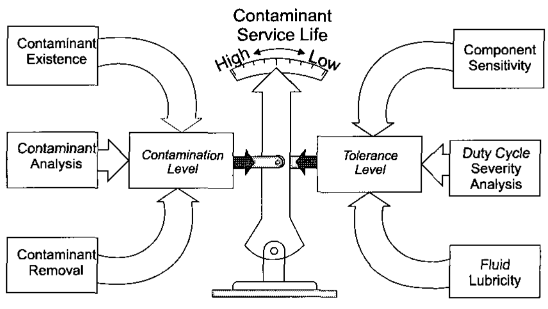


Fig. 1 Contamination control balance[1]

Research on contamination sensitivity of fuel pumps, due to the nature of fuel, requires equipment made from expensive material which are corrosion resistant and explosion resistant. Thus, only large companies such as Delco and Visteon were able to conduct such research and it was not introduced to Korea previously.

Solid contaminants in the fuel increase the wear on the fuel pump surfaces, making relative movements, causing internal leakage resulting in the reduction of the discharge flow rate. In addition, the erosion of the injector reduces the service life,[5] and the fuel spray characteristics are affected causing poor fuel economy and air pollution.[6] Thus, to improve the fuel efficiency and to reduce the exhaust gas of automobiles, it is necessary to maintain the function of the fuel filter and the cleanliness of the fuel according to the contamination sensitivity of the fuel pump. At Keimyung University a "Component Fuel Contamination Performance Test Stand" was developed and a series of experiments were conducted for the automotive fuel filter.[7,8,9] The objective of this research is to obtain the contamination sensitivity coefficient of a typical fuel filter of a Korean automobile through experiments. Later the results can be utilized to optimize the selection of filters to increase the service life of fuel filters.

2. Theory of Contamination Sensitivity

The critical performance parameters of the hydraulic pump which decline due to wear and contamination, are internal leakage and volumetric efficiency. The theory of contamination sensitivity of hydraulic pumps assumes that contamination particles of all sizes in the oil contribute to the reduction of discharge flow rate of the pump.[10] As time progresses the decrease in the discharge flow rate is represented by the product of the contamination sensitivity coefficient and the contamination particle exposure rate. The contamination particle exposure rate is the product of the flow rate and the density of the contamination particles, and the discharge flow rate reduction caused by a specific contamination particle size is as indicated in Eq.(1).

$$\frac{dQ_j(t)}{dt} = -S_j Q_j(t)\, n_j(t) \tag{1}$$

In Eq.(1), Q is the pump's discharge flow rate($ml/\min$), S is the contamination sensitivity coefficient($ml/\min \cdot unit$), n represents the contamination density($units/ml$), subscript j is the contaminant size order. In other words, $j = 1, 2, 3, \ldots, 9$ represent $0 \sim 5$ μm, $5 \sim 10$ μm, $10 \sim 20$ μm,. . . . , $70 \sim 80$ μm, respectively.

During the experiment contamination particles of specific sizes are crushed by the relatively moving surfaces of the fuel pump and density changes occur exponentially as indicated in Eq.(2).[10]

$$n_{j(t)} = n_{o,j}\, e^{-t/\tau_j} \tag{2}$$

Here, τ is the time constant (min.) obtained through the experiment, and the subscript o indicates the initial value.

Eq.(3) can be derived when Eq.(2) is substituted in Eq.(1).

$$\frac{dQ_j(t)}{Q_j(t)} = -S_j n_{0,j}\, e^{-t/\tau_j} dt \tag{3}$$

When Eq.(3) is integrated and reordered the following equation is obtained.

$$S_j = \frac{-1}{\tau_j n_{0,j}} \ln\left(\frac{Q_{f,j}}{Q_{0,j}}\right) \tag{4}$$

Here, the symbol f represents the field value.

Generally, the contamination sensitivity test[11] is conducted using nine different ISO test dusts[12]($0 \sim 5$ μm, $0 \sim 10$ μm, $0 \sim 20$ μm, . . . , $0 \sim 80$ μm) starting from the smallest size order. The major component of the test dust is silica and the distribution of the size and number of particles when 1 gram of particles are mixed in 1 liter of clean oil is indicated in Table 1.

It is assumed that all the contaminant particles in the oil contribute to the reduction of discharge flow rate of the pump. The contamination sensitivity coefficient($S_j, j = 1, 2, \ldots, 9$) for each contamination particle size order can be obtained by starting with calculating S_1 which is the smallest size particle and then successively calculating the rest. For example, the reduction of the discharge flow rate of a pump due to contamination particles in size of $0 \sim 10$ μm, is equivalent to the sum of the reduction of discharge flow rate caused by contamination particles of sizes $0 \sim 5$ μm, and $5 \sim 10$ μm.

Table 1 Test dust distribution: number of particles per milliliter in size order(I, μm) in one milligram per liter of size range (R μm)

I \ R	0-5	0-10	0-20	0-30	0-40	0-50	0-60	0-70	0-80
1-5	3167.3	2167.1	1692.1	1452.2	1357.4	1308.5	1282.7	1268.2	1257.9
5-10	0	653.99	510.65	438.56	409.64	394.89	387.10	382.73	379.61
10-20	0	0	162.33	139.33	130.14	125.46	122.98	121.59	120.60
20-30	0	0	0	21.153	19.758	19.046	18.670	18.406	18.309
30-40	0	0	0	0	5.0930	4.9097	4.8130	4.7583	4.7197
40-50	0	0	0	0	0	1.6729	1.6396	1.6213	1.6082
50-60	0	0	0	0	0	0	.66602	.65845	.65308
60-70	0	0	0	0	0	0	0	.30249	.30005
70-80	0	0	0	0	0	0	0	0	.15088

Thus, the contamination sensitivity coefficient of contaminant particles in size $0 \sim 5$ μm becomes

$$S_1 = \frac{-1}{\tau_1 n_{o,1}} \ln\left(\frac{Q_{f,1}}{Q_{o,1}}\right) \tag{5}$$

And the sensitivity coefficient for contaminant particles in the larger size ranges can be obtained by Eq.(6) as follows.[10]

$$S_j = \frac{-1}{\tau_j n_{o,j}} \ln\left[\frac{Q_{f,j^*}}{Q_{o,j^*}} - \sum_{i=1}^{j-1}\left(e^{-S_i n_{o,i}\tau_i} - 1\right)\right]$$

$$j = 2, 3, \ldots, 9 \tag{6}$$

In Eq.(6) j^* indicates the order of the jth size range of the contaminant particles($0 \sim 5$ μm, $5 \sim 10$ μm, . . . , $70 \sim 80$ μm) which is used for testing the contamination sensitivity. In other words, each of $j^* = 1, 2, 3, \ldots, 9$ indicates the test order using contaminant particles of sizes $0 \sim 5$ μm, $0 \sim 10$ μm, $0 \sim 20$ μm, . . . , $0 \sim 80$ μm respectively.

From Eq.(6) it can be seen that the contamination sensitivity coefficient of the pump is a function of the particle crushing time constant (τ), initial density of the contamination particle(n_o), and the reduction rate of the discharge flow rate(Q_f / Q_o). The sum of the flow reduction rate caused by all the contamination particles in the oil represents the pump's displacement efficiency. According to Finch[1,4], after testing 200 pumps the results indicate that the particle crushing time constant τ turned out to be 9 minutes regardless of particle type or size. Since the initial density of contamination particles can be controlled by the test condition and the reduction of the pump's discharge flow rate can be measured by experiments, the pump's contamination sensitivity coefficient can be calculated for each contamination particle size order.

3. The Experiment

3.1 Experimental Apparatus

Fig. 2 is the schematic of the test stand for measuring the contamination sensitivity of the pump. It consists of a reservoir, test pump, pump drive, contaminant injection system, heat exchanger, flow monitor, pressure gage, thermometer, and a clean-up control filter.

In this study, the experiment for the sensitivity of the fuel pump is based on Lee's[7,8,9] "fuel system contamination function tester" where the capacity of the injector is 500 ml , and the length to diameter ratio(L/D) is 10. The pump used in the experimental set up is an in-tank fuel pump for the Avante by Hyundai Motors. It is a fixed volume valve type pump actuated by a motor. The rated voltage is 12V and at a load pressure of 200 kPa, the minimum discharge flow rate must be 50 l/hr. The oil used in the experiment is the Stoddard Solvent[12] which was maintained at 20 ± 0.5 $^\circ C$ during the test. The particle coefficient analyzer LaserNet Fines-C[13] by Spectro Inc. was calibrated according to the ISO 11171[14] prior to the experiment.

Fig. 3(a) and Fig. 3(b) are the cut off view of the fuel pump and the attached fuel pump on the contamination performance tester respectively.

3.2 Experimental Procedure

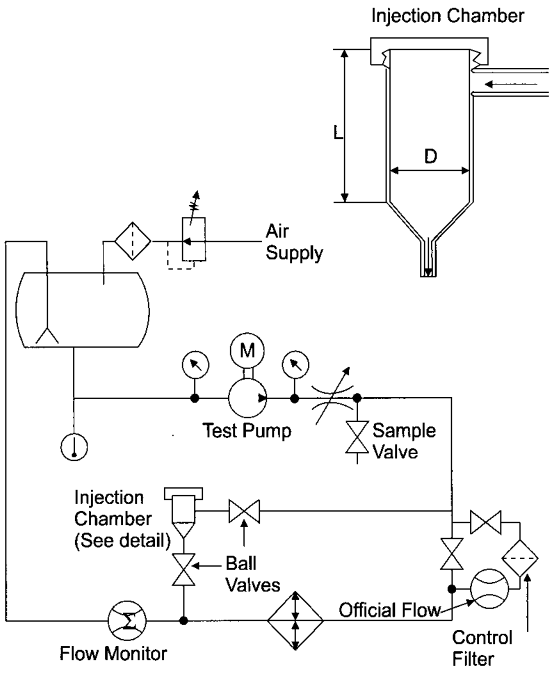
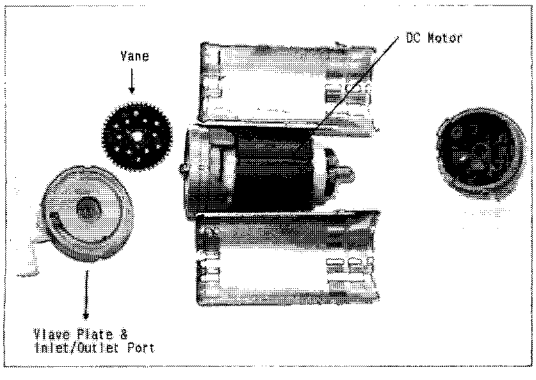
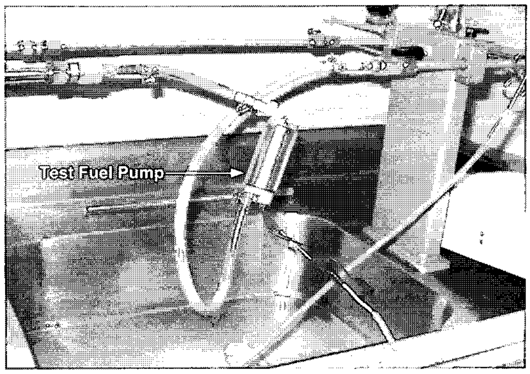


Fig. 2 Schematic of contamination sensitivity test stand for a fixed-displacement pump

1) Fill 4 *Ls* of the fuel to be tested in the orifice.
2) Activate the oil circulation pump and displace the oil at a rate of 5 *L/min*.
3) Circulate and flush the fluid until the contamination level becomes 10 *mg/L* (approximately 1,440 particles per ml which are larger than 10 μm).
4) Divert the flow from the clean-up filter so that it is directed to the pump contamination sensitivity tester.
5) Install the fuel pump.
6) Supply a rated voltage of 12 Vs to the fuel pump to activate it.
7) The rated discharge pressure of the fuel pump is set at 200 *kPa*. Use the throttle valve and operate the fuel pump to adjust the discharge pressure as indicated below. The following break-in procedure of the fuel pump is conducted prior to the contamination sensitivity test.
   a) 15 minutes at 25 % of the rated pressure
   b) 15 minutes at 50 % of the rated pressure
   c) 15 minutes at 75 % of the rated pressure
   d) 60 minutes at 100 % of the rated pressure
8) After completing step 7) of the experiment, the pump discharge flow rate(reference flow rate, Q_r) is measured and recorded. This is the initial flow rate $Q_{o,1}$ just before starting the contamination sensitivity test indicated in Eq.(4).



(a) Cutoff view of test fuel pump



(b) Fuel pump in test stand

Fig. 3 Configuration of test fuel pump

9) The density of each injected contaminant is standardized to 300 *mg/L*. Thus, the weight of the contaminant particle for each size order can be calculated as follows.
   $g_j = 0.3 g/L \times 4L = 1.2(g)$
10) A slurry of contaminant particles for each size order is prepared(0 ~ 5 μm, 0 ~ 10 μm, 0 ~ 20 μm, . . . , 0 ~ 80 μm): 50 *ml* of test fluid and 1.2 *g* of contaminant particles are shaken and mixed in a clean bottle[15].
11) The pump is run at a rated discharge pressure of 140 *kPa*.
12) The ball valve is opened to mix the slurry of 0 ~ 5 μm contaminant particles into the system for 1 minute.
13) The fuel pump is operated for 30 minutes and the flow rate is measured in 5 minute intervals.
14) After 30 minutes the final discharge flow rate of the pump(Q_f) is measured and recorded.
15) Make sure that the orifice contains 4 *L* of test fluid. Then circulate it through the clean-up filter and flush it until the contamination level becomes 10 *mg/L* .
16) Return to step 9) and use the slurry with the next larger size of contaminant particles and repeat the experiment with larger contaminant particles in the size range of up to 0 ~ 80 μm.

3.3 Experimental Results

Fig. 4 displays the changes of the fuel pump discharge flow rate during the contamination sensitivity test as time progresses. As it can be noticed in Fig. 4 the discharge flow rate of the fuel pump diminishes from the initial flow rate of 1.403 $L/\min$ before starting the experiment to 0.534 $L/\min$ at the finish as the experiment progresses.

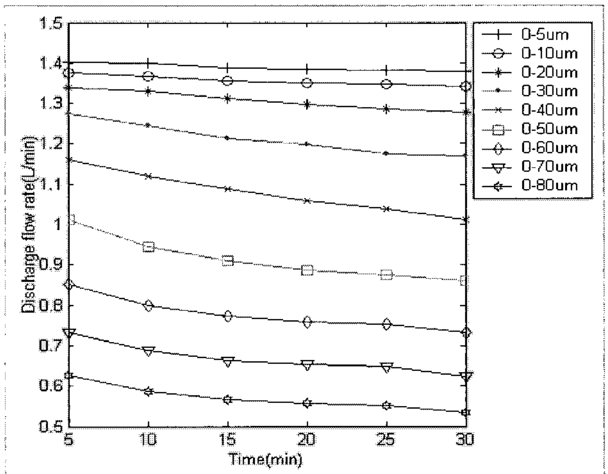
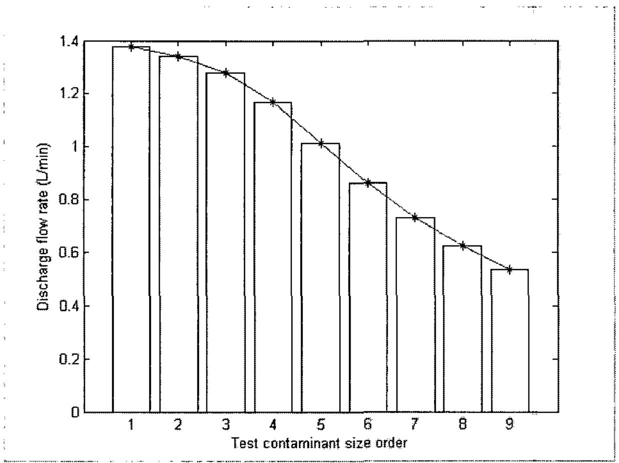


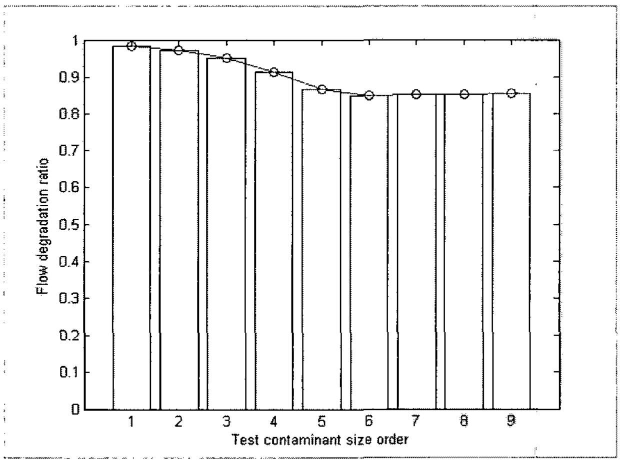
Fig. 4 Discharge flow rate variation in fuel pump contamination sensitivity test

The greatest reduction rate during the experiment can be found in the contaminant particle size range of 0 ~ 50 μm. This may be caused by the clearance between the outer diameter of the pump's vain and the inner diameter of the valve which is approximately 40 μm. Thus, contaminants with particle size of 40 ~ 50 μm compared to other particle sizes caused most of the abrasive wear during the relative movement of the newly designed pump resulting in an increased amount of inner leakage.

In Fig. 5(a) and Fig. 5(b) the final flow volume(Q_{f,j^*}) after the contamination sensitivity test and the ratio of the initial flow volume to the final flow volume($Q_{f,j^*}/Q_{o,j^*}$) for each contaminant particle size order(0 ~ 5 μm, 0 ~ 10 μm, 0 ~ 20 μm, . . . , 0 ~ 80 μm) are displayed. As it can be seen in Fig. 5(a) the final flow volume decreases as the experiment is continued using larger contaminant particle sizes. However as it can be noticed in Fig. 5(b), the ratio of the initial flow volume to the final flow volume($Q_{f,j^*}/Q_{o,j^*}$) decreases as the contaminant particle size order increases. It gradually decreases until it reaches particle size order 0 ~ 50 μm($j^*=6$) and then increases slightly. As it was indicated in Fig. 4, contaminant particles of sizes greater than 50 μm are too large to fit in a clearance of 40 μm between the outer diameter of the vain and the inner diameter of the valve thus the amount of abrasive wear during the relative movement is minor.



(a) Flow degradation curve, Q_{f,j^*}



(b) Flow degradation ratio curve, $Q_{f,j^*}/Q_{o,j^*}$

Fig. 5 Results of the contamination sensitivity test

Fig. 6 is the composite result of calculating the contamination sensitivity of the fuel pump using the test data from Fig. 4 and the result of substituting the values from Table 1 into equations (5) and (6). As it can be seen in Fig. 6 with contaminant particle size order 40 ~ 50 μm the greatest contamination sensitivity coefficient was found to be 5 x 10^{-6} $L/\min \cdot particle$.

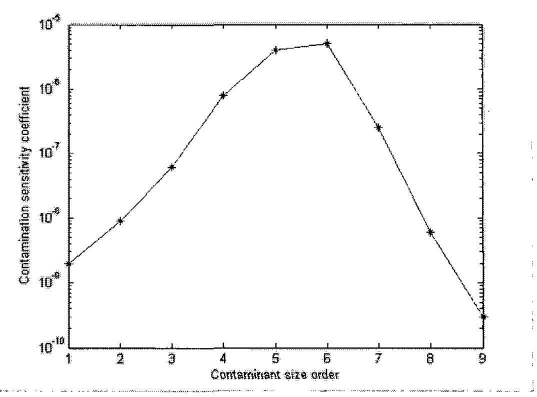
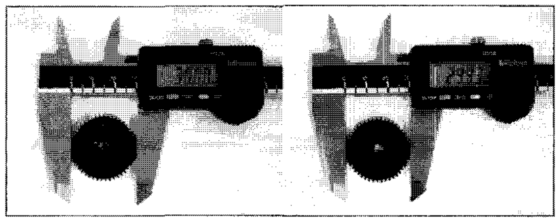


Fig. 6 Contamination sensitivity coefficient of fuel pump

Fig. 7(a), Fig. 7(b) show the vain disc plate before and after the contamination sensitivity test respectively. Before the test the outside diameter of the vain was 30.00 mm but after the experiment it reduced to approximately 29.93 mm(a reduction of 70 μm).

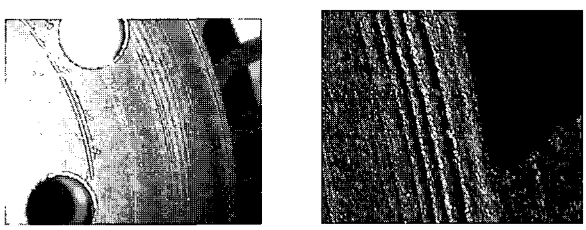


(a) Before the test (b) After the test

Fig. 7 Vane disc before & after the test

The results closely represent the findings by Fitch and Hong,[4] and Lee[16] who tested the contamination sensitivity of gear pumps where the clearance between the relatively moving surfaces is similar to the maximum contaminant particle sizes causing abrasive wear.

Also Fig. 8(a) and Fig. 8(b) are the enlarged views of the side of the disk enlarged 8 times and 20 times respectively to observe wear conditions. As it can be observed in the figure, abrasive wear is caused by contaminant particles scratching the disc surface.



(a) x8 (b) x20

Fig. 8 Disc surface pictures after the test

4. Conclusion

In this study a contamination sensitivity test was conducted for the most widely used Korean fuel pump. The contamination sensitivity coefficient was calculated based on the tests measuring the discharge flow rate of the fuel pump using a test fluid mixed with ISO test particles of various size ranges.

The discharge flow rate of the fuel pump changed initially from 1.403 $L/\min$ gradually reducing to 0.534 $L/\min$ at the end of the experiment. The flow rate decreased steeply during the test interval using the contaminant particle size order 0 $\sim$ 50 μm, and the maximum contaminant sensitivity coefficient was found at the contaminant size range of 40 $\sim$ 50 μm with a value of 5×10^{-6} L / min · *particle*.

After the experiment it was found that the outside diameter of the vain was reduced by 70 μm which is close to the largest size of the test particle(80 μm). The reduction of discharge flow rate, in other words the cause of the increase in the inner leakage, is due to the abrasive action incurring during the relative movement between the contaminant particles and the vain disc. This was confirmed by investigating the enlarged pictures of the vain disc surface.

Thus, to avoid the reduction of discharge flow rate and to increase the service life of the fuel pump, the proper filter must be selected and utilized. The fuel filter used in this study requires a highly efficient filter with a filtering range(β ratio[1]) for contaminant particles of size order 30 $\sim$ 70 μm. Further studies are being conducted on the proper selection of filters to increase the service life of the fuel pump based on past studies on filters[7,8,9].

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