THE FUEL PUDDLE DYNAMICS IN THE SPARK IGNITION ENGINE

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1.0 Abstract. The mixture formation process in the spark ignition engine takes place in front of the inlet valve, except for engines with the direct petrol injection. Part of the injected fuel is deposited on the channel wall and valve back face and creates fuel puddles. The fuel puddles serve as fuel reservoirs.

The dynamics of the fuel puddles influences the mixture formation process and production of harmful emissions, especially during transient conditions.

The behaviour of the fuel puddles on the two different locations is studied and explained. The model based on energy and mass conservation laws is used for the purpose of this paper.

This paper resulted from co-operation between STU and Laboratorium für Motorsysteme ETH Zürich.

2.0 Introduction

The task of mixture preparation equipment is to keep correct quantization of fuel, fuel atomization and to rectify created mixture into the cylinder. In order to fulfil the vehicle's exhaust emission standards it is necessary to maintain a constant air to fuel ratio under wide variety of conditions.

Only one cylinder, fully warmed-up port fuel injected SI engine is studied.

The mixture formation phenomenon is non-linear process. The amount of the injected fuel over different air excess ratio (AER) and engine load is shown in Fig 2.1.

The mixture formation process is based on the fact that not whole injected fuel enters the cylinder. The fuel injected can reach the manifold walls where it creates the fuel puddles. The fuel puddles on the two different locations are taken into account for the purpose of this paper. The first fuel puddle is on the Channel Wall (Cha) and the second one is on the Valve Back Face (VBF), Fig. 2.2. The fuel from the fuel puddles can evaporate and flow to the cylinder. The fuel in the cylinder is composed of the drops, vapours and liquid drained from the both fuel puddles.

The goal of this paper is to describe and explain the non-linearity of the mixture formation phenomena.

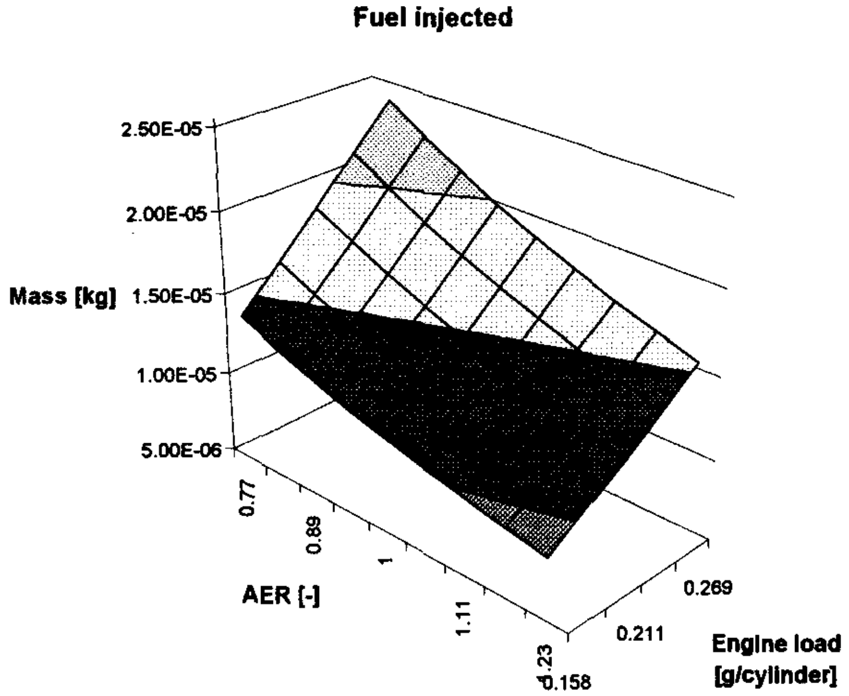

Fig. 2.1 Amount of the fuel injected

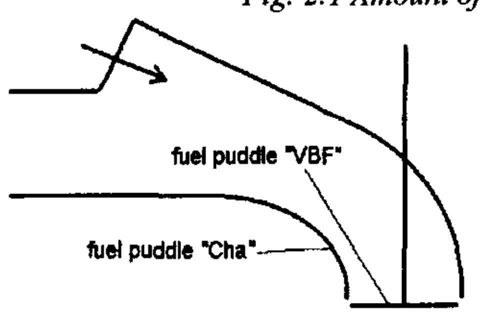

Fig. 2.2 Scheme of the intake manifold in front of the intake valve

3.0 Model

In this work is used control oriented mathematical model of the mixture formation phenomena ("PMFM-model" – Project Mixture Formation Model) [1], [2]. "PMFM-model" is based on energy and mass conservation laws and provides the information about amount of the fuel in the fuel puddles.

The main features of the model are as follows. The gas exchange modelling is based on measured pressures in the inlet and exhaust system. There is an estimated two-dimensional gas velocity field in the inlet port. Fuel droplets are injected into this field. The injector is characterised by the droplet size and spatial distribution, by opening and closing time and by droplets starting velocity. A two-dimensional trajectory, the evaporation and secondary break-up of every single droplet, which represents a packet of droplets, are then calculated. Droplets can impinge onto port walls or enter the combustion chamber. The port walls and the poppet surface are considered separately. The puddles evaporate, flow and so they can reach the combustion chamber. If liquid fuel enters the combustion chamber, it immediately evaporates. There is a transfer function that gives the combustion chamber's state at the exhaust valve opening from the state at the inlet valve closing. The thermodynamic state is calculated by a

table function that is identified by cylinder pressure indication experiments at steady engine operating.
The fuel used in the "PMFM-model" is a blend of six single hydrocarbons. Its composition is expressed by the mass fraction of each fuel component and the composition of the injected fuel is defined in Tab. 3.1.

Hydrocarbon	Chem. formula	Mass fraction [-]	$T_{B,norm}$ [K]	Density at 298 K [kg/m^3]
Cyclopentane	C_5H_{10}	0.15	322,40	746.90
Benzene	C_6H_6	0.20	353,24	871.20
2-Methylhexane	i-C_7H_{16}	0.20	363,20	671.90
2,2,3-Trimethylpentane	C_8H_{18}	0.25	383,20	711.00
Ethylbenzene	C_8H_{10}	0.15	409,35	864.00
1,2,4-Trimethylbenzene	C_9H_{12}	0.05	442,50	872.00

Tab. 3.1 Composition of the injected fuel
To study the mixture formation phenomenon the five engine loads at one engine speed were set. The engine speed was kept at 2000 rpm and loads were 0.158, 0.183, 0.211, 0.240 and 0.269 g air per cylinder corresponding to absolute manifold pressure 35.0, 40.0, 45.0, 50.0, 55.0 kPa. The amount of the injected fuel is set to produce AER in range from 0.77 to 1.23.
The engine load range is limited due to the fact, that "PMFM-model" is verified on this range.

4.0 The mixture formation phenomenon

The injected fuel impinges on the channel wall and valve back face. The total amount of the fuel on the channel wall and valve back face over different air excess ratios and engine loads is shown in Fig. 4.1 and Fig. 4.2.

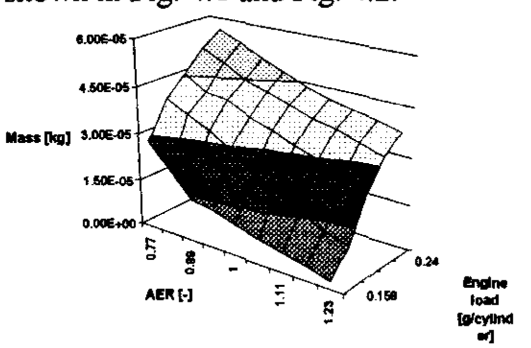

Fig. 4.1 Amount of the fuel on the Cha

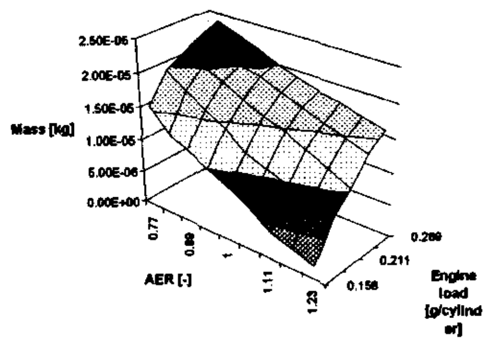

Fig. 4.2 Amount of the fuel on the VBF

As was already mentioned, the fuel from the fuel puddles can evaporate and flow into the cylinder.
The dependence of the total fuel evaporated from the fuel puddles at different engine loads is in Fig. 4.3 and dependence of the fuel drained from the fuel puddles to the cylinder in Fig. 4.4. The amount of the injected fuel is set to produce stoichiometric conditions.

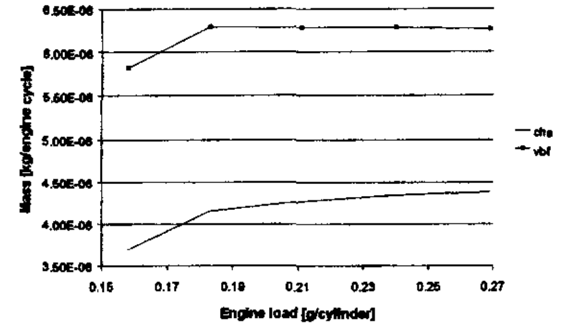

Fig. 4.3 Evaporation from the fuel puddles (AER = 1.0)

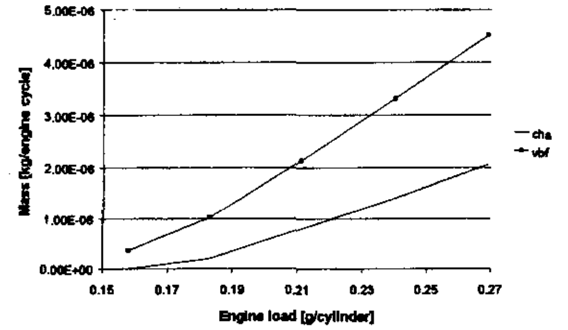

Fig. 4.4 Fuel puddles flow (AER = 1.0)

As can be seen in the region of the low engine load, the main part of the mixture formation process is evaporation of the fuel. The saturation point is reached with increasing engine load i.e. it is not possible evaporate more fuel in the volume in front of the intake valve. The portion of the fuel drained from the fuel puddles to the cylinder increases with further increasing engine load. It can be assumed that in higher engine loads the fuel puddle flow will be the main phenomenon of the mixture formation process.

One engine operating point is chosen. The operating point is engine load at 0.211 g air per cylinder and engine speed is set to 2000 rpm. The amount of the injected fuel is set to produce steady state condition with AER in range from 0.77 to 1.23.

The dependence of the loss of the fuel from the fuel puddles (evaporation and fuel puddle flow) on the AER can be observed in the Fig. 4.5 and Fig. 4.6.

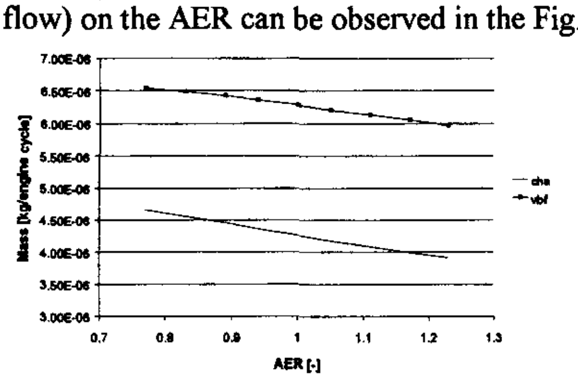

Fig. 4.5 Evaporation from the fuel puddles (engine load = 0.211 g/cylinder)

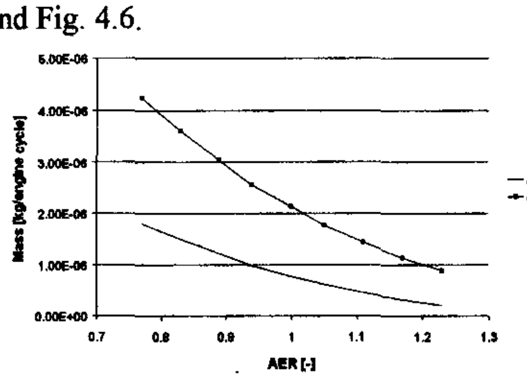

Fig. 4.6 Fuel puddles flow (engine load = 0.211 g/cylinder)

As from Fig. 4.5 can be seen the evaporation from the fuel puddles is linear function of the AER. This can be explained as follows. The operating point of the engine (engine load 0.211 g/cylinder, engine speed 2000 rpm) does not change therefore with more fuel injected more fuel is evaporated.

The dependence of the fuel puddles flow on the AER is non-linear. The fuel puddle flow can be explained as follows. The friction between gas and the liquid fuel causes a fuel flow in the fuel puddle. The fuel puddle flow is based on [3], [4], [5]. The shear stress "τ" between the gas and liquid phase is expressed by Eq. 4.1.

$$\tau = \frac{1}{2} f \cdot \rho \cdot w \cdot |w| \qquad \text{Eq. 4.1}$$

This stress is transformed into the fuel due its viscosity. Newton's viscosity law is applied i.e. there is a linear profile of the velocity over hight of the fuel puddle. The fuel mass flow rate is state by Eq. 4.2.

$$\dot{m} = \frac{1}{2} \frac{\tau}{\mu} \rho \cdot b \cdot h^2 \qquad \text{Eq. 4.2}$$

The dependence of the fuel puddle flow on the squared hight of the fuel puddle is in Fig. 4.7 and Fig. 4.8. The breath of the intake manifold is constant.

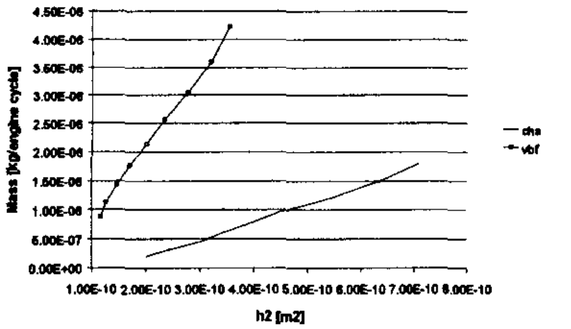

Fig. 4.7 Fuel puddles flow (engine load = 0.211 g/cylinder)

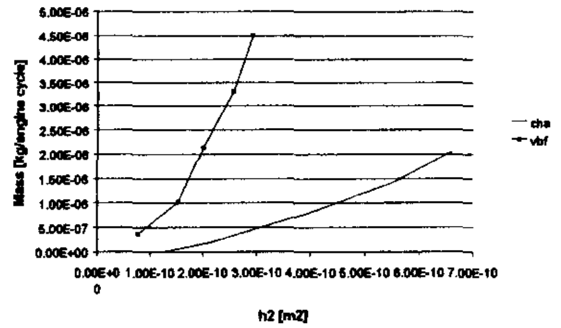

Fig. 4.8 Fuel puddles flow (AER = 1.0)

The fuel puddle flow is also non-linear function of the squared hight of the fuel puddle. This phenomenon is caused by changing the physical properties "τ", "μ", "ρ". When the fully warmed-up engine is considered, than the temperature of the channel wall and intake valve does not change. Variation of the composition of the fuel in the fuel puddles (Fig. 4.9 - Fig. 4.12) is responsible for the change of the physical properties "τ", "μ", "ρ".

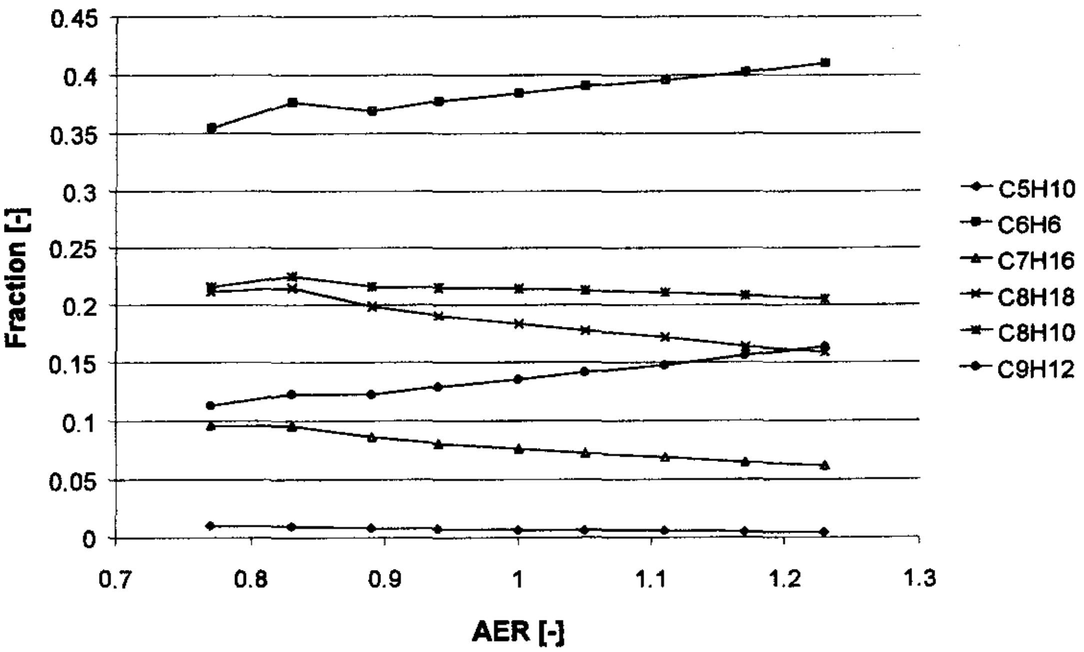

Fig. 4.9 Fractions of the fuel components on the Cha (engine load = 0.211 g/cylinder)

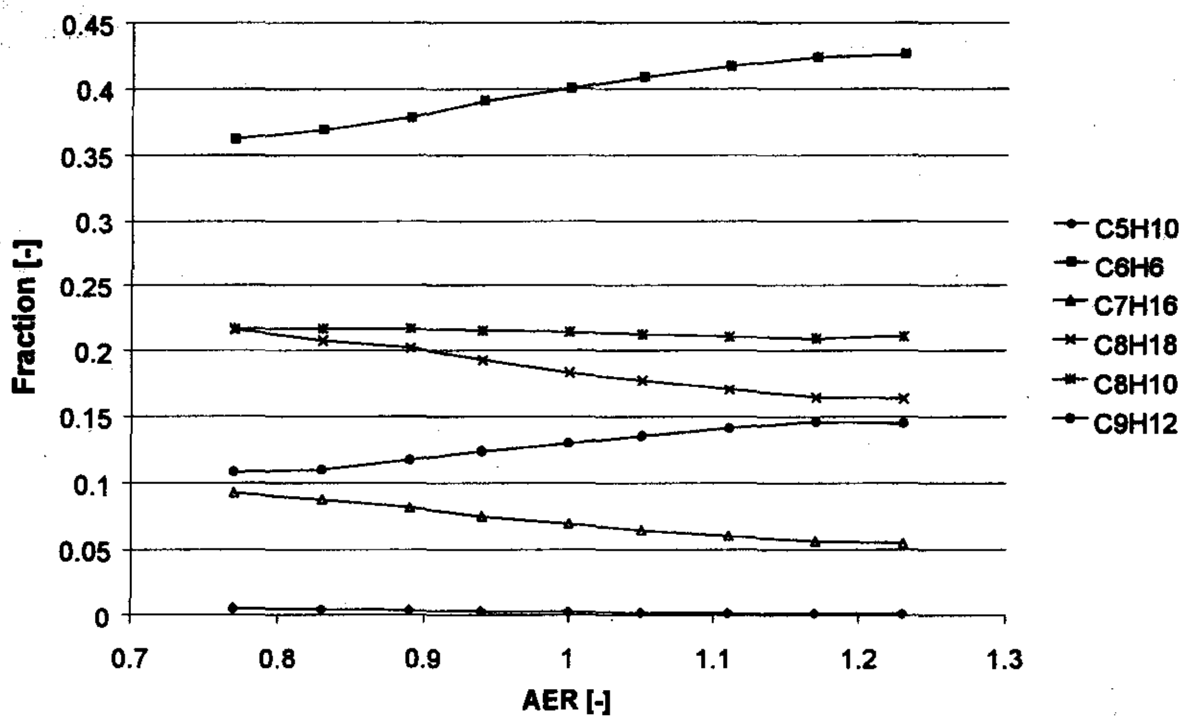

Fig. 4.10 Fractions of the fuel components on the VBF (engine load = 0.211 g/cylinder)

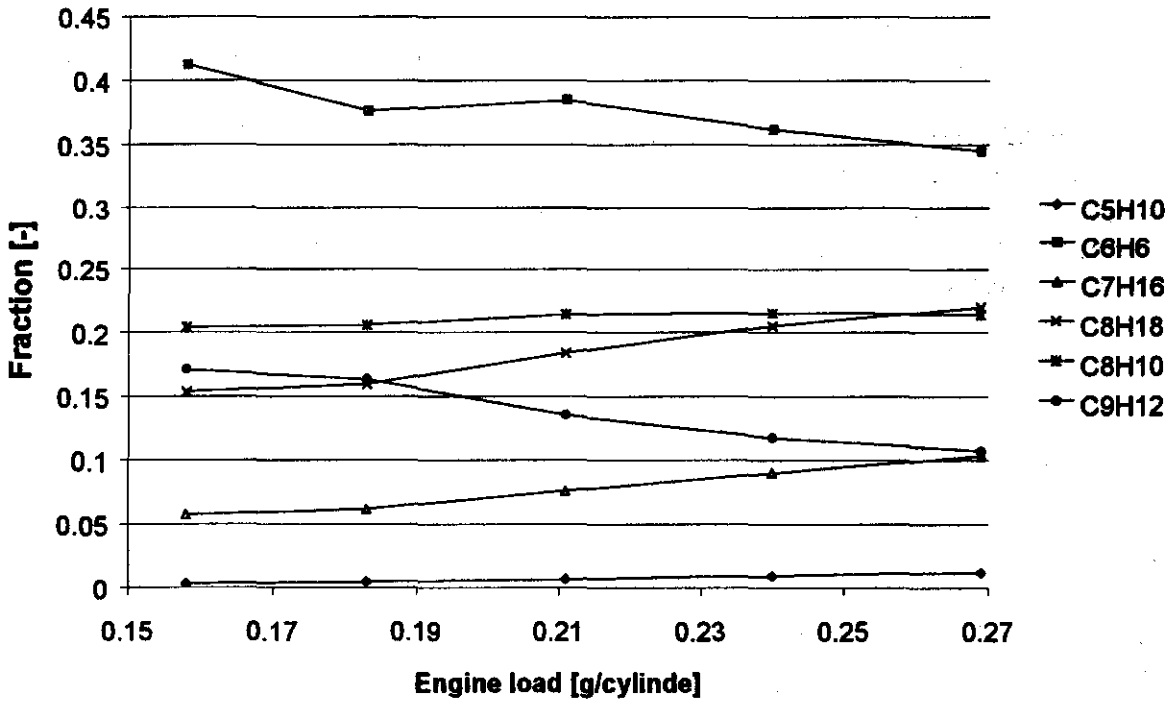

Fig. 4.11 Fractions of the fuel components on the Cha (AER = 1.0)

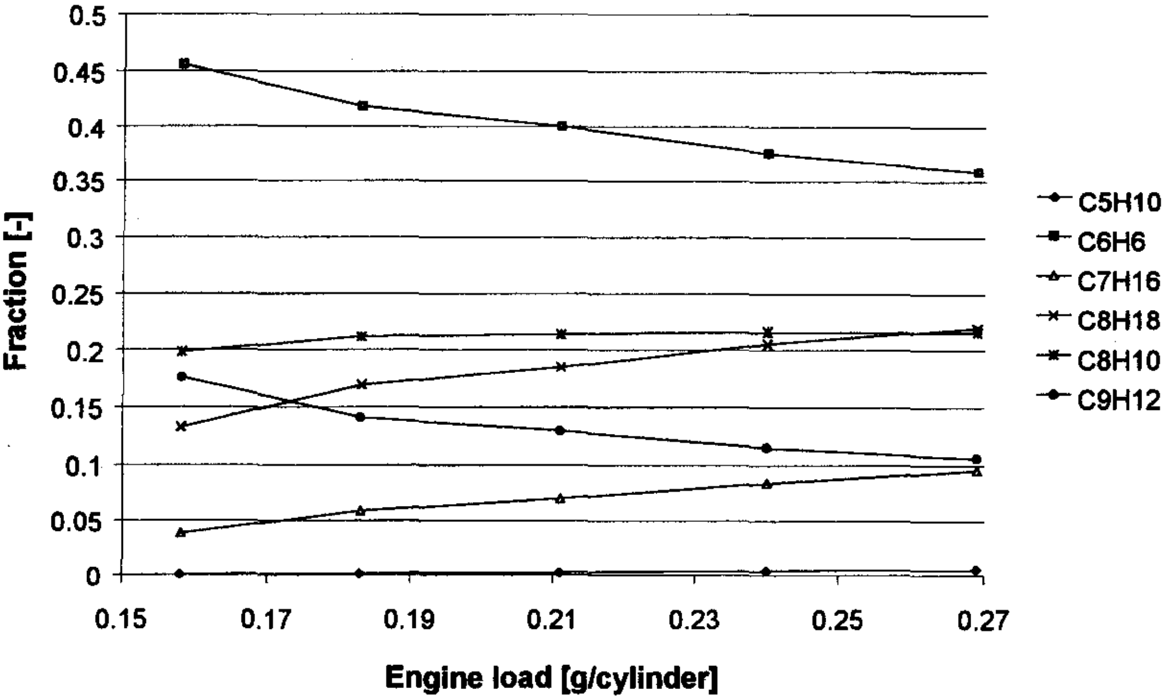

Fig. 4.12 Fractions of the fuel components on the VBF (AER = 1.0)

Fractions of the heavy fuel components in the fuel puddles are increasing with increasing AER (less fuel injected) and vice versa, Fig. 4.9 and Fig. 4.10. Fractions of the light fuel components are increasing with decreasing AER (more fuel injected). Similar behaviour can be observed also in Fig. 4.11 and Fig. 4.12. As engine load (increase of the absolute intake manifold pressure, which act against evaporation) increases, the fractions of the light fuel components in the fuel puddles increase too.
This phenomenon leads to the conclusion that the fuel puddle become more "light" and can more easily flow with more "light" fuel in the fuel puddle and so more fuel is getting into the cylinder.

5.0 Conclusion

Description of the mixture formation process with more component fuel has been presented. The mixture formation phenomenon is non-linear process. The droplets of the injected fuel can evaporate and so are deposited on the intake manifold walls where they create fuel puddles. The fuel reach the cylinder in a several different ways, as droplets, fuel vapours and liquid drained from fuel puddles. Mass conservation laws is fulfilled, amount of the injected fuel is equal to total amount of the fuel in the cylinder for every fuel component.
The non-linear fuel puddle flow has been described and explained in details. The composition of the fuel in the fuel puddles is strongly dependent on the engine load and AER and much differs from the composition of the injected fuel. Only heavier fuel components remain in the fuel puddles at lower engine loads and higher AER (lean mixture). The fuel in the fuel puddles is denser and it flows more freely. Light fuel components remain also in the fuel puddles with increasing engine load and at lower AER (rich mixture). Thereby fuel in the fuel puddles become sparser and it flows less freely. Due to the fuel puddle flow more fuel is getting to the cylinder. This variation of the composition of the fuel puddles leads to the non-linearity observed in Fig. 4.4 and Fig 4.6.

6.0 References

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7.0 Nomenclature

b	m	Breath of the intake manifold
f	-	Friction coefficient
h	m	Height of the intake manifold
m	kg	Mass
$T_{B,norm}$		Boiling point at normal pressure
w	$m\ s^{-1}$	Velocity
μ	Pa s	Dynamics viscosity
ρ	$kg\ m^{-3}$	Density
τ	Pa	Shear stress