

Analysis on Mechanism of Early Clogging in Suction Filter with Use of Ethanol Blended Fuel and Development of Long-life Filter

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ABSTRACT

The authors have developed a long-life suction filter to cope with fuels containing ethanol. In the fuel system of small motorcycles, the suction filter protects parts such as the fuel pump, injector, pressure regulator, etc. from dusts in the fuel. It is known that in conventional suction filters, when compared with neat gasoline, the filter life is shorter by 50% if it is used with a fuel containing 25% ethanol. In addition to the study on the correlation between the ethanol concentration and the dust dispersion in the fuel, our study has clarified how the early clogging occurs, i.e., the dusts dispersed in the ethanol-containing fuel coagulate again when passing through the multi-layered suction filter, and trapped predominantly by the lower-most layer having the finest mesh-size. Considering that the cause of dust coagulation is the flow field that occurs in the filter layer, the coagulation acceleration layer that accelerates coagulation by creating flow fields, placed in the upper layer, has been added in the newly developed long life filter. The new filter permits trapping of dusts in the coarse upper layer of the multi-layered filter, preventing concentration of trapping in the fine, lower-most layer, thus doubling the filter life when compared to the conventional filter.

1. Introduction

Having the global environmental issues, soaring crude oil price, demands for freeing from petro-fuel dependence, etc. in the backgrounds, the sales of automotive fuel of ethanol blended gasoline are increasing worldwide in these days. It is highly likely that the areas where ethanol blended fuels are predominantly used will spread wider in the future. Under such circumstances, there has been such an issue that, in the fuel system of small motorcycles, the suction filter, which is located in the suction side of the fuel pump, becomes clogged in earlier stages when it is used with ethanol blended fuels. The clogging of suction filter may cause immediate effects on deteriorations of engine performances of the motorcycles. In view of that, short service cycle intervals are determined for the filter changes when ethanol blended fuels are used, and the periodical replacements are conducted at the service shops accordingly. However, from the customers' standpoint, in relation to the reduction of running cost, a long-life filter to cope with ethanol blended fuels has been called for.

We therefore analyzed how the early clogging of the

filter occurred when the ethanol blended fuel was used, and targeted at the development of a long-life suction filter having a service life which was the same as or longer than the life of a conventional filter used with neat gasoline even when the ethanol blended fuel was used.

2. Overview of Fuel System in Small Motorcycles

Explained in this chapter is the fuel system of a small motorcycle. As Fig. 1 shows, a suction filter is incorporated in the fuel system in a small motorcycle to protect parts such as a fuel pump, an injector, a pressure regulator, etc. from damages caused by the dust contained in the fuel. Most of small motorcycles adopt the fuel system with only the suction side filter without the main filter, considering the benefits of cost reduction and small design, as shown in Fig. 2. However, as the system doesn't have the main filter, early clogging of the suction side filter becomes a concern.

With this type of system for small motorcycles, when the suction filter becomes clogged, the pressure loss between the filter and the fuel pump increases and may

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negatively affect the engine performances. Therefore, the suction filter should have the characteristics of trapping the large amount of dust yet not getting clogged in early stages. As Fig. 3 shows, the suction filter has the construction to trap dust particles of various sizes by each layer of laminated unwoven cloths having different mesh sizes. Note that the term “filter” used in this paper hereafter refers to the fuel suction filter having this multi-layered construction.

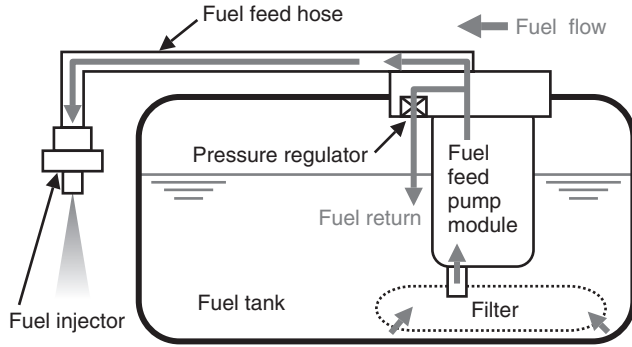


Fig. 1 Structure of fuel supply system on small motorcycles

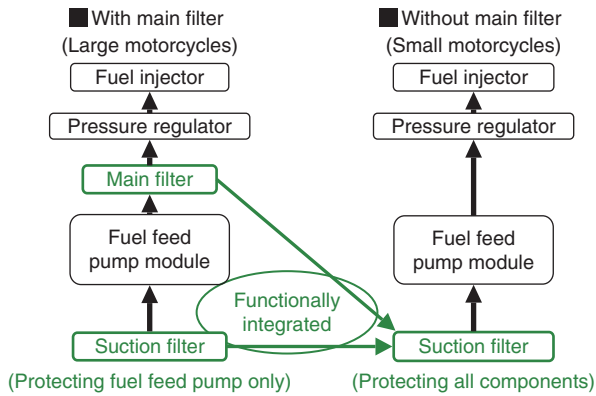


Fig. 2 Schematic diagram of fuel supply system for small motorcycles

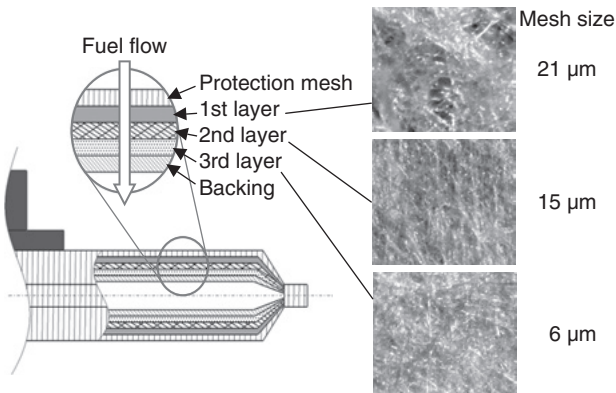


Fig. 3 Typical structure of multi-layered nonwoven fabric filter

3. Early Clogging of Suction Filter Caused by Ethanol Blended Fuel and Associated Issues

As Fig. 4 shows, it was confirmed that the filter, which was free of problem when used with gasoline, became clogged in shorter time when used with the gasoline containing 25% of ethanol (hereafter referred to as “E25”), and the filter replacement interval was halved. Figure 5 shows how the early clogged filter looks. It was revealed that dust was predominantly trapped in the finest (6 μm) layer of the unwoven cloths. With this result, we turned our attention to the differences in the degrees of the dust dispersion depending on the ethanol content. Figure 6 shows conditions of the dust when it is put in E25 and neat gasoline. As we can see from the figure, the dust in ethanol blended fuel is dispersed without forming lumps while the dust in neat gasoline settles in large-grain conditions.

Based on the facts described above, we assumed that early clogging would occur because of the concentration of trapped dust on a single layer of the fuel filter with its tendency to be dispersed in ethanol blended fuels. With this

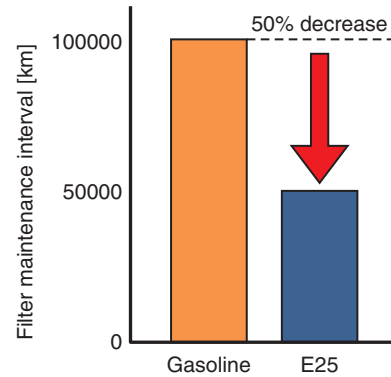


Fig. 4 Filter maintenance interval

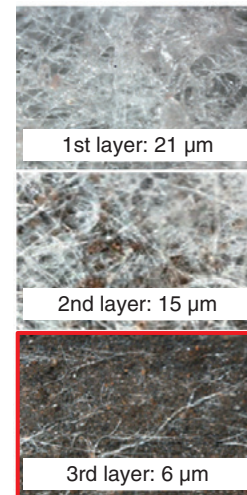


Fig. 5 States of filters in E25

assumption, we decided to put our research focus on the following three key points.

- (1) To clarify the relationship between the ethanol concentration and the dust dispersion in the fuel
- (2) To clarify the impacts of dust dispersion in the fuel to the clogging of a filter and its mechanism
- (3) To develop a long-life fuel filter that can cope with ethanol blended fuels

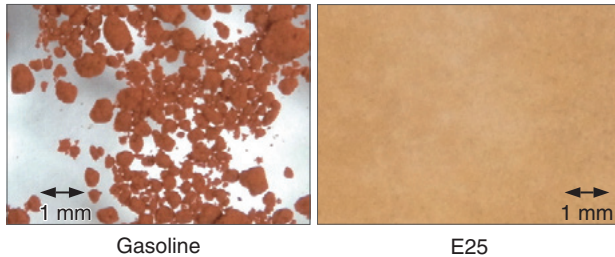


Fig. 6 Comparison of state of dispersion of dust particles in fuel

4. Clarify Relationship between Ethanol Concentration and Dust Dispersion in Fuel

To evaluate the states of dispersion and the coagulation of dust in the fuel for analyzing how they occur, it was necessary to quantify the conditions of dispersion and the status of coagulation. In this chapter, we introduce the physical nature of dust in the fuel, the dispersion assessment method, and how dust disperses.

4.1. Dusts in Fuel

Fuels for automotive applications contain a large amount of fine dust. 40000 to 300000 dust particles larger than 1 μm are contained in 1 ml while the amount varies from region to region. Figure 7 shows distribution of cumulative particle size (particle count basis, average of various countries). 99% of dust in fuel is smaller than 5 μm , which is smaller than the finest mesh size of the filter layer. The fine dust smaller than 10 μm is classified in the particle category referred to as “colloidal dispersion system,” which is characterized by the property of being less affected by the gravity and/or the buoyancy in a liquid and staying in the liquid phase. In addition to that, 50% to 80% of the dust in fuel is composed of three compounds, i.e., SiO_2 , Fe_2O_3 , and Al_2O_3 , which are the components of general soil and are blown up in the air by wind, etc., to creep into the fuel in the process of transportation or while filling the fuel.

4.2. Conditions of Dust Dispersed in Fuel

The conditions of dust dispersed in the fuel can be measured with the particle size analyzer utilizing laser diffraction scattering method. Figure 8 shows results of measurements conducted for each ethanol concentration

with identical test powders of JIS Class 8 mixed in the fuels with the same concentration. The median diameter indicated in the result of measurements is the value that defines the condition of the dust dispersion, where the dust count based method was employed for the measurement. When the median diameter D50% is 0.6, it is defined that 50% of dust particles in the solution is of a diameter smaller than 0.6 μm . It can be remarked that the smaller the number, the more the dust is dispersed. It was understood from the results of measurements that the median diameter of dust became smaller as the ethanol concentration in the gasoline increased, and when ethanol was 100%, the median diameter was approximately 1/4 compared to neat gasoline. It was therefore understood that the dust in the fuel dispersed more along with an increase of ethanol content.

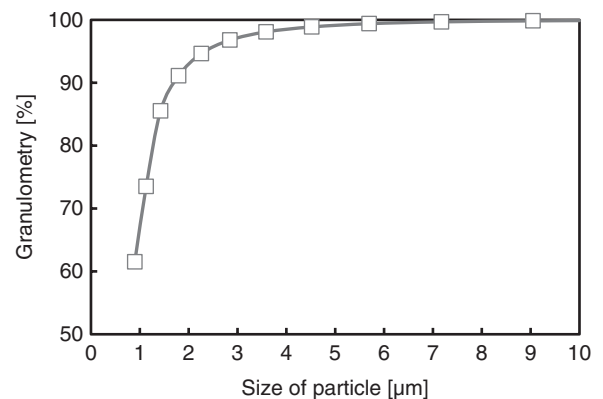


Fig. 7 Cumulative particle size distribution of average dust particles in fuel in major countries (Particle count basis)

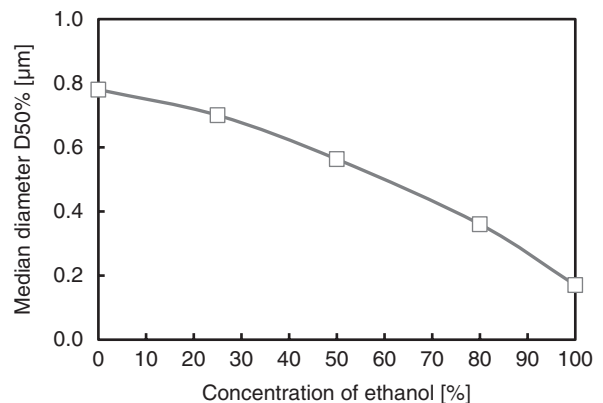


Fig. 8 Ethanol concentration in gasoline and median diameter of dust particles contained in fuel

5. Impacts of Dispersion of Dusts in Fuel on Clogging of Filter and How Clogging Occurs

To clarify the impacts of dust dispersion on the filter life by using actual motorcycle, it requires the corresponding

operational test of 100000 km. Therefore, it is practical to conduct unit test for evaluating the life of filter. Here, we introduce the filter life assessment method and the acquired results.

5.1. Introduction of Unit Test Device

Figure 9 shows overview of the filter life test device we used in the experiments. As shown, the suction filter was immersed in the test fuel, while the fuel pump was operated. And the dust of JIS Class 8 was put in as a test powder at a constant interval. As the dust clogged in the suction filter, the pressure difference between the filter and the fuel pump (filter pressure loss) increased. We assessed filter life from the amount of dust thrown into the fuel when the pressure loss exceeded 30 kPa. Hereafter the filter pressure loss is referred to as “pressure loss”.

5.2. Correlation between Filter Life and Ethanol Concentration

Figure 10 shows combined data of the filter life at each ethanol concentration measured by the test device shown in Fig. 9 and the results of median diameter D50% for different concentrations of ethanol. It was clarified that the more the dust in the fuel was dispersed, the shorter the filter life became.

Moreover, the suction filter, used in the unit test with E25 and clogged in early stage, was disassembled and the condition was checked to see captured dust in each layer. Through the tests, it was found that, as Fig. 11 shows, the dust was trapped predominantly in the finest 6 μm layer just like when the filter clogging occurred in the actual usage.

As mentioned in Chapter 5, more than 99% of dust was composed of particles smaller than 5 μm , which was smaller than the minimum mesh size of filter. We turned our eyes to why dust was predominantly trapped in the 6 μm mesh size layer, which should allow the dust particles to pass through, nevertheless.

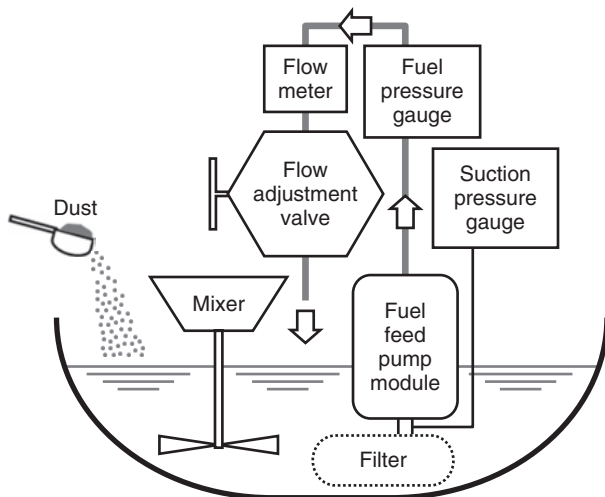


Fig. 9 Schematic view of filter test

In an attempt to clarify how the dust particles smaller than the filter mesh were trapped, we prepared the filter having only a single finest layer (6 μm) and the three-layered filter, which has the same specifications as mass production products, and conducted filter life tests using E25 fuel. Figure 12 shows the relationship between the amount of

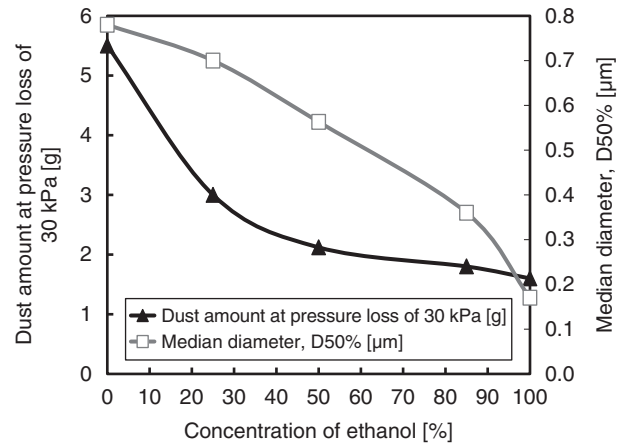


Fig. 10 Relationship between amount of dust particles and median diameter, D50%

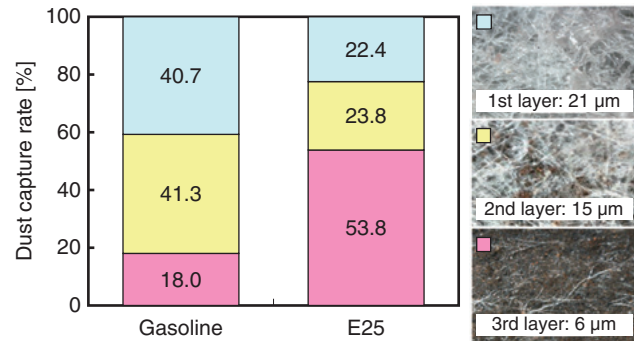


Fig. 11 Comparison of capture efficiency of filter in gasoline and E25

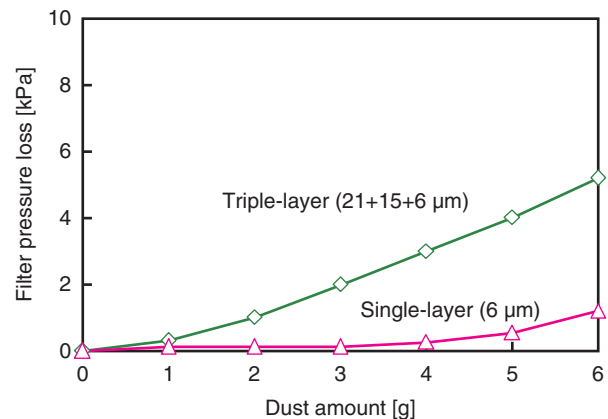


Fig. 12 Pressure loss for different filter structures

dust mixed into the fuel and the filter pressure loss for each type of filter. From the results, the filter life was shorter in the multi-layered filter than the single-layer filter. The pressure loss was increased by only approximately 1.0 kPa with the single-layer filter even after mixing 6 grams of dust. The reason was considered as the dust smaller than 5 μm , which was accounted for more than 90% of total dust in the fuel, passed through the filtering layer. Meanwhile, in the multi-layered construction, the dust that should have passed were trapped. We supposed some phenomenon occurred and the dust coagulated when passing through the filtering layers of the multi-layered construction and predominantly trapped in the lowermost finest layer. We therefore switched our attention onto the dynamics that work on the dust in the fuel, which is of colloidal dispersion.

5.3. Force That Affects Colloidal Particles in Liquid

In the colloidal chemistry, it is commonly known that the dispersion and the coagulation of colloidal particles are considered based on the balance between the repulsive force and the attractive force among the particles. The typical force that disperses colloidal particles is the repulsive force caused by electrostatic repulsive forces. Figure 13 shows the manner of repulsion of colloidal particles caused by the electrostatic repulsive force. Electrostatic repulsion forces are generated between colloidal particles which have the layer of the same polarity of ions formed by the pairs of opposite ions adhering on the surface of the colloidal particles.

On the other hand, regarding the force to coagulate colloids, the van der Waals force (or van der Waals interaction) works. Figure 14 shows the manner the coagulation of colloidal particles due to the van der Waals force. The van der Waals force works, just like when it works on atoms or other molecules, as an attractive force on the colloidal particles with the intensity inversely proportional to the sixth power of the distance between particles.

With expressing the electrostatic repulsive force (repelling force) as V_R , and the van der Waals force (attractive force) as V_A , here we call the combined force of these two forces as “total potential” (V_{total}). The dispersion and the coagulation of colloidal particles are determined by the total potential. That is what they call DLVO (Derjaguin-Landau-Verwey-Overveek) principle⁽¹⁾.

Figure 15 shows the relationship between the repulsive

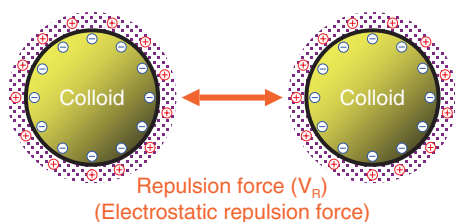


Fig. 13 Schematic representation of electrostatic repulsion force

force, attractive force and V_{total} which are working on particles, in relation to the distance between particles. As the distance between particles shortens, the impacts of electrostatic repulsive force increase, causing the particles to repel each other. However, as the van der Waals force has such a nature that the force is inversely-proportional to the sixth power of the distance between particles, it is considered that when the particle-to-particle distance further shortens and becomes less than approximately 5 nm, the V_{total} turns to the side of attractive force⁽¹⁾. Accordingly, in the situations in which collisions or contacts of particles occur, the distance between particles is shortened enough to make the V_{total} change to an attractive force, causing the particles to coagulate as a result⁽⁴⁾.

5.4. Polarity of Solution and Dispersion and Coagulation of Colloidal Particles

The electrostatic repulsive force is significantly affected by the ion concentration in the solution. It is one of the known facts in the particle technology that the effect of ions on colloidal particles varies depending on the polarity of the solvent, because ions are situated in the status of being dissolved in water. The gasoline is a non-polar solvent

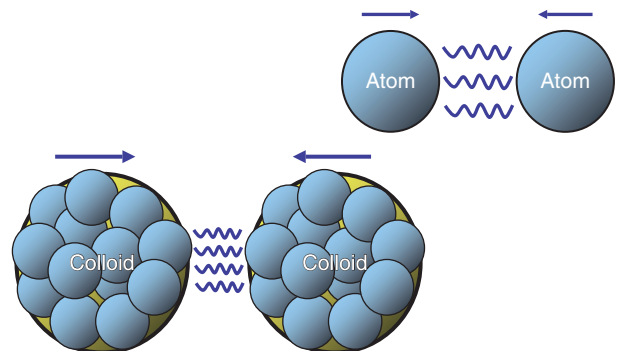


Fig. 14 Schematic representation of van der Waals force

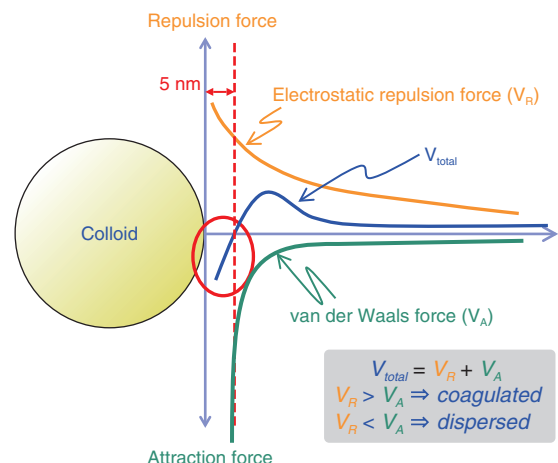


Fig. 15 Interactive action of repulsion and attraction forces and DLVO theory

and a hydrophobic solution having very low water content in the liquid. In the gasoline containing little water, only few ions adheres on the surfaces of colloidal particles as shown in Fig. 16⁽¹⁾. Accordingly, the electrostatic repulsive force becomes weak, and the van der Waals force becomes predominant, allowing easy coagulation of colloidal particles.

On the other hand, it is known that ethanol is a solvent with polarity being able to be mixed with both water and gasoline, and ethanol molecules adhere on the surface of colloidal particles in radial direction pivoted by the hydrophilic groups which have absorbed molecules of water⁽²⁾. Figure 17 shows the manner of the said phenomenon. As the absorbing layer created by ethanol molecules becomes a cause of repelling force and blocks coagulation of colloidal particles with each other resulting in having the tendency of dispersion⁽²⁾. Consequently, as the ethanol concentration lowers, the influence of absorbing layer by the ethanol molecules adhered on the surface of colloids becomes weak, allowing easy coagulation of dust particles with each other.

5.5. How Clogging Occurs in Multi-layered Filter

According to the DLVO principle, it is necessary to reduce the distance between the particles to let the dispersed dust particles coagulate. To reduce the distance between dust particles in a liquid, a flow field, where a velocity gradient occurs in the flow speed, is necessary. The occurrence of a flow field can be seen in a simple flow structure such as in a cylinder. As the flow velocity in a cylinder differs on the cylinder wall and in the center, the flow field becomes

Because few ions are present,
the van der Waals force has a strong effect

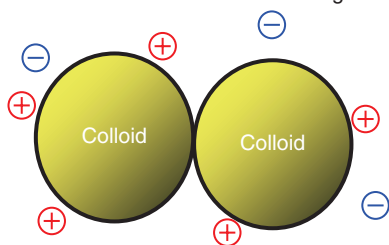


Fig. 16 Mechanism of coagulation in gasoline

Amphipathic molecules form micelles surrounding
core dust particles and are surface-active

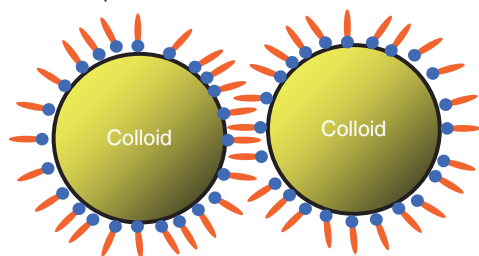


Fig. 17 Mechanism of dispersion in ethanol blended fuel

uneven having a velocity gradient. Due to the close encounters of the dust particles with various velocities due to the flow field, a coagulating force works on the colloids in the liquid⁽⁴⁾. Figure 18 shows the manner the said phenomenon occurs. Similarly, the uneven flow field occurs everywhere in the filtering layer composed of unwoven cloth as Fig. 19 shows. Accordingly, it is presumed that the dust particles collide with each other repeatedly when passing through the filter fabric, causing progression of coagulation.

Figure 20 is an image picture of the manner the dust is trapped by the filter in the gasoline and in E25 fuel. In the gasoline, the dust in the fuel is under coagulated conditions to some extent, and is trapped even in the coarse upper layers. As the dust can be trapped gradationally by each layer depending on the dust size, the dust does not concentrate on a specific layer, allowing effective use of the multi-layered construction. Meanwhile in E25, the dust particles under the dispersed conditions travel in the filtering layers experiencing the congregation due to the flow fields inside of the filter when passing through the filter, and as a result, predominantly trapped by the finest layer in the lowermost layer. That's how the difference occurs in the filter lives between the situations in gasoline and in ethanol blended fuel.

From the findings above, the processes causing premature clogging when using ethanol blended fuel can be summarized into the following three factors.

- (1) Dust is under dispersed conditions in the fuel.
- (2) Dust coagulates when passing through the filter.
- (3) Trapping concentrates in the lowermost fine layer.

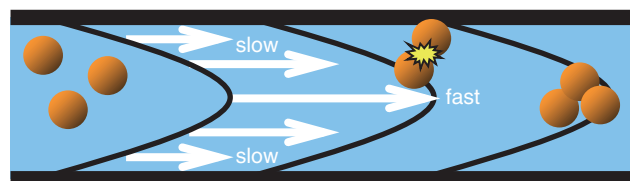


Fig. 18 Schematic representation of flow fields in cylinder

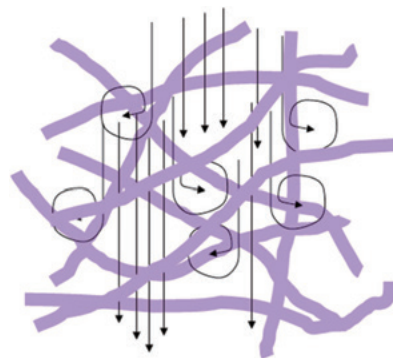


Fig. 19 Schematic representation of flow fields in suction filter

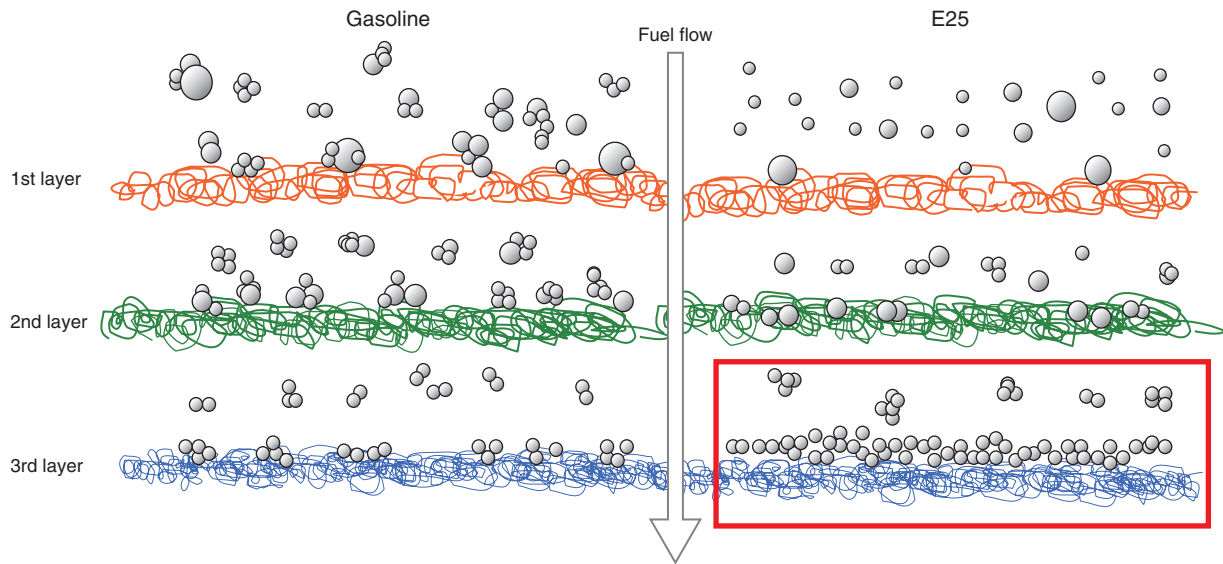


Fig. 20 Schematic representation of dust capture by the filter

6. Consideration of Long-life Filter That Copes with Ethanol Blended Fuel

6.1. Consideration of Coagulation Acceleration Layer

The cause of shorter filter life was the concentration of the dust in the finest filter layer at the lowermost position which hampered the effective use of filters in the upper layers. Keeping that in mind and to positively take advantage of the phenomenon that dust coagulate when passing through the filter, a spongy layer was added on the upper layer of filter. This layer was placed to accelerate the coagulation process to some extent before the dust reached the filtering layers. This layer was named as “coagulation acceleration layer”. By adding the said layer it is aimed to extend its service life without making extensive modifications to the filter configuration currently existing.

6.2. Decision of Specs of Coagulation Acceleration Layer

The aim of coagulation acceleration layer was to create flow fields which make the dispersed dust particles collide with each other to have them coagulated. Accordingly, the coagulation acceleration layer itself is not aiming at trapping of the dust. Figure 22 is the schematic drawing of the coagulation acceleration layer. The holes in the acceleration layer create flow fields. The size of the holes affects the intensity of the flow fields, and the thickness of the coagulation acceleration layer influences the length of time the dust stays in the flow field.

In the attempt to select the specification that maximized the life extension effects, we considered two parameters, i.e., the thickness of the layer and the diameter of the holes. We assessed the coagulation effects from the standpoint of

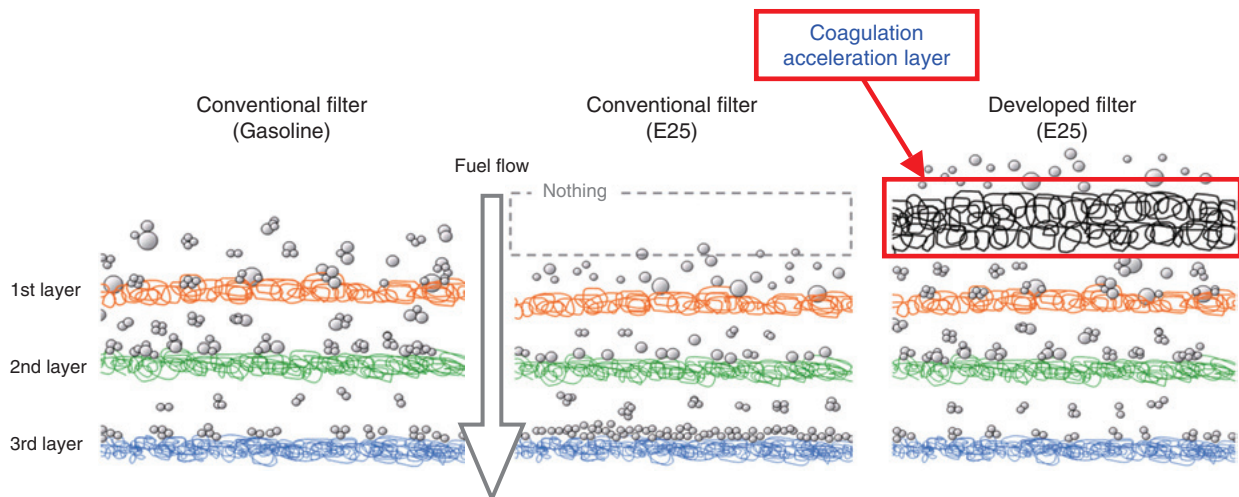
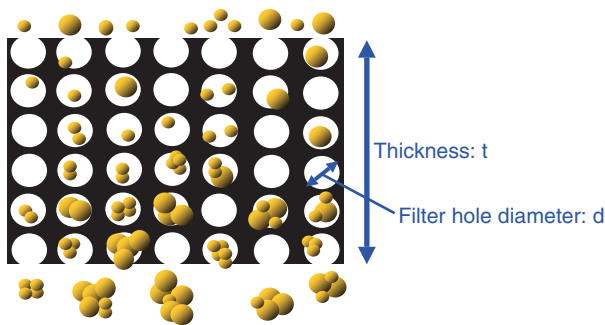


Fig. 21 Schematic representation of effect of coagulation acceleration layer

the average number of holes in the unwoven cloth through which the dust particles passed through for the entire thickness of the layer. Here, the thickness of accelerator layer divided by the average diameter of holes was defined as “mean hole number of dust passage.”

Figure 23 shows the results of studies on the optimum design of coagulation acceleration construction using the index of the mean hole number of dust passage, as mentioned above. It was understood, from the relationship between the mean hole number of dust passage and the amount of the dust when the pressure loss reached to 30 kPa, that the effectiveness became the highest when the mean hole number got somewhere around 30.



Mean number of holes that a dust particle passes while it goes through the filter layer (coagulation acceleration layer)

$$= \frac{t \text{ (Thickness)}}{d \text{ (Average filter hole diameter)}}$$

Fig. 22 Schematic representation of coagulation acceleration layer

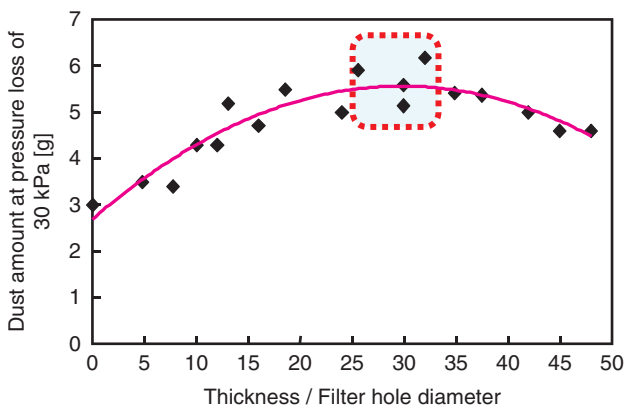


Fig. 23 Relationship between conditional parameters of coagulation acceleration layer and dust amount at predetermined pressure loss

7. Validation

Taking into consideration the test results shown in Fig. 23, we developed the new filter with the coagulation acceleration layer having mean hole number of 30

(Fig. 26), and compared the filter life with the conventional filter using E25 fuel. Fig. 24 shows the results of the validation tests. The new filter doubled the service life of a conventional filter without increasing the filters' surface area. Concerning the dust trapping composition of each filtering layer, the equivalent level of composition at each layer for dust trap, as with gasoline, was attained as shown in Fig. 25 without causing concentration in the lowermost layer.

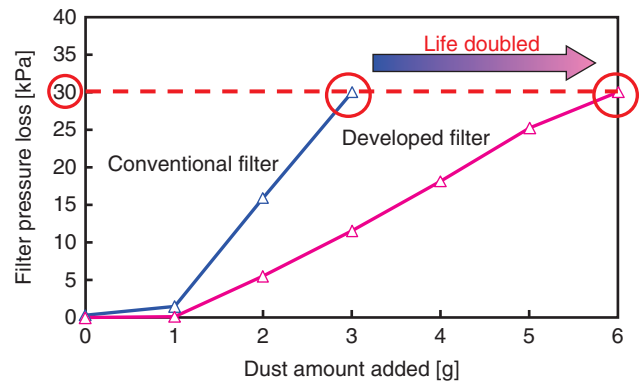


Fig. 24 Comparison of pressure loss between developed filter and conventional filter

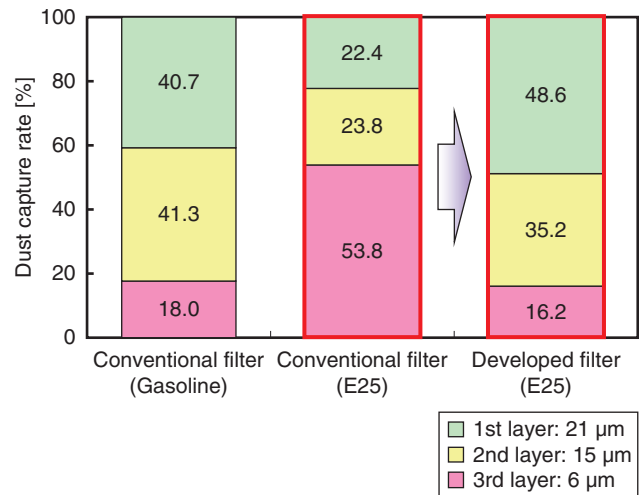


Fig. 25 Comparison of filter capture efficiency

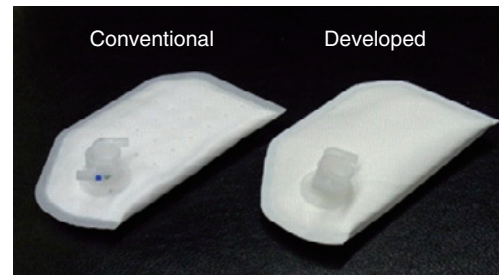


Fig. 26 External view of newly developed filter

8. Conclusion

We clarified the mechanism of how the early clogging of the filter with use of ethanol blended fuel occurs, and we developed the long-life suction filter that can cope with market demands on filter life where ethanol blended fuel was mainly used. The following process of early clogging was defined;

- (1) In alcohol fuel, dust disperses, and coagulates when passing through the filter having a multi-layered construction.
- (2) The coagulated dust is trapped predominantly by the fine bottom layer, reducing the service life of the filter.

We have developed the new filter with a coagulation acceleration layer added at the uppermost layer based on the findings mentioned above, thus doubling the service life while maintaining the same size of the filter.

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