ANTON ČERNEJ D.Sc.
ŽELIMIR DOBOVIŠEK D.Sc.
BREDA KEGL D.Sc.
The Faculty of Mechanical Engineering
University of Maribor
Maribor, Smetanova 17

Prometna tehnika - Traffic engineering
Izvorni znanstveni članak - Original Scientific Paper
U. D. C. 629.114.4:669
Primljeno - Accepted: 20 Jul. 1996
Prihvaćeno - Approved: 4 Sep. 1996

THE PRACTICAL CFIE MATCH TO POWER ARTICULATED TRUCK ENGINES

SAŽETAK

PRAKTIČNA PRILAGODBA KLASIČNIH UREĐAJA ZA UBRIZGAVANJE GORIVA U MOTORIMA VELIKE SNAGE ZA TERETNA VOZILA

U radu su navedeni i opisani osnovni zahtjevi s obzirom na sustav za ubrizgavanje goriva kod pojačanih turbo artikularnih Dieselovih motora teretnih vozila. Dan je primjer pristupa prilagodbi opreme za ubrizgavanje goriva radi poboljšanja Dieselovih motora za teške uvjete rada. Primjena pumpe za ubrizgavanje sa šupljom bregastom osovinom može omogućiti daljnje proširenje njene uporabe kako bi se poboljšao rad Dieselovih motora.

Symbol

BSFC - break specific fuel consumption
°CAM - camshaft angle
CFIE - conventional fuel injection equipment
DI - direct injection
F/A - fuel/air ratio
FIE - fuel injection equipment
FIKE - fuel injection kinetic energy
FSHE - fuel specific heating value
FAM - fuel air mixing rate
HC - hydro carbons
HP - high pressure
HV - heayv duty
ID - injection delay
IR - injection rate
MIP - mean injection pressure
MIR - mean injection rate
MPDR - mean piston displacement rate
OP - over penetration
PN - spray penetration length
RPM - rotation per minute
SI - spray interaction
SOR - MIR/MPDR - spread over ratio
VCO - valve covered orifice

d - nozzle hole diameter
d_{32} - Sauter mean diameter
h_n - nozzle needle lift
p_I - pressure after fuel pump section
p_{II} - pressure in front of injection nozzle
m_a - mass of entrained air
m_f - mass of injected fuel
p_{sr} - mean injection pressure
p_{sr1} - reference mean injection pressure
R_p - plunger diameter match ratio
s_t - plunger stroke
s_T - spray penetration length
Q_c - fuelling
φ - pump camshaft angle
φ_{ub} - injection duration

1. INTRODUCTION

Fuel injection process affects fuel/air mixing rate [1] by:

design - fuel spray arrangement
- injection rate diagrams
- fuel atomisation (d_{32})

control - timing adjustment
- IR shaping.

This simple scheme, however, may be portrayed for the air borne fuel. On the contrary, in the case of fuel impingement FAM from wall is controlled by air motion. It is world wide accepted that in order to upgrade and to uprate DI diesel engine FIE technology is to be redefined [2] and one has to apply:

– higher injection pressure
– finer fuel atomisation
– maximum number of nozzle holes, without swirling air for HV engines
– IR shaping
– speed and load dependent timing.

IR shaping is related mostly to the initial and to the end duration phase of fuelling [3].

No doubt that:

- *Limiting* the amount of fuel injected during the ignition delay period reduces the rate of cylinder pressure rise and hence NO_x emission. Therefore, a controlled initial IR is required.
- *Modest* spill rate and slow needle closure produce:
  - (i.) poor atomisation toward the end of injection
  - (ii.) reduced mean injection pressure
  - (iii.) stretched duration of injection
- *Excessive* peak injection rate creates over-impingement followed by:
  - (i.) wallquenching
  - (ii.) BSFC deterioration
  - (iii.) worsening of HC emission.

To meet emission regulations and to save fuel economy, the current FIE must produce a high injection pressure along with IR shaping and timing control. However, a high injection presure:

- makes *IR control* difficult, hence IR phase - shaping is more complex
- demands a high mechanical and hydraulic *stiffness* of the FIE and its drive.

Lead - wise the following is a listing of the major ones:

- *Increase* of the pressure squareness or to purposely increase the mean injection pressure instead of peak pressure
- *Increase* injection pressure up to optimised upper limit
- *Reduction* of trapped volume ratio of the FIE (HP) hydraulic system
- *Appreciation* of the principal governing relationship between MIR and MPDR (Fig. 1).

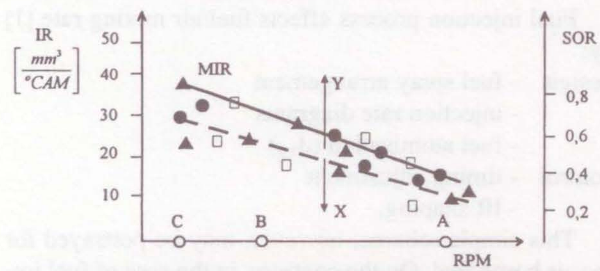

Figure 1 **- A general trend of full load relationship between the spread over ratio (SOR) and rotational speed A - rated conditions, B - peak torque conditions, C - lowest full loaded speed, X - toward finer atomisation, Y - toward shorter injection**

Fig. 1 indicates that to meet better atomisation a smaller nozzle (in direction X in Fig 1) flow area should be applied. A smaller total nozzle flow area imposes a higher mean injection pressures and an improved FAM rate as indicated in Fig. 2.

Better atomisation means smaller Sauter mean diameter, but the energy required for spray disintegration is strongly dependent on d_{32} (see Fig. 3).

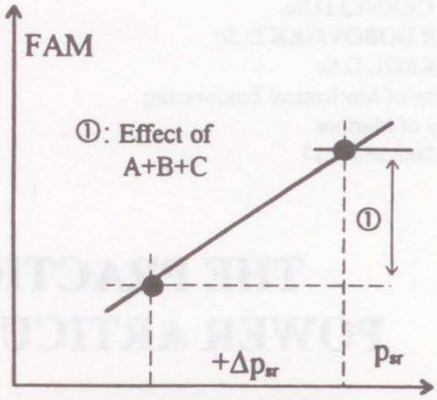

Figure 2 **- Increasing mean injection pressure psr improves FAM rate due to: A + B + C effect (see Fig. 1)**

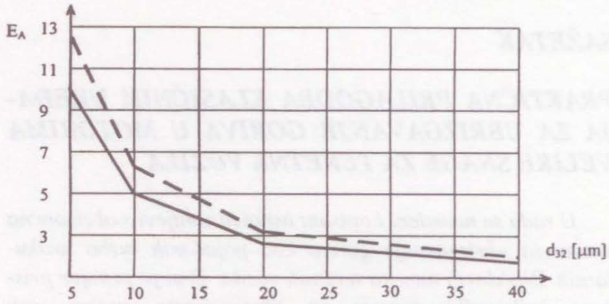

Figure 3 **- Specific fuel atomisation energy EA (CALCULATED) VS Sauter mean diameter (fuel D2), – – – surface fuel tension 0.0315 N/m, ——— surface fuel tenesion 0.0253 N/m**

Fig. 4 indicates that the fuel consumption increases with the increase of injection pressures if not compensated with a more efficient combustion.

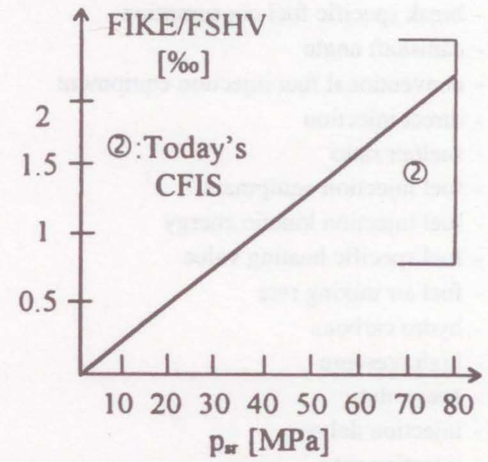

Figure 4 **- The correlation between FIKE/FSHE ratio and mean injection pressure (p_{sr})**

2. THE MATCH APPROACH TO IMPROVE FAM RATE WHEN BOOSTING

The test engine was a four stroke DI, water cooled version with the 150 mm piston diameter. Combustion

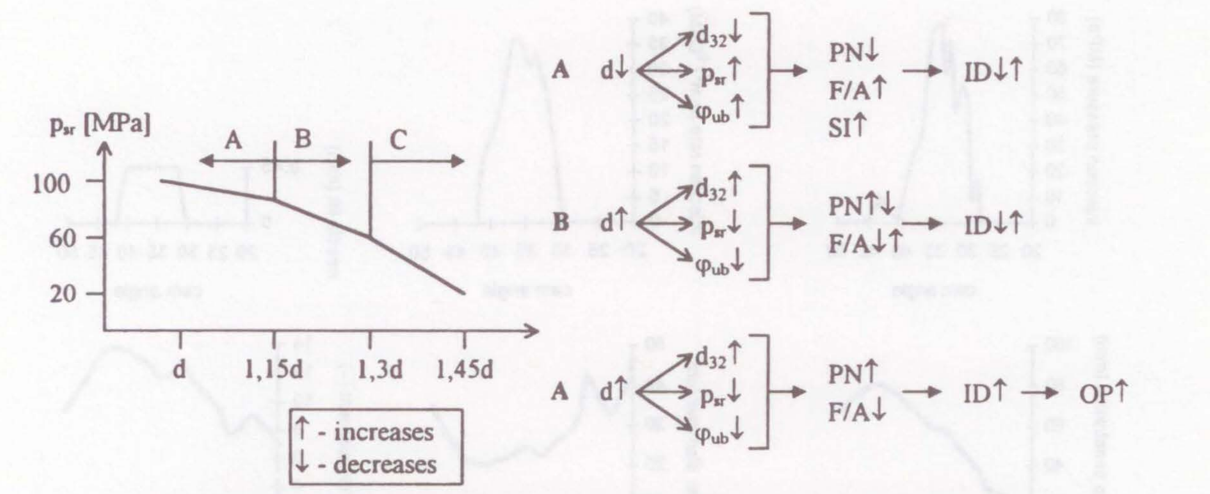

Figure 5 - **Effect of psr and d on spray characteristics (PN - spray penetration length, F/A - fuel/air ratio, SI- spray interaction, ID - injection delay, OP - over penetration)**

chamber was quiescence and open, of Mexican hat type. It means that impingement may not be severe and VCO nozzle may be comfortably arranged.

However, Fig. 5 indicates that all spray characteristics are affected when the nozzle hole dia is changed. Also the pump and the pump drive loading should be reconsidered in the case if the total nozzle flow area is reduced.

Here, it should be pointed out, that when boosting the environmental aspects could not be neglected, regarding gaseous emissions, particulates and noise.

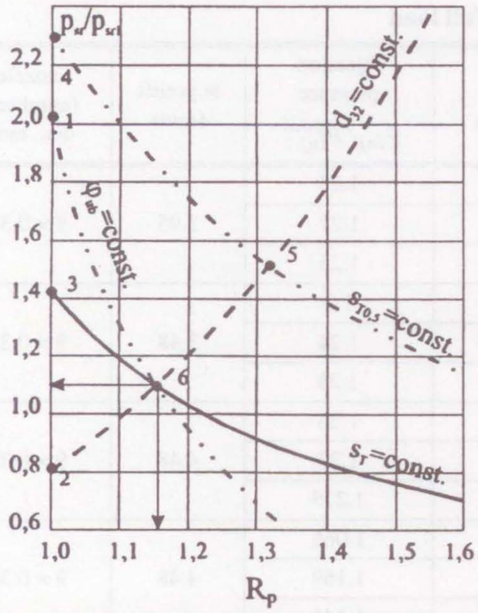

Figure 6 - **Matching diagram, a comparison with FIE of optimum design (denoted with 1)**

Figure 6 depicts the applied match. The calculations showed that for 40% upratings in power the conditions 5 in Fig. 6 should satisfy the optimum requirement, which further means the invariable d_{32} and the spray penetration distance in ignition delay phase ($S_{T0,5}$). Accordingly, the 9x0.35 mm nozzle hole arrangement, centrally positioned injector and VCO nozzle configuration was applied.

3. FIE PUMP

At the beginning of the test it was not possible to match a high MPDR with an elastic pump drive. Also modest plunger dia and full lift had not offered much space for FIE uprating. For this reason a hollow cam profile was applied with a high prelifting in combination with "over-retraction" during injection (via a large total nozzle flow area). This "pulsating inertia emptying" produced pressure oscillations and spray characteristic changes as pointed out in diagrams in Fig. 7. Main match data are presented in table 1.

Table 1 - **Main injection and spray characteristics at rated conditions (1000 CAM-RPM)**

fuelling (mm^3/st)	286.84
mean injection rate (mm^3/°CAM)	23.13
injection duration (°CAM)	12.40
injection duration (ms)	2.07
mean injection pressure p_{II} (MPa)	46.05
mean injection pressure p_I (MPa)	52.07
Maximal injection pressure p_{II} (MPa)	85.33
Maximal injection pressure p_I (MPa)	93.48
vapour volume (mm^3)	89.58
fuelling during first 0.5 ms (mm^3)	40.14
fuelling up to angle $\varphi_x = 30°$	0.39
fuelling up to h_n^{max} (mm^3)	19.84
air entrainment - mean value (m_a/m_f) (-)	11.01
spray tip penetration - mean value (mm)	53.49
spray angle - mean value (°)	13.71
Sauter diameter - mean value (μm)	28.22

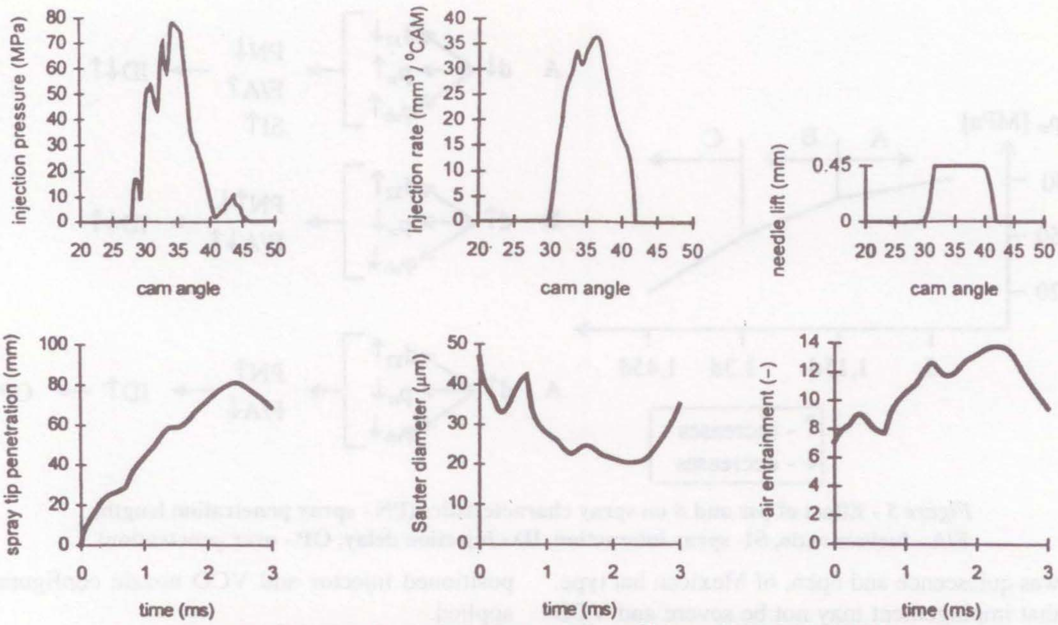

Figure 7 - **Calculated match data at rated conditions, 1000 CAM-RPM**

As a consequence, the oscillations of injection pressure created the oscillating of air entraiment (Fig. 7) causing a high FAM rate. With overretraction the spill rate is improved (Fig. 8) and with it also the soot emission.

4. COMPARISONS

In table 2 the comparisons between the new matched FIE and the FIE of optimum design goal are presented.

Table 2 **- The comparison of test bench experimental results at full load**

Test No.	RPM pump	fueling q_c/q_c^{goal}	injection duration t_{inj}/t_{inj}^{goal}	mean injection rate MIR/MIR^{goal}	injection pressure p_{inj}/p_{inj}^{goal}	at prelift (mm)	nozzle (number × dia., mm)
A1	650	0.969	1.015	0.96	1.25		
A2	825	0.984	1.0345	0.958	1.27	3.95	9 × 0.33
A3	1000	1.027	1.075	0.953	1.25		
A4	650	0.969	1.078	0.906	1.2		
A5	825	1	1.12	0.898	1.24	3.48	9 × 0.33
A6	1000	1.045	1.15	0.905	1.23		
A7	650	0.969	1.109	0.88	1.26		
A8	825	0.984	1.07	0.98	1.27	4.48	9 × 0.33
A9	1000	1.045	1.07	0.969	1.275		
B1	650	0.968	0.937	1.042	1.066		
B2	825	1	0.948	1.06	1.169	4.48	9 × 0.35
B3	1000	1.062	1	1.059	1.141		
D1	650	0.922	0.922	1.008	1.078		
D2	825	0.952	0.965	0.993	1.099	4.48	9 × 0.35
D3	1000	0.993	1	0.99	1.18		
D4	650	0.922	0.968	0.959	1.114		
D5	825	0.952	0.948	1.011	1.149	4.25	9 × 0.35
D6	1000	0.993	1	0.99	1.163		

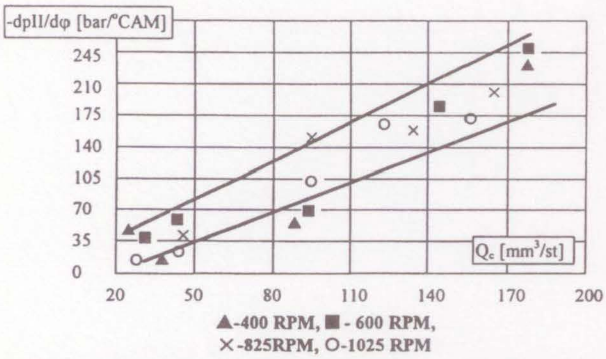

Figure 8 - **Spill rate ($dp_{II}/d\varphi$) correlation vs. Fuelling (Q_c)**

Goal sample case means the engine is equipped with a strong compact fuel injection in-line pump.

Table 2 indicates, that with a precise match it is possible to obtain nearly the same performance of this inexpensive version of FIE as in the case when the same engine was equipped with the FIE of modern compact design.

5. CONCLUSIONS

- FIE boosting for purpose should be exercised by the calculation at first
- FIE uprating should consider mechanical rigidity of the pump drive and the contact pressures between cam and tappet roller
- HOLLOW cam may offer extension in the pump application. However, reintraint cam produces higher pumping torques and therefore in the case of light weight design, nozzle flow area should be adjusted. To avoid poor spray atomisation, oscillating pressure diagrams may be met by overretraction via larger total nozzle flow area.

SUMMARY

Basic requirements related to fuel injection system of upgraded turbocharged articulated truck diesel engines are listed and discussed. An example of the FIE matching approach to upgrading of a heavy duty diesel engine is presented. The application of hollow cam fuel injection pump may offer a further extension of its use in order to uprate diesel engine performance.

ACKNOWLEDGEMENT

This research project was sponsored by the Ministry of Science and Technology of the Republic of Slovenia (Project No. J2-7655-795).

LITERATURE

[1] **P. HERZOG**: VDI Fortschritt-Berichte, Reihe 12 Nr. 127

[2] Ricardo Group News, Issue 38, Nov. 1989.

[3] **A. CERNEJ, Ž. DOBOVIŠEK**: "High pressure injection and diesel economy and emissions", Project DOE No JF940, Int. report 2/3, University of Maribor, Maribor Feb. 1992.