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Taguchi Method 을 이용한 DME 고압 연료 펌프에 대한 고성능 수치 해석

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A Numerical Analysis for High Performance on DME High Pressure Fuel Pump Using Taguchi Method

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Abstract>> Using numerical analysis, various factors influencing the performance development of high-pressure pumps for Dimethyl Ether (DME) engines were identified and the impact of each factor was evaluated using Taguchi method. DME fuels are more compressive than diesel fuels and have the lower heat generation, so it is necessary to increase the size of the plunger and speed (RPM) of the pump as well. In addition, it is necessary to change the shape and design of control valve to control the discharge flow and pressure. In this study, various variables affecting the performance and flow rate increase of high-pressure pumps for DME engines are planned using Taguchi method, and the best design method is proposed using correlation of the most important variables. As a result, we were able to provide the design value needed for a six-liter engine and provide optimal conditions. The best combination factors to optimize the flow rate at RPM 2,000 and diameter plunger with 20 mm. The regression equation can also be used to optimize the flow rate; -8, 13+0, 2552 RPM +54, 17 diam. Plunger.

Key words : Dimethyl ether(디메틸에테르), Conversion(변환), Numerical analysis (수치 해석), Taguchi method(다구찌 방법), Flowrate(유량)

1. Introduction

Diesel and gasoline engines are being developed with an emphasis on energy economy and pollution reduction as energy and environmental challenges become increasingly apparent. Recently, researchers have proposed the types of fuel that have the potential for zero-emission. Dimethyl ether (DME), which is made from natural gas and has lately been acknowledged as a new clean fuel, will provide a solution for energy security and environmental conservation. DME combustion and emissions study was started in 1995 and have public attention as a clean fuel around 1996.[1-3].

Dimethyl ether (DME) has been the subject of numerous studies to establish its suitability for use as a fuel in diesel-cycle engines[3-5]. DME appears to be a good, efficient alternative fuel for diesel engine with nearly no smoke during combustion. This is due to its low auto-ignition temperature and near-instantaneous vaporization when injected into the cylinder, as well as its high oxygen concentration (about 35% by mass) and the lack of C-C bonds in the molecular structure[4,6]. In addition, to be liquid, dimethyl ether requires roughly 75 pounds per square inch of pressure. A high-pressure pump is required due to the characteristics of DME, which also makes it easier to evaporate at room temperature and reduces the pump's flow rate[7,8].

In order to optimize the flow rate of DME using high-pressure fuel pump, improvisation of some parameters is required. Velocity and area are factors that effected the flow rate[9,10]. It means that plunger diameter as an area and RPM as velocity can be improved and inputted in several ways of optimization flow rate. The one of the most optimization way is Taguchi method[11]. Taguchi method has been utilized in the industry to determine characteristics that are critical to achieving aims. Recently the researchers have applied the Taguchi method to optimal analysis. Using a thermodynamic model, Akay and Yurtcan[12]. studied the suitability of several types of biodiesel for optimizing engine performance. On diesel/biodiesel engines with port-injecting LPG, Mrzljak et al.[13] used the Taguchi method to determine combustion characteristics and optimum variables.

In this paper, Taguchi method was used to create experiment plans shown in Table 1, which is a very effective methodology to acquire the optimum flow rate with combination parameters that influence the flow rate.

2. Method

2.1 Pump and fuel specification

The independent high pressure fuel pump used in the experiment is shown in Fig. 1 and detailed specifications are shown in Table 1. It has four fuel discharge parts, so it can send out a lot of flow, and it was adopted in this experiment because it is the most

Table 1. Specification of plunger type high pressure pump and fuel

Type	Independent injection piston pump
Maximum pressure	680 bar
Maximum flow rate (diesel)	133 LPH (1,000 RPM, 300bar)
Maximum speed	1,450 RPM
Number of piston	4
Maximum temperature	80°C
Cylinder diameter	100 mm
Cylinder length	100 mm, 90 mm
DME density	663 kg/m^3
DME bulk modulus	6370 bar
Absolute viscosity	0.12 cP

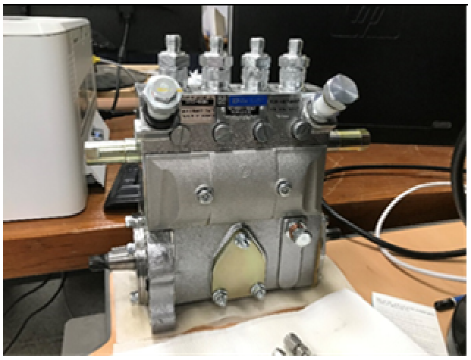

Fig. 1. Independent injection pump

used type among fuel devices of diesel engines.

Fig. 1 shows the independent high-pressure fuel pump utilized in the experiment, with precise specifications listed in Table 1. It has four fuel discharge components, allowing it to transfer a large amount of flow, and it was chosen for this study since it is the most common form of fuel device for diesel engines.

2.2 Simulation condition

A schematic diagram of the DME fuel supply system is showed in Fig. 2 used in this investigation. At the front end, DME from the fuel tank passes through a flow meter and into the feed pump, which provides fuel to the entire system. Fig. 3 shows the whole research process and method that used in this study.

2.3 Taguchi technique

Taguchi Method is used in experimental design to produce an optimum response by involving many factors with different levels. In the industry, Taguchi method is using to decide which factor is important and influenced. Through the setting of design parameters Taguchi method can optimizes qualitative characteristics. The experimental data is then subjected to an analysis of variance (ANOVA) to determine the relative influence of the factors. The mathematical equation indicate the term variation as follows

Total sum of square:

$$SS_r = \sum_{i=1}^{n}(y_i^2 - CF) \quad (1)$$

Where CF is correlation factor

$$CF = (\sum_{i=1}^{n}(y_1))^2 /n \quad (2)$$

Total sum and factor of the sum of squares are required for calculating for ANOVA. ANOVA can be calculated with equations below:

$$\text{Mean variance: } MS_{RPM} = \frac{SS_{RPM}}{f_{RPM}} \quad (3)$$

$$\text{F-ratio: } F_{RPM} = \frac{MS_{RPM}}{V_e} \quad (4)$$

Pure sum of squares

$$SS'_{RPM} = SS_{RPM} - (V_e \text{ x } F_{RPM}) \quad (5)$$

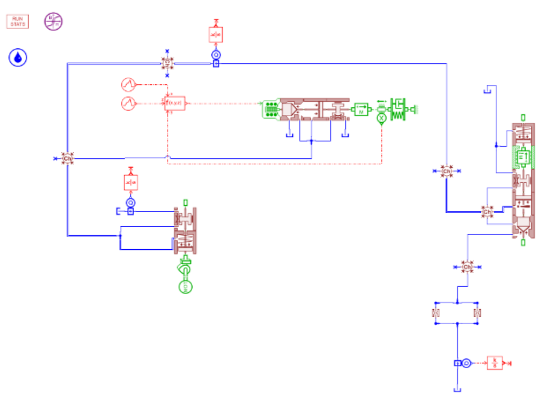

Fig. 2. High pressure fuel pump using AMESIM

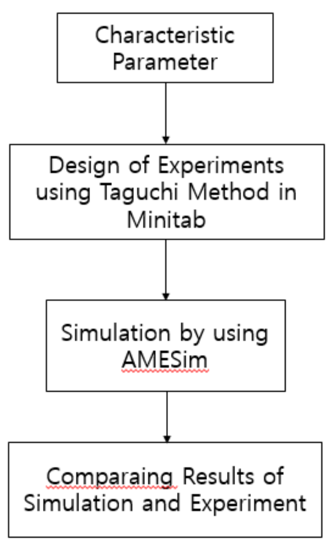

Fig. 3. Flow process of research

Percent contribution:

$$\rho_{RPM} = \frac{SS'_{RPM}}{SS_T} \quad (6)$$

Where:

SS_{RPM} : sum of square

F_{RPM} : degrees of freedom (DOF) of RPM

V_e : variance for the error term

The signal-to-noise (S/N) ratio in Taguchi methods[14] is needed to evaluate the variation of performance of an output characteristic. The flow rate of fuel consumption in the experiments belongs to the larger-the-better quality characteristics in the following equation below:

$$\text{S/N ratio} = -10 \log \left(\frac{1}{n}\left(\sum_{i=1}^{n}\frac{1}{y_i^2}\right)\right) \quad (7)$$

Table 2. Experiment plan

No. of experiment	RPM	Diam. plunger (mm)
1	1,000	10
2	1,000	15
3	1,000	20
4	1,600	10
5	1,600	15
6	1,600	20
7	2,000	10
8	2,000	15
9	2,000	20

In this study the L_9 orthogonal array is used as an unsaturated design as RPM and Diameter Plunger with three levels in every parameter are chosen as two factors for high pressure fuel pump using DME as fuel. Table 2 shows the experiment plan that can be used to the simulation or experiment as the next phases.

Table 3. Flow rate result of simulation

No. of experiment	RPM	Diam. plunger (mm)	Flow rate (LPM)
1	1,000	10	1.472
2	1,000	15	3.925
3	1,000	20	7.36
4	1,600	10	1.412
5	1,600	15	6.278
6	1,600	20	11.772
7	2,000	10	2.817
8	2,000	15	7.852
9	2,000	20	14.723

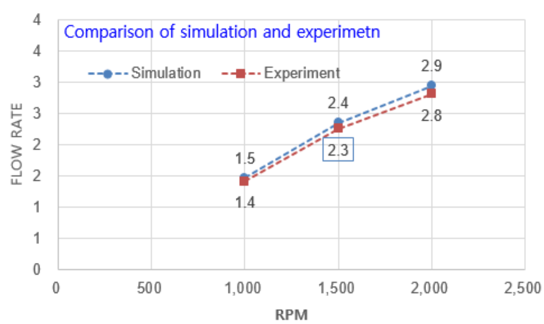

Fig. 4. Validation simulation

Table 4. ANOVA result

Parameters	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution
Speed (rpm)	2	99003	99003	49502	6.2	0.059	17.21%
Diam. plunger	2	444235	444235	222118	27.82	0.004	77.23%
Error	6		440158	6002	73.33	0.000	
Residual error	4	31936	31936	7984			
Total	8	575175					

3. Result

3.1 Result of simulation

The results of the simulation is the flow rate from every parameters that inputted. Table 3 shows flow rate as the result after simulation. Fig. 4 shows the validation of simulation with experiment using diameter plunger in 10 mm of high pressure fuel pump. And the result of these results will be inputted to Taguchi method calculation in the next phase.

Because the simulation produced comparable results as the experiment and the simulation's dependability was established, factors influencing the pump's performance and durability were explored using the simulation.

3.2 Result of Taguchi Method

By using Eq. (6), the ANOVA was used to determine the most significant factors and quantify their influence on flow rate. Table 4 displays the ANOVA results.

The contribution level for parameters to the flow rate DME by using high pressure fuel pump is from 17, 21% (at RPM) and 77, 23% (at Diameter Plunger). The result shows that the variant of diameter plunger will give high contribution of optimization of DME's flow rate. Table 5 is supported this statement by showing also that diameter plunger factor is in the 1st rank that affected to the optimization DME's flow rate.

Table 5. response for signal to noise ratios

Level	Speed (rpm)	Diam. plunger
1	46.42	42.29
2	50.5	50.81
3	52.44	56.27
Delta	6.02	13.98
Rank	2	1

Table 6 represents the regression equation by using the coefficients of every factor of flow rate.

This equation can be used to obtain the flow rate optimum of DME with the high pressure fuel pump.

S/N response curves graphically represent the optimization of the DME's flow rate as a function of parameter level, with the highest S/N ratio indicating the best factor combination as shown in the Fig. 5.

The optimum factors combination for the optimum DME's flow rate is at RPM 2,000 and at diameter plunger 20 mm.

Table 6. Coefficients of regression equation

Term	Coef.	SE Coef	T-value	P-value	VIF
Constant	-813	138	-5.9	0.001	
Speed (rpm)	0.2552	0.0628	4.06	0.007	1.00
Diam. plunger	54.17	6.33	8.56	0.0000	1.00

Regression equation
Flow rate= -813+0.2552 RPM+54.17 Diam. plunger

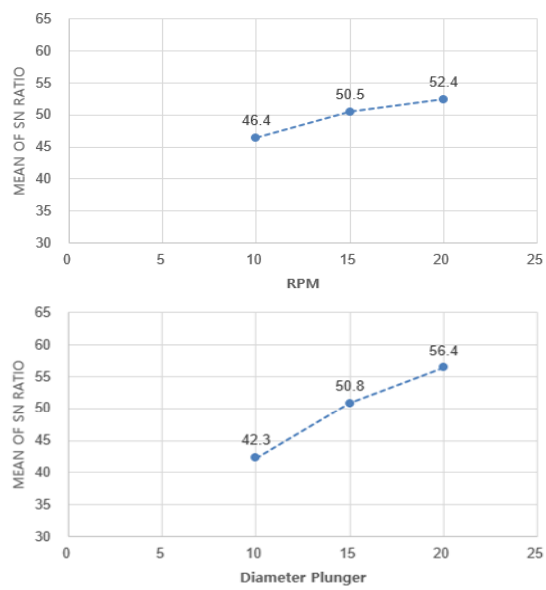

Fig. 5. S/N responses of the RPM and diameter plunger

4. Conclusions

In this study has been determined that the optimal operating factors for optimizing the DME's flow rate, RPM and diameter plunger by using Taguchi method. The DME flow rate is largely influenced by plunger diameter; the larger the plunger diameter is used it will increase DME flow rate. The best combination factors to optimize the flow rate at RPM 2,000 and diameter plunger with 20 mm. The regression equation can also be used to optimize the flow rate; -8, 13+0, 2552 RPM +54, 17 Diam. Plunger. The correlation flow rate between simulation and experiment is almost similar.

Taguchi Method can be one of the alternative for designing an experiment of flow rate because it reduce the variation in a process through robust design of experiments.

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