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Emission Reduction of a Stoichiometric Gasoline Direct Injection Engine

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ABSTRACT

During the development of conventional PFI engines, WOT (Wide Open Throttle) performance tends to be sacrificed for exhaust emission reduction in order to meet the latest emissions regulations. To satisfy both power and emissions, a new V-6 engine employing stoichiometric gasoline direct injection, the 3GR-FSE, with variable intake and exhaust valve timing systems, was developed and meets the ULEV exhaust emission standard without sacrificing WOT performance. It is generally understood that THC emissions are reduced during warm-up through quick catalyst light-off by retarding ignition timing. However, the effect of this is limited by engine torque fluctuations. Under this warm-up condition, stratified charge combustion is known to significantly improve the engine torque fluctuation and enable more retard ignition timing. Furthermore, by using the variable exhaust valve-timing system, the internal EGR gas assists fuel spray atomization, increasing the expansion ratio to promote HC combustion in the chamber. As a result, THC emissions are reduced.

INTRODUCTION

As the interest in global environmental protection increases, harmful exhaust gas emissions need to be reduced. This is especially true in cold start conditions, where it is crucial to decrease exhaust gas unburned hydrocarbon emissions. Fig.1 illustrates the transition of HC emissions for the FTP mode on an LEV engine. More than 80% of the total HC emissions are produced during cold conditions. So, quick catalytic converter light-off is required to reduce engine out HC emissions during cold start.

REQUIRED LEVEL OF CATALYTIC CONVERTER ACTIVATION AND ENGINE-OUT HC EMISSION

To accomplish this, TMC (TOYOTA MOTOR CORPORATION) first investigated the amount of engine out HC emissions produced with a known exhaust gas heat energy in the catalytic converter as shown in Fig.2. The supplied exhaust gas heat energy to the catalytic converter is calculated by exhaust gas amount and temperature during 20 seconds of fast idling, and divided by catalytic converter capacity. The target line is from an empirical formula gathered from vehicles that meet the ULEV standard. This line is an upper limit and the target region is below the target line. The target is set to reduce engine-out

(THC:Total Hydrocarbon)

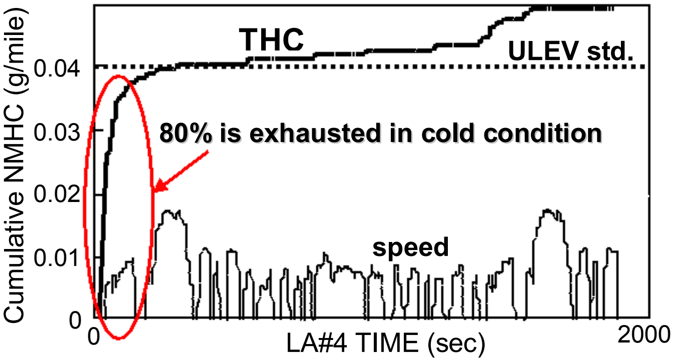


Fig. 1 Transition of HC emissions for FTP mode with LEV engine calibration

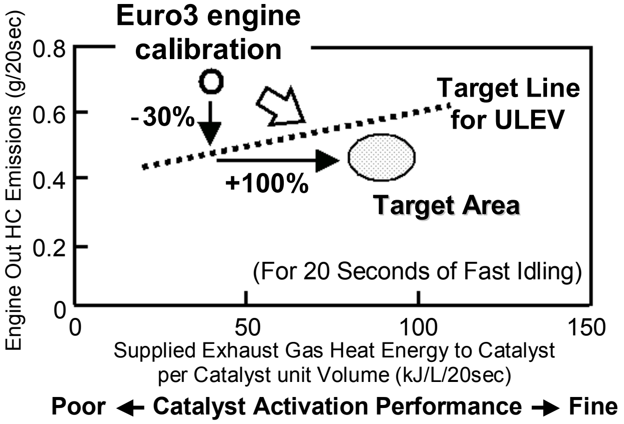


Fig. 2 Required level of exhaust gas heat energy supplied to the catalytic converter and engine-out HC

HC emissions by 30% and to double the supplied exhaust gas heat energy as compared to the first stoichiometric gasoline direct injection engine TOYOTA introduced to the European market for Euro3.

CATALYTIC CONVERTER WARM-UP PERFORMANCE IMPROVEMENT

(1) A/F OPTIMIZATION

To improve catalytic converter warm-up performance, it is most effective to increase the exhaust gas temperature during the cold engine condition. As shown in Fig. 3, stoichiometric combustion raises the exhaust gas temperature the most. In addition, the catalytic converter activating temperature decreases when there is an oxidation atmosphere in the catalytic converter, enabling the early reduction of HC emissions. To balance both of these, we set the A/F to 15 from 15.5 just after cold start.

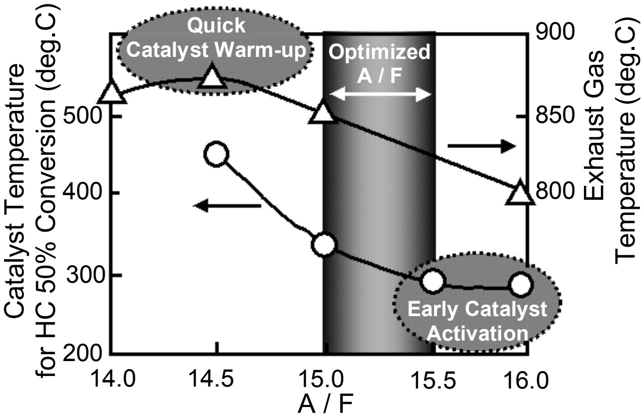


Fig. 3 Required A/F for catalytic converter activation and the rise of exhaust gas temperature

(2) USING STRATIFIED CHARGE COMBUSTION TO RETARD IGNITION TIMING

Exhaust gas temperature increases when ignition timing is retarded. Vehicle noise and vibration, caused by engine torque fluctuations limit this effect. The high degree of injection timing freedom, an advantage of the direct injection system, was used to improve the combustion fluctuation between cycles in the cold engine condition. In other words, the stratified charge combustion that is realized by the fuel injected at compression phase enables spark ignition timing to be retarded much further than in the homogeneous charge combustion system where fuel is injected in the intake phase. Furthermore, as shown in Fig.4, the stratified charge combustion makes it possible to retard spark ignition timing further than the PFI engine utilizing Intake Air Control Valve under fast idle condition of the engine.

The CFD(Computational Fluid Dynamics) analysis calculates how the stratified mixture is formed under the fast idle condition. The calculated cylinder model and the outline of the calculation method are shown in Fig. 5. A DDM spray model, verified by the test of a slit-nozzle injector, was used to calculate the mixture gas formation. Fig. 6 illustrates the stratified mixture formation calculated by the CFD analysis described above. Fuel is injected at the compression phase and guided to the vicinity of the ignition plug by the piston cavity wall. As a result, a combustible gas mixture is formed around the ignition plug when retarded ignition timing is used.

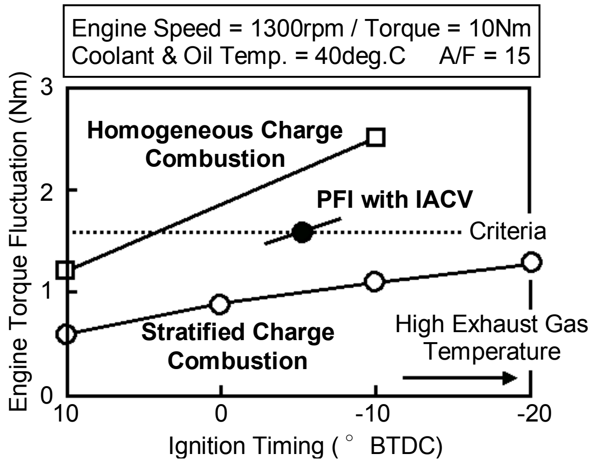
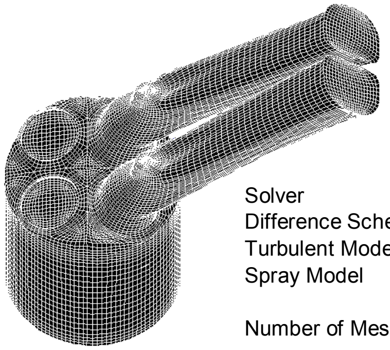


Fig. 4 Engine torque improvement from stratified charge combustion



Solver : Star-CD
Difference Scheme : MARS
Turbulent Model : κ - ε
Spray Model : DDM

Number of Mesh : 120000

Fig. 5 Model for CFD analysis

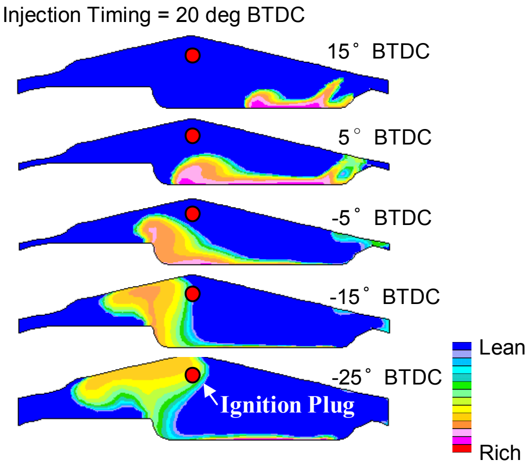


Fig. 6 CFD analysis on stratified mixture formation

Also, the strong fuel penetration, which is generated by high fuel pressure, forms a strong turbulent flow promoting fuel and air mixing. As shown in Fig.7, these stratified charge combustion effects enable the in-cylinder pressure to rise earlier than with homogeneous charge combustion. By decreasing the initial 10% of the heat-release period by 36%, the fluctuation rate of the mean effective pressure is improved.

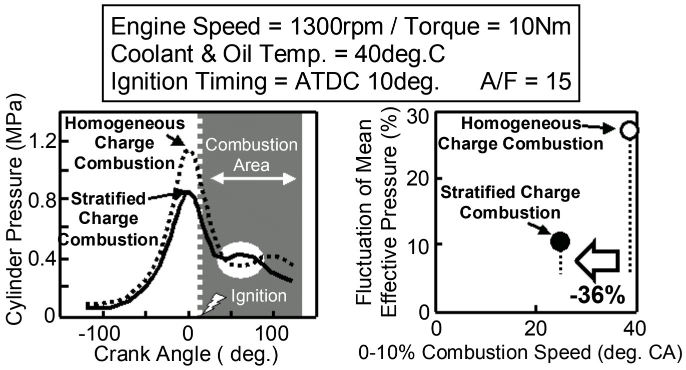


Fig. 7 Improvement of combustion speed using stratified charge combustion

(3) PISTON CAVITY OPTIMIZATION

Homogeneous combustion does not require a deep piston cavity. The cavity, which guides the stratified gas mixture to the vicinity of the ignition plug, is required for improved cold start emissions. Also, catalytic converter warm-up performance can be significantly improved by adapting stratified combustion as described above. Fig. 8 illustrates the effect of piston cavity depth on WOT performance using homogeneous charge combustion, and on engine torque fluctuation using stratified charge combustion during cold engine conditions. The ability to guide the stratified gas mixture during the cold start condition depends on the cavity depth. However, in the case of a deep cavity, the amount of fuel wetted on the piston surface is increased and an over-rich zone of gas mixture tends to form in the cavity. As a result, a cavity shallow enough to avoid such effects was selected for this engine. This cavity depth also confirmed that it is simple to achieve a high compression ratio, and that cooling loss can be reduced.

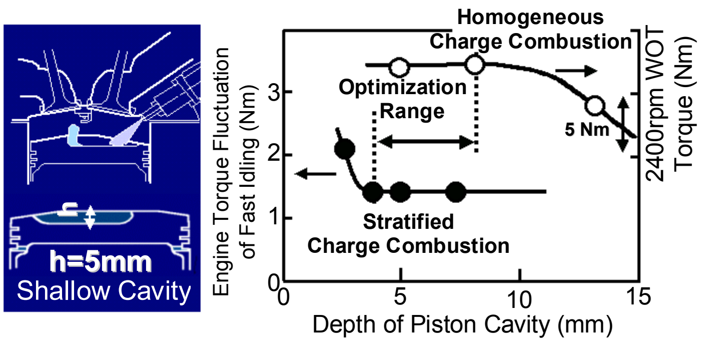


Fig. 8 Piston cavity effects

(4) STRATIFIED CHARGE FORMATION OPTIMIZATION

Fig. 9 illustrates how the air-fuel mixture concentration near the ignition plug affects engine torque fluctuation. The stratified mixture is produced by injecting half of the required fuel twice, once in the compression phase and once in intake phase, while varying the injection quantity and rate. Rather than the strong stratified air-fuel mixture that injects the whole quantity in the compression phase, this weak stratified air-fuel mixture improves engine torque fluctuation. From this study, we have found that there is an optimal rate of injection.

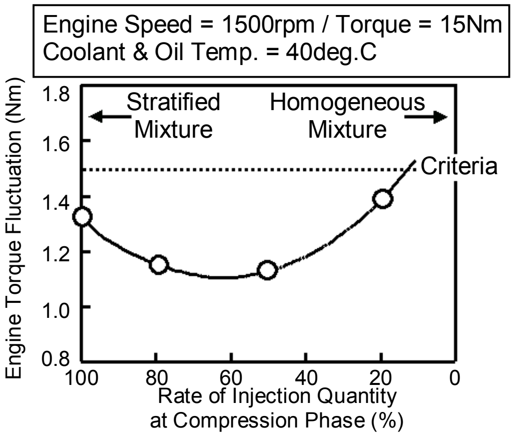


Fig. 9 Improvement of engine torque fluctuation using stratified charge formation

The result of using LIF(Laser-induced Fluorescence) to visualize air-fuel mixture formation is shown in Fig. 10. Fuel concentration is calculated by mixing dimethyl aniline in fuel as a fluorescent substance, and analyzing the luminescence amount when irradiating with an ultraviolet laser. When the whole injection quantity of fuel is injected in the compression phase, the average A/F ratio in the vicinity of the ignition plug is as rich as 10:1 and the air-fuel-mixture near the cylinder wall is heterogeneous. However, by using weak stratified charge, the over-rich air-fuel mixture at the ignition plug region can be avoided. Moreover, sufficient mixing time is spent forming the homogeneous-lean air-fuel mixture, and improves not only the heterogeneous air-fuel mixture near the cylinder wall but also the fluctuation between cycles of air-fuel mixture concentration near the ignition plug. The effect is shown in Fig. 11.

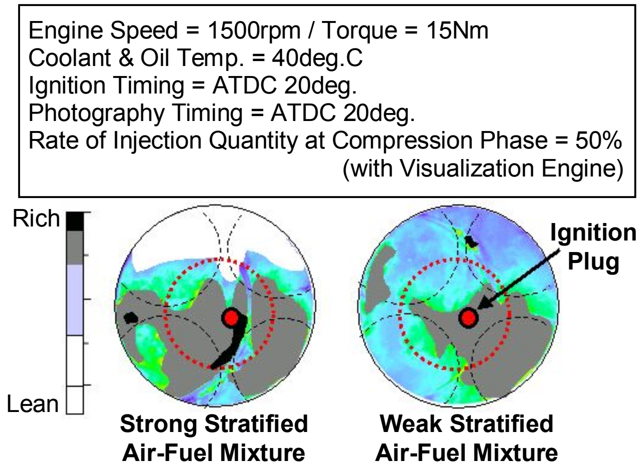


Fig. 10 LIF analysis on stratified mixture formation

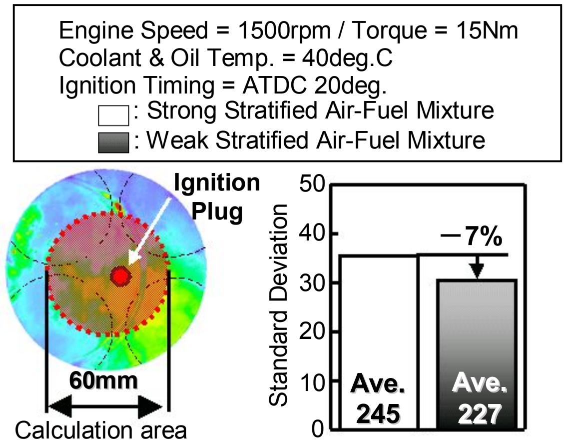


Fig. 11 Fluctuation reduction from improved air-fuel-mixture formation

The effect of optimizing the stratified charge formation is collectively shown in Fig.12. By forming the homogeneous lean air-fuel mixture in the entire combustion chamber, and forming a "not too rich air-fuel mixture" in the vicinity of the ignition plug, engine torque fluctuation improved and the rich limit was expanded.

(5) EXHAUST GAS TEMPERATURE

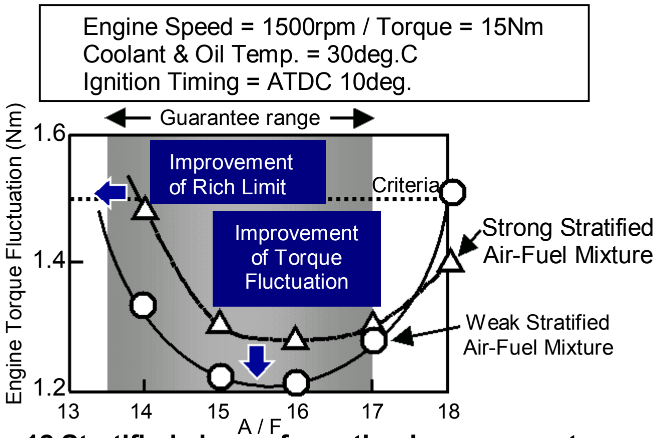


Fig. 12 Stratified charge formation improvement

IMPROVEMENTS

Fig. 13 illustrates the effects of the weak stratified air-fuel mixture under an engine fast idle condition. As shown in the engine test results, exhaust gas temperature can be significantly increased and ignition timing can be retarded. This effect is limited by the engine torque fluctuation to avoid vehicle noise and vibration. A 500 deg. C exhaust temperature increase was obtained compared with a conventional PFI engine at the same torque fluctuation condition.

VARIABLE EXHAUST VALVE TIMING SYSTEM TO REDUCE ENGINE-OUT HC

The variable intake and exhaust valve timing systems adopted for this gasoline direct injection engine were designed to achieve high performance, low fuel consumption and low exhaust emissions. The exhaust variable valve timing (Ex-VVT) system is especially useful in the cold engine condition to reduce engine-out HC emissions. Fig. 14 illustrates the relationship between the engine torque fluctuation and engine-out HC emissions when Ex-VVT timing is retarded. There is an optimal point that can reduce engine-out HC by retarding Ex-VVT timing without worsening engine torque fluctuation.

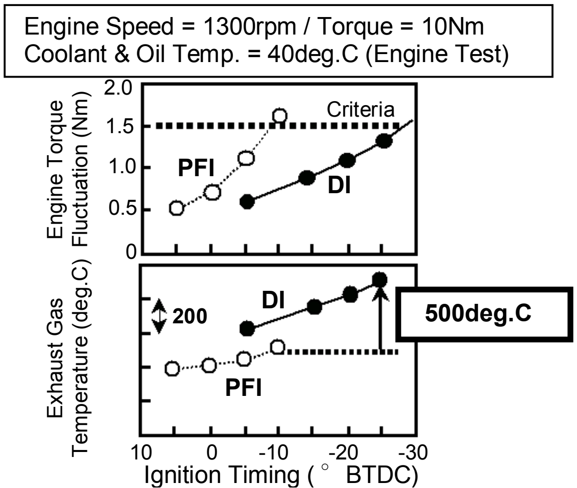


Fig. 13 Exhaust gas temperature improvement using stratified charge combustion

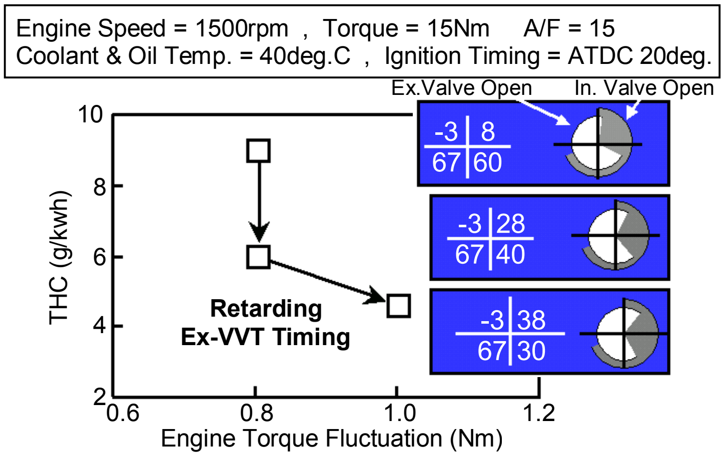


Fig. 14 Reduction of engine out HC from Ex-VVT retard timing

Fig. 15 compares the in-cylinder pressure and temperature just after cold start, with and without retarded Ex-VVT timing. It turns out that in-cylinder temperature increases at top dead center by retarding Ex-VVT timing. It is the result of in-cylinder mass increasing as the combusted gas is blown back into the cylinder by retarding the exhaust valve close timing after the top dead center. The atomization of the fuel injected in the compression phase is promoted by this high cylinder temperature, and has led to the air-fuel mixture improvement. Furthermore, by retarding the exhaust valve open timing, the burning time, which is from ignition to discharge, increases and HC combustion is promoted in the high temperature cylinder.

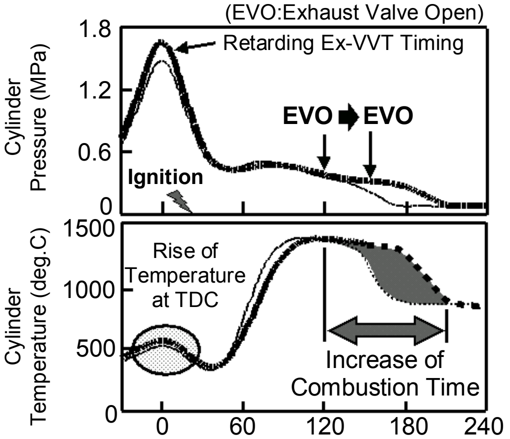


Fig. 15 In-cylinder pressure and temperature with and without Ex-VVT timing retard

RESULT OF CATALYTIC CONVERTER ACTIVATION AND ENGINE-OUT HC EMISSIONS IN THE COLD ENGINE CONDITION

Fig. 16 illustrates the improvements of the supplied exhaust gas heat energy to the catalytic converter and the amount of engine-out HC emissions during 20 seconds of fast idling. By utilizing the weak stratified air-fuel mixture, which is advantageous to retarding spark ignition timing, improved catalytic converter warm-up performance is achieved. And, by retarding Ex-VVT timing, the reduction of engine out HC emissions is also achieved. These improvements enable us to meet the ULEV emission standard.

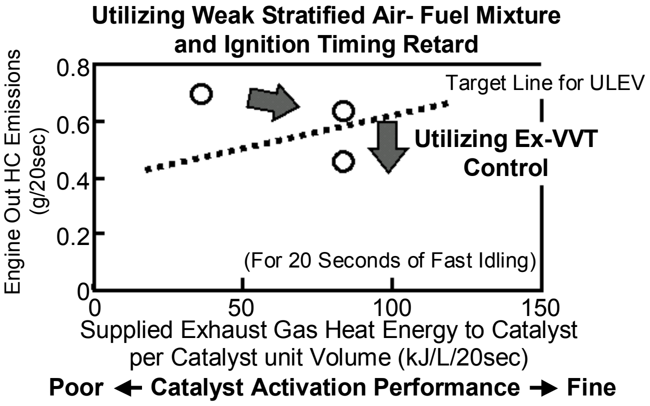


Fig. 16 Result of catalytic converter activation and engine out HC emissions

CONCLUSION

We have developed a V6 3.0L stoichiometric gasoline direct injection engine, the 3GR-FSE, to reduce cold HC emissions using fuel-injection-timing control and an Ex-VVT system. This improvement enabled us to meet the ULEV emission standard and the Japanese SULEV and Euro4 emission standards.

1. We have improved the catalytic converter warm-up performance by adopting a weak stratified air-fuel mixture, enabling exhaust gas temperatures to rise by retarding the ignition timing.
2. We have reduced the engine-out HC emissions by fuel atomization and by promoting in-cylinder HC combustion through the adoption of Ex-VVT retard control.
3. The ignition-timing-retard control is effective in raising the exhaust gas temperature. However, two concerns arise that need to be addressed: an increase in engine noise and the reduction of engine vacuum for braking systems. It is important to further technical advances to reduce engine out HCs and improve low-temperature catalyst activity.

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