THE POSSIBILITY OF THE SI ENGINE CO2 EMISSION REDUCTION WITH THE APPLICATION OF CNG-HYDROGEN BLENDS

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Abstract

The influence of hydrogen-methane blends application in SI engines on their CO_2 emission is the main goal of this paper. The 1.6 liter engine alternatively fed with either petrol, CNG and with methane-hydrogen blends has been tested in the research program. The possibility of passenger car engine operation on H_2-CH_4 mixtures has been demonstrated in the paper, with the underlining of the potential of those mixtures in the increasing of the engine efficiency. Necessary changes in strategy of engine regulation, especially in air/fuel ratio, ignition advance and EGR rate, were noticed and prepared. The methane-hydrogen blends, which were used in the research programme featured ratios as follows: 5%, 10% and 15% of hydrogen. For selected engine operating points, following data has been acquired: in cylinder pressure variation, crank angle, manifold pressure and finally mass fuel consumption. On the basis of registered data for all fuels - burned temperature in cylinder has been estimated, as well as the charge combustion ratio, and the heat release rate. With help of mathematical model describing the exhaust gases formation it has been possible to estimate the NO, CO and CO_2 emission level. Obtained results made it possible to compare the combustion process for all tested fuels and pointed on the significant influence of hydrogen percentage for the methane-hydrogen blends, on the CO_2 emission reduction up to 20%. Negative aspects of chosen blends application have been also describe in the paper, especially of increasing engine thermal load.

Keywords: *CNG, Hydrogen, Mixtures, Passenger car engine, Combustion analysis*

1. Introduction

A significant reduction of CO_2 emission in the road transport is a major challenge for next years. In the combination with efficient powertrain technologies, the potential of natural gas is excellent for comparably light and cost effective reduction of CO_2 and toxic emission in the future [1-2]. We can say that natural gas vehicles (NGVs) are potential alternative to petrol vehicles in the short time. However, in the effort to reduce their pollutants further NGVs have been run on Hythan® (i.e. mixtures of 20% by volume of H_2 are trademarked by Hydrogen Consultants Inc.). These vehicles have lower range compared to conventional vehicles due to lower on-board energy density. Hydrogen is a good additive to methane due to its characteristic. Based on hydrogen properties (Tab. 1) it can be noticed that hydrogen burns at air fuel ratio of 9, while methane and gasoline are capable to burn at air fuel ratios no lower than 1.9 and 1.4. Hydrogen mass specific lower heating value of 119.930 kJ/kg is nearly three times bigger than methane or petrol. Hydrogen density of 0.0838 kg/m^3 (at normal temperature and pressure) volumetric low heating value equals 10.046 kJ/m^3 and it is lower than methane 32.573 kJ/m^3 and petrol 195.8 kJ/m^3. In a consequence hydrogen occupies a greeter proportion of volume with respect to air. An approximate seven-fold increase in the burning speed of hydrogen flame (265-325 cm/s) over methane or petrol results in shorter burn time. This shorter burn time results from lower heat transfer from hydrogen flame, compared to the ones of either methane or petrol flame. Burning temperature as another important property, based on flame temperature in air - hydrogen burns hotter than methane but cooler than petrol. As a result of detailed analysis of the hydrogen properties, mixtures of hydrogen and conventional fuels have been examined. In their experiments Stebar, Parks, Varde showed hydrogen ability to extend the lean limit of combustion and possibility of reducing CO, HC and CO_2 by using mixtures of hydrogen and petrol [3-5]. Mixtures of hydrogen and conventional fuels were tested by many researches and car producers through the World but the most theoretically based experiment was carried out by Karim on CFR engine [6]. During this experiment fuel mixtures with up to 80% hydrogen in methane by volume were tested while varying air fuel ratio and spark advance at 900 rpm and full load. Hydrogen addition was shown to decrease optimum spark timing. Results of indicated power output and indicated efficiency were reported at spark timings of 10^o, 20^o, 30^o BTDC at air fuel ratios varying from 1.53 to 0.76. Spark timing shows an adverse effect on thermal efficiency. The knocking region was defined for different compression ratios and different mixtures of methane/hydrogen. In 1996 Collier presented a study on 4.6 litter 8-cylinder engine powered with mixtures 0, 10, 20, 30, 40 and 50% hydrogen in methane by volume. Hydrogen addition resulted in the increased emissions of NO_x and lower production of HC in the lean region at 1700 rpm. For particular case of 30% hydrogen mixture, at air fuel ratio 1.53 the engine was tested at various speeds (1700, 2350 and 3000 rpm) for various loads. NO_x production tended to raise with increasing load, while hydrocarbons emissions were decreasing with increasing load independently to engine speed.

Tab. 1. Main properties of hydrogen, methane and petrol [8]

	Hydrogen H_2	Methane CH_4	Petrol
Air-fuel ratio lower limit	~9	~1.9	~1.4
Range of burning [% gas volume in air]	4-75	5.3-15.0	1.2-6.0
Minimal ignition energy [mJ]	~0.02	~0.28	~0.25
Burning speed [m/s]	~2.90	~0.38	~0.37-0.43
Adiabatic flame temperature [K]	~2318	~2190	~2470
Selfignition temperature [K]	~858	~813	~500-750
Density [kg/m^3] at 293.15 K and 101.3 kPa	0.082	0.717	4.4
Stoichiometric air to fuel ratio [kg/kg]	~34	~17.2	~14.8
Volumetric lower heating value [MJ/kg]	~3.37	~2.56	~2.79
Mass lower heating value [MJ/kg]	~120	~50	~44.5

Brake thermal efficiency improved with increasing load at 2320 rpm [7].

For all of the tested cases, the ability to achieve leaner combustion with the increasing amount of hydrogen was noticed. Traditional gasoline engines have been designed to run at near stoichiometric air-fuel ratios, with power controlled by throttle. Utilizing the unique lean burn property of hydrogen power control can be achieved by altering the air/fuel ratio, as was shown in [8]. Preliminary results of data analysis set on standard petrol engine powered by different hydrogen-methane mixtures, 5, 10, 15, 20 and 30% have been presented in this paper. Engine performance and selected parameters of the combustion process for the engine fuelled by petrol, methane and mixtures of methane and hydrogen were compared and discussed.

2. Measurement set-up

The tested engine was an Opel Astra naturally aspirated four cylinder petrol engine with displacement of 1.6 l with power output of 55 kW at 5200 rpm and torque of 128 Nm at 2600 rpm. This engine was modified in a way allowing its CNG propulsion without compression ratio variations. The engine was operated on strictly stoichiometric ratios and used one TW catalyst. Test procedure provided analysis at the idle and for selected higher RPM's at the wide open throttle. Studies provided in-cylinder pressure registration in the crank angle domain for two different series. First series featured engine running on petrol, while the second one was registered for methane hydrogen mixtures operation. Experimental setup included pressure transducer type 6121, 2613B charge amplifier, crankshaft speed and position sensor DPA type by Kistler. Data were acquired through an eight channel NI board of the PCI-6143 type, driven by an application compiled in the LabView environment. Engine load variation was realized with the help of the BOSCH FLA 203 roller bench. Exhaust gases were registered by a fast response Pierburg HGA 400 5GR gas analyzer, while fuel consumption was measured respectively for petrol with the use of precise Pierburg PLU 401 device, while gaseous fuel consumption was registered by a tensometric balance. Experimental setup diagram has been presented on the Fig. 1.

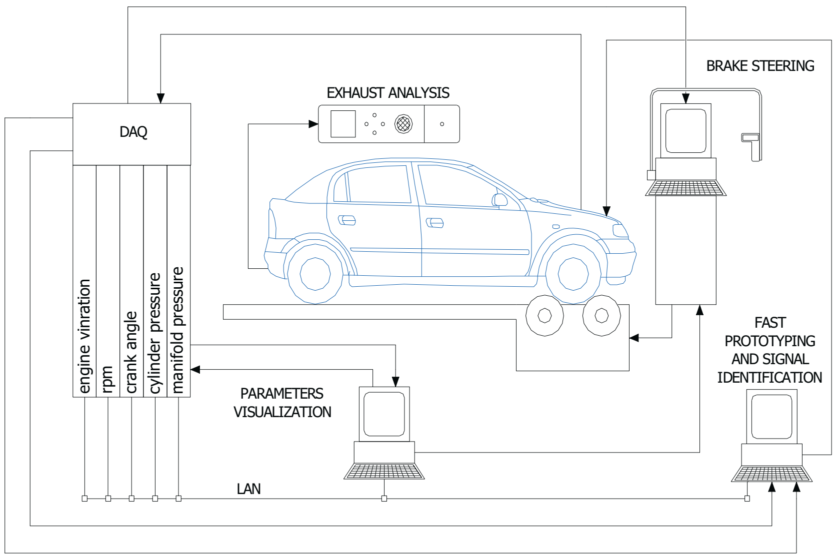

Fig. 1. Schematic diagram of experimental setup

Fig. 2. Engine comparment of tested vehicle

A B

Fig. 3. Special container for gaseous fuel (A) and engine crank angle encoder (B)

Tab. 2. Main characteristics of the tested engine

Type	Four cylinder in-line
Displacement	1600 dm^3
Bore	79.0 mm
Stroke	81.5 mm
Compression ratio	9.6
Exhaust valve opening	41^o BTDC
Exhaust valve closing	11^o ATDC
Inlet valve opening	11^o BTDC
Inlet valve closing	41^o ATDC
EGR ratio	0 %

Registered for the tested engine in-cylinder pressure traces in the crank angle domain were the bases for further model calculations.

3. Experimental Results and Discussion

All measurements were made at 1500, 2000, 2500, 3000, 3500 and 4000 rpm, with the throttle wide open (WOT). Those conditions were chosen because results gave possibility to prepare engine characteristics for all fuels. All tests of Opel engine were done for stochiometric mixtures and with spark advance timing provided by engine ECU. Comparisons of operating characteristics of tested engine powered by all fuels were presented on Fig. 4.

During engine tests following main parameters were registered:

- cylinder pressure,
- TDC recognition,
- rpm,
- manifold pressure,
- mass fuel consumption,
- air mass flow rate.

Numerical calculations carried on the basis of a mathematical model [13, 14] made it possible to estimate and compare:

- in-cylinder pressure and mass fraction burned increase for the engine running on petrol and gaseous fuels in the function of the crank angle,
- mass fraction burned for engine running on petrol and alternatively on CNG and CH_4 and H_2 mixtures, in the function of crank angle,
- maximum in-cylinder temperature, exhaust gases temperatures for the engine fed with petrol and gaseous fuel, in the function of engine crank angle,

- combustion process products both in the function of crank angle (in their formation process), as well as a summary values in the entire cycle.

Selected results obtained for 2500 rpm were presented in the Fig. 4-7. Cylinder pressure and its rise rate for all of the fuels were presented on Fig. 5. The mean burned temperature as a function of crank angle for all fuels are presented on Fig. 6. Mass fraction burned and its rise are presented on Fig. 7, while heat realease and heat realease rise on Fig. 7.

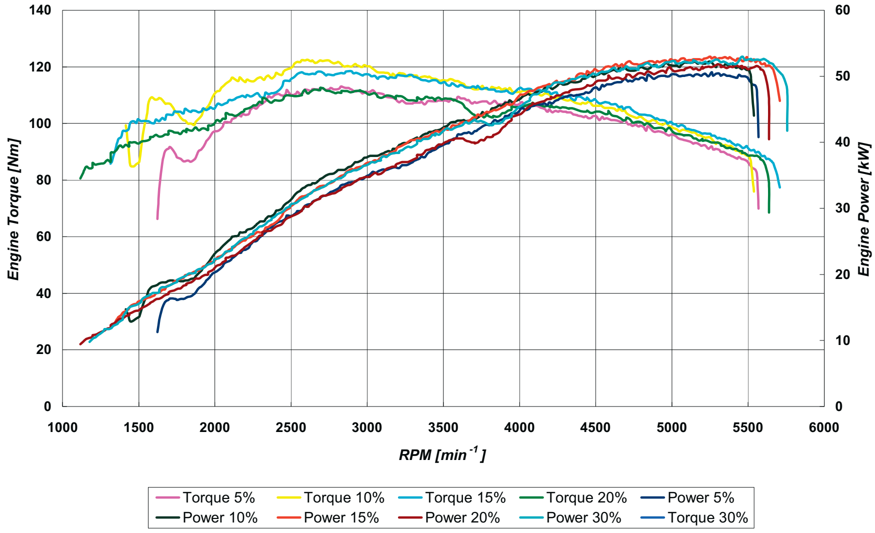

Fig. 4. Engine power and torque for all fuels

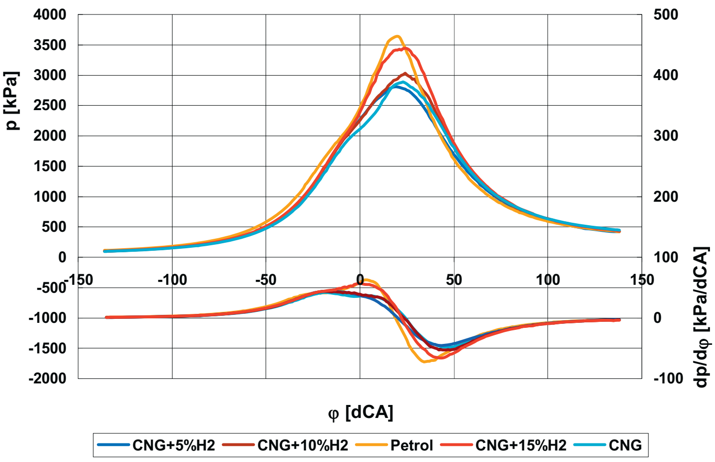

Fig. 5. Cylinder pressure and rate of pressure rise as a function of crank angle for tested engine (for rpm = 2500 and full load)

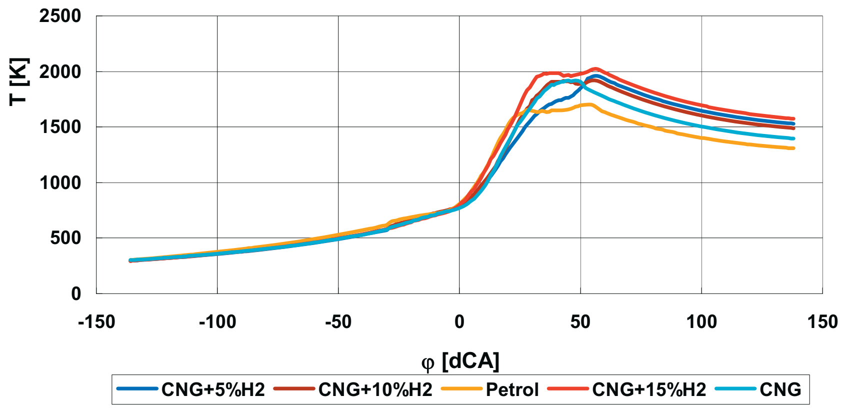

Fig. 6. Mean burned temperature as a function of crank angle for rpm = 2500 and full load

The addition of 5% and 10% of H_2 in gaseous mixture did not influence pressure trace and rate of pressure rise. For the 10% H_2 mixture consisted maximum pressure is bigger and smoothly delayed compared to CNG. Burning temperatures for those mixtures are the same as for CNG and about 300 K bigger than for petrol. For 15% H_2 mixture all parameters do already vary significantly. In this case the trace of pressure is different when compared to CNG and maximum value of pressure increase. The burning temperature increases more than for all other cases including petrol. Mass burned ratio presented as a function of crank angle for this mixture varies less as for petrol, but the heat release is bigger than for petrol.

H_2 accelerates the combustion primarily in the initial combustion stage, Fig. 9, case of 5% mass fraction burned. For 10% mass fraction burned the time of combustion is increasing with increasing addition of H_2.

When compared to CNG (with 98% of Methane) hydrogen addition up to 15% was shown to lower the partial burn limit. Coresponding decrease in brake power up to 8% was noticed. What concerns pollutants prodution - hydrogen addition up to 15% results in the decrease in CO_2 up to 26%, CO emission drop up to 40% and the increase in NO emissions aprroximately 30%

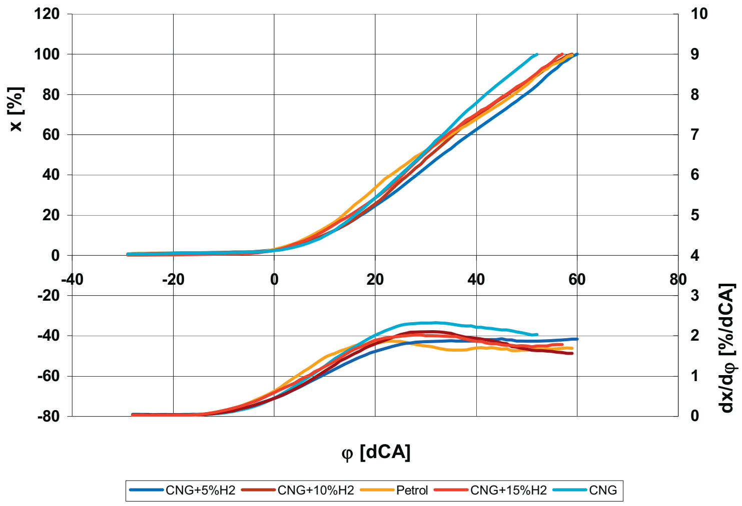

Fig. 7. Mass fraction burned and ratio of mass fraction burned rise as a function of CA for rpm = 2500 and full load

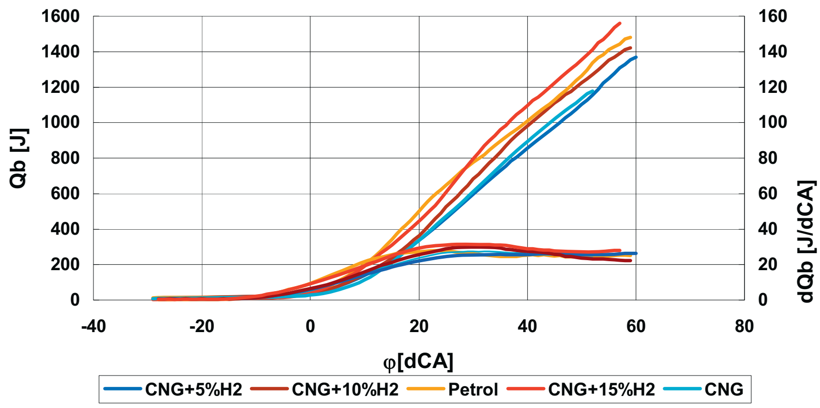

Fig. 8. Heat realese and heat realease rise as a function of cranck angle for rpm = 2500 and full load

4. Conclusions

From the environmental, economical and technical perspectives, blending the natural gas with relatively small amounts of hydrogen can significantly improve the emission characteristics of the IC engine. In the described experiment, fuel supply system was designed and implement in a way that provided the engine with hydrogen /natural gas mixtures in variable proportions. The composition of those mixtures can be set independently of engine operation. For practical applications some minimal modifications are necessary to set variable mixtures compositions dependently to engine load with the minimal pollution optimization.

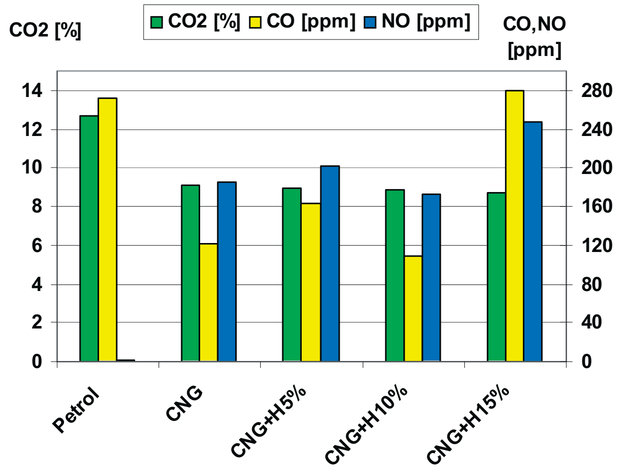

Fig. 9. Calculated CO_2, NO and CO emission

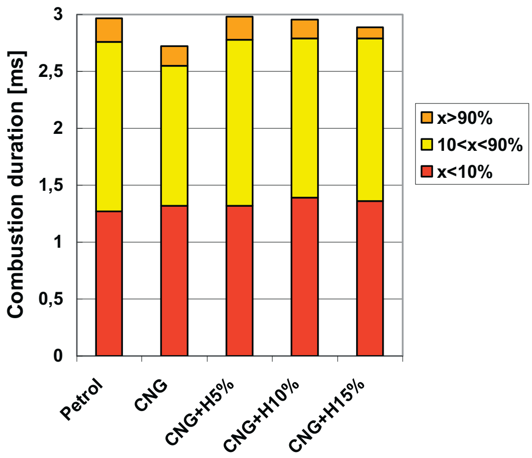

Fig. 10. Comparition of combustion duration of all fuels used during tests for rpm = 2500 and full load

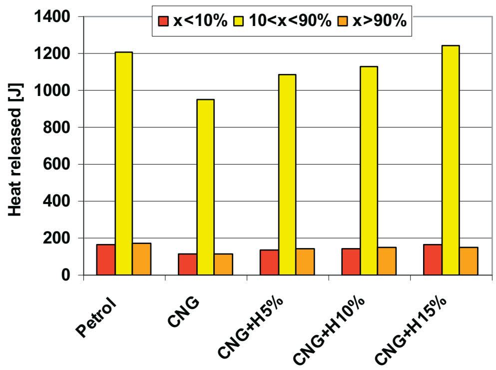

Fig. 11. Energy amounts produced in subsequent combustion process phases

The possibility of passenger car engine operation on H_2-CH_4 mixtures has been demonstrated in the paper, with the underlining of the potential of those mixtures in the increasing of the engine efficiency. Necessary changes in strategy of engine regulation, especially in air/fuel ratio, ignition advance and EGR rate, were noticed and prepared.

The best combinations of EGR ratios, hydrogen share amounts in the fuel and spark timing for optimal in-cylinder pressure characteristics providing moderate combustion temperatures and low expansion cylinder temperatures are being currently tested on a dedicated gas engine.

References

[1] Bach, C., Lämmle, C., Bill, R., Soltic, P., Dyntar, D., Jammer, P., at al., *Clean engine vehicle, a natural gas driven Euro-4/SULEV with 30% CO_2 emission*, SAE Paper 2004-01-0645, 2004.
[2] Berner, H-J., Bargende, M., *Ein CO_2 - minimales Antriebskonzept auf Basis des Kraftstoffes Erdgas*, Haus der Technik Fachbuch Band 37, Expert Verlag, Essen, 2004.
[3] Stebar, R. F., Parks, F. B., *Emission control with lean operation using hydrogen-supplemented fuel*, SAE Paper 740187, 1974.
[4] Parks, F. B., *A single-cylinder engine study on hydrogen-rich fuels*, SAE Papers 760099, 1999.
[5] Varde, K. S., *Combustion characteristics of small spark ignition engines using hydrogen supplemented fuel mixtures*, SAE Paper 810921, 1981.
[6] Karim, G. A., Wierzba, I., Al-Alousi, Y., *Methane-hydrogen mixtures as fuels*, Int. J. Hydrogen Energy, 1996, 21 (7).
[7] Collier, K., Hoekstra, R. L., Mulligan, N., Jones, C., Hahn, D., *Untreated exhaust emission of a hydrogen-enriched CNG production engine conversion*, SAE Paper 960858, 1996.
[8] Bauer, C. G., Forest, T. W., *Effect of hydrogen addition on the performance of methane-fueled vehicles*, International Journal of Hydrogen Energy, 26 (2001).
[9] Flekiewicz, M., *Studium eksperymentalne nad wykorzystaniem mieszanin metanowo-wodorowych do zasilania silników ZI*, Zeszyty Naukowe Politechniki Śląskiej, seria Transport, 46, 2007.
[10] Flekiewicz, M., Flekiewicz, B., *Mieszanina wodoru i gazu ziemnego do napędu silników spalinowych*, www.kape.gov.pl
[11] Flekiewicz, M., Kubica, G., *The practical verification of the mathematical model of gas engine powered by LPG*, Proceedings of 8th European Automotive Congress, Bratislava 2001.
[12] Mackowski, J., Wilk, K., *The effect of the mixture and flame front initial temperature on the heat transfer between the zones in the CI engine*, 12th International symposium in combustion process, Bielsko Biała, Poland 1991.
[13] Flekiewicz, M., Kubica, G., Wilk, K., *The Selected aspects of exhaust gases composition in gas engines*, Proceedings of International Symposium "Motauto'02", Russe 2002.
[14] Flekiewicz, M., Kubica, G., Wilk, K., *An Attempt of prediction of exhaust gases composition in SI engines alternatively powered by petrol and LPG,* VIIth International Conference GAS ENGINE 2006.

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