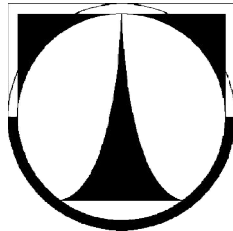


TECHNICAL UNIVERSITY OF LIBEREC
FACULTY OF MECHANICAL ENGINEERING
DEPARTMENT OF VEHICLES AND ENGINES

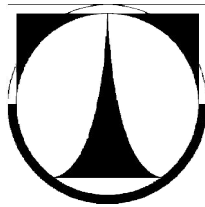


INJECTION OF LIQUID LPG
INTO THE INTAKE MANIFOLD OF THE ENGINE

DOCTORAL DISSERTATION

Liberec, 2013

**TECHNICAL UNIVERSITY OF LIBEREC
FACULTY OF MECHANICAL ENGINEERING
DEPARTMENT OF VEHICLES AND ENGINES**



Ing. Nguyen Thanh Tuan

**INJECTION OF LIQUID LPG
INTO THE INTAKE MANIFOLD OF THE ENGINE**

Doctoral Dissertation

Supervisor: Prof. Ing. Stanislav Beroun, CSc.

Liberec, 2013

Declaration

I have been notified of that Copyright Act No. 121/2000 Coll. Applies to my thesis in full, in particular Section 60, School Work.

I am fully aware that the Technical University of Liberec is not interfering with my copyright by using my thesis for the internal purposes of TUL.

If I use my thesis or grant a license for its use, I am aware of the fact that I must inform TUL of this fact, in this case TUL has the right to seek that I pay the expenses invested in the creation of my thesis to the full amount.

I compiled the thesis on my own with the use of the acknowledged sources and on the basis of consultation with the head of the thesis and a consultant.

Date:

Signature:

ACKNOWLEDGMENT

First and foremost, I would like to express my sincere gratitude to my supervisors Professor. Ing. Stanislav Beroun, CSc for his guidance, great support and encouragement throughout my PhD research studies. Without his guidance and persistent help this dissertation would not have been possible.

I would like to extend my sincere thanks to all the colleagues at the Department of Vehicle and Engines for their support of my work in the Laboratory at Technical University of Liberec, especially to Ing. Pavel Brabec, Ph.D., Ing. Dráb Ondřej and Ing. Dittrich Aleš.

I wish to thank doctoral committee members and friends as a this dissertation would have been impossible without their support.

Lastly, thanks to my family for their unconditional support, encouragement and love. They give meaning to my accomplishments. And most of all, my little daughter, Nguyen Thuy Khanh, who kept me smiling during tough times in the PhD pursuit.

Thank you.

ANNOTATION

The dissertation concerns to the formation of a mixture of liquid LPG injected into the intake manifold of the engine. The main problem is the research process flow of liquid LPG from the electromagnetic control valve in the injector, which is a very intense evaporation of LPG in the channel before the injector outlet nozzle. Evaporation occurs at very low temperatures and after that “icing” takes forms around the surface of the injector. Ice breaks off from the injector and moves into the engine cylinder. The pieces of ice in the cylinder engine can cause engine running irregularities and increase concentrations of unburned hydrocarbons in exhaust gases.

To solve this problem, the researcher is motivated to liquid LPG injection into the intake manifold of the engine. Therefore this research focused on the course of LPG pressure in the channel of the end part of the LPG injector. Mathematical formation and computational model of the liquid LPG was injected into the intake manifold. A significant part of the work also deals with an experimental investigation of pressure in the channel of the end part of the LPG injector and temperatures near the outlet nozzle of the end part of the injector.

KEYWORDS:

Liquefied petroleum gas, the end part of the injector, liquid phase LPG injection, icing phenomenon, LPG pressure course, the channel of the EP, computational model, electromagnetic valve, outlet nozzle of the channel...

CONTENT

1. INTRODUCTION.....	10
1.1.Basic properties of LPG	11
1.1.1.Specific volume, relative density	13
1.1.2.Vapor pressure	13
1.1.3.Limits of flammability	14
1.1.4.Boiling points.....	14
1.1.5.Critical temperature.....	15
1.1.6.Viscosity of LPG.....	16
1.1.7.Latent heat.....	17
1.2.LPG as an alternative fuel for internal combustion engine.	17
1.2.1.Combustion properties	18
1.2.2.Mass per unit volume.....	19
1.3.Advantages and disadvantages of LPG as an engine fuel	20
1.3.1.Advantages of LPG in comparison to conventional fuels.....	21
1.3.2.Disadvantages of LPG in comparison to the conventional fuels	23
2. FUEL SYSTEMS FOR SI ENGINES RUNNING ON LPG	24
2.1.Injection gas phase LPG into the intake manifold (gas LPG injection system)	24
2.1.1.Multipoint gas injection	24
2.1.2.Multipoint sequential gas injection system	25
2.2.Injection of liquid LPG into the intake manifold (liquid phase LPG injection system).....	27
2.3.Direct injection LPG in the cylinder of the engine.....	28
3. PARAMETERS OF THE SI ENGINE RUNNING ON LPG	30
3.1.Environmental impact (exhaust emission of LPG engines and petrol engines)	30
3.2.Efficiency and performance.	31
3.3. The reason of decrease power of LPG engines	32
4. THE MIXTURE FOMATION IN THE LIQUID LPG INJECTION SYSTEM.	35
4.1.Problems analysis of an engine with liquid LPG MPI system.	36
4.1.1.Fundamentals of fuel injection.....	36
4.1.2.Analysis of problems at the LPG injectors	37
4.1.3.Analysis of next problems of liquid LPG injection	40
4.2.Fuel injection duration and amount of LPG injected.	43
5. AIMS OF DISSERTATION.....	45
5.1. Motivation	45
5.2. Objectives of the dissertation	46
6. THEORETICAL BASES	48
6.1. LPG liquid injection system – the basic form	48

6.2.Theoretical analysis of process in the end part of the LPG injector	50
6.2.1. Theoretical analysis of LPG course in the channel and effects of surrounding environment.	50
6.2.2. Estimative calculation of the fresh mixture temperature in the intake manifold	60
7.EXPERIMENTS.....	62
7.1.Experimental devices	62
7.2.Data acquisition systems	65
7.3.Measurement program and result of experiments.	65
7.3.1.Experiments without heating elements	66
7.3.2.Experiment with heating elements	69
8.COMPUTATIONAL SOLUTION OF LIQUID LPG INJECTION INTO INTAKE	
MANIFOLD.	78
8.1.The basic geometric parameters of the end part of LPG injector.	78
8.2.Sample and step of calculation.	78
8.3.Structure of the computational model	79
8.4.Calibration of the computational model, calculative results and discussions	81
8.4.1.Pressure course of LPG in the channel.	81
8.4.2.Temperature course of LPG in the channel and at outlet nozzle.	84
8.4.3.Density of LPG, vapor quality.	86
8.5.Temperature of cylinder charge mixture and estimate of engine performance.	87
9.CONCLUSION.....	91
 REFERENCES	 93
LIST OF AUTHOR’S PUBLICATION	97
Appendix 1: Sketch and drawing of the end part of the injector	100
Appendix 2: Window image of computational model in the excel sheet.....	101
Appendix 3: Temperature of LPG at ON and velocity of damp steam LPG at ON	102

COMMONLY USED SYMBOLS, SUBSCRIPTS AND ABBREVIATIONS

1. Symbols

A	Theoretical consumption of air for fuel	kg/kg
c_p	Specific heat at constant pressure	J/kg.K
L	Specific latent heat	J/kg
M_t	Torque	Nm
m	Mass	kg
$\dot{m}$	Mass flow rate	kg/s
n	Engine speed	RPM, min^{-1}
p	Pressure	MPa, bar
$p_{\max}$	Maximum pressure	MPa
P	Power	kW
Q	Total heat transfer	J
r	Individual gas constant	J/kg.K
S	Area	m^2
t	Temperature	$^{\circ}\text{C}$
T	Temperature	K
V	Volume	m^3
x	Vapor quality	-

2. Greek letters

α	Crank angle	
Δ	Finite change in quantity	
ω	Mass fraction	
ρ	Density	kg/m^3
ε	Compression ratio	
λ	Excess-air ratio	
κ	Specific heat capacities ratio	
β_{crit}	Critical expansion ratio	

3. Subscripts

comp	Computational
crit	Critical point
evap	Evaporation
inj	Injection
int	Intake port
reg	Regulation
liq	Liquid
theor	Theoretic
5C	5°C

4. Abbreviations

CA	Crankshaft angle
DA	Dawoo-Avia

DI	Direct injection
ER	Air equivalent ratio
ECU	Control unit system
FM	Fresh mixture
EP	The end part of injector
EV	Electromagnetic valve
GDI	Gas direct injection
HHV	High heating value
LPG	Liquefied petroleum gas
LHV	Low heating value
MON	Motor Octane Number
MPI	Multipoint injection
NCV	Net calorific value
RPM	Revolution per minute
RON	Research octane number
SI	Spark ignition engines
SOI	Start of injection
ON	Outlet nozzle
TDC	Top dead center
VP	Vapour pressure

1. INTRODUCTION

Environmental issues regarding the emission of conventional fuels such as gasoline and diesel are of serious concern worldwide. The standard emission from conventional fuel vehicles are hydrocarbon (HC), carbon dioxide (CO₂), carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter (PM), etc. These emissions are harmful gases which can have an adverse impact on the human body and destroy the environment since they are key agents in the formation of the greenhouse effect, acid rain and global warming. Therefore, alternative fuels such as natural gas (NG), liquefied petroleum gas (LPG), alcohols... are being considered to replace the role of conventional fuels in order to reduce these harmful emissions in the atmosphere. It is possible that these alternative fuels contribute to a significant reduction in vehicle emissions worldwide [39].

Natural gas had long been introduced to the market where application of cleanliness is emphasized. Liquefied petroleum gas (LPG) is one of the members of natural gases and has been declared as the "cleaner fuel"[38]. LPG has been increasingly chosen as the preferred burning fuel for all types of vehicles due to its advantageous fuel properties. LPG has a high octane number of about 112, which enables a higher compression ratio to be employed and gives more thermal efficiency [10]. Due to the gaseous nature of LPG fuel distribution between cylinders is improved and smoother acceleration and idling performance are achieved. Fuel consumption is also better in comparison with gasoline [38]. LPG is proven to have lower emission of pollutants such as HC, CO₂, CO and NO_x if compared to the conventional fuels.

A lot of research has been done to prove that vehicles using LPG as the burning fuel show no decrease in efficiency as compared to the conventional fuel operating vehicles along with their advantage of reduction in emitted gases from the exhaust of an engine. Besides, LPG has the capability to reduce the noise from a running engine, help effectively decrease noise pollution in urban areas especially during the traffic congestion period.

The price of LPG is low compared to other hydrocarbon fuels such as gasoline and diesel. Even the cost of LPG in fleets is lower than those of gasoline for a range of 15% to 30% [39]. Moreover, the fueling station cost is either equivalent to, or lower than, that for a

comparably sized gasoline dispensing system [37]. Due to the abundance of LPG and important energy and environmental advantages, LPG can be promoted for use in vehicles.

However the use of LPG requires fueling, maintenance and storage facilities to be upgraded to a certain standard to ensure the operational safety of its users. Clean Air Technologies information Pool (2005) [37] showed that LPG storage and distribution location must meet a certain distance requirement to isolate it from residential properties and underground storage tanks. Maintenance facilities must include the detector to sense LPG leakage to prevent explosion due to leaks.

There are three methods for synthesis of LPG. First, LPG is synthesized from syngas. The second method is indirect synthesizing LPG from syngas, synthesis of methanol or dimethyl ether (DME) from syngas, conversion of methanol or DME into hydrocarbon of LPG fraction (Olefin and paraffin), and then olefin hydrogenation to LPG. The last method is a semi indirect synthesis of LPG from syngas, synthesis of DME from syngas or methanol and conversion of DME into LPG in presence of hydrogen [1].

1.1. Basic properties of LPG

Liquefied petroleum gas (LPG) is a colorless, odorless and it is used as a fuel in heating appliances and vehicles. In addition, it is increasingly replacing chlorofluorocarbons as an aerosol propellant and as a refrigerant to reduce damage to the ozone layer [1].

LPG consists mainly of a mixture of paraffinic hydrocarbons with three or four carbon atoms (propane, butane and isobutane) and smaller amounts of unsaturated hydrocarbons (olefins). It may also contain small amounts of hydrocarbons with two or five carbon atoms, and is obtained by extraction from so called natural gas or, in refineries, by treating crude oil.

Varieties of LPG bought and sold in variety composition of propane and butane. The common composition of LPG contains 60% volume of propane and 40% volume of butane. However there are some variations of LPG composition as dictated by its usages and applications. Commercial Propane predominantly consists of hydrocarbons containing three carbon atoms, mainly propane (C_3H_8) [5].

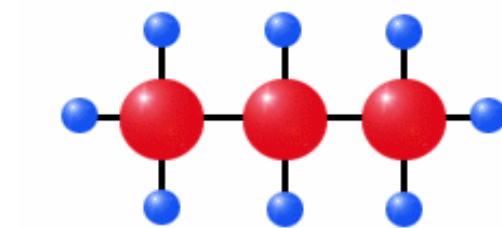


Figure 1.1: Atomic structure of propane [1]

Commercial Butane predominantly consists of hydrocarbons containing four carbon atoms, mainly n-butanes and iso-butanes (C_4H_{10}).

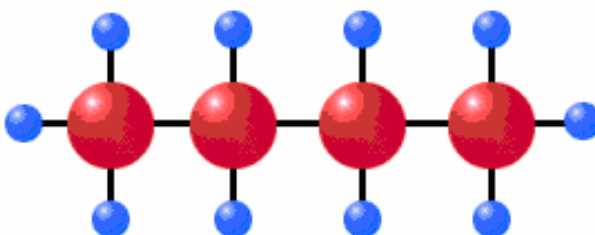


Figure 1.2: Atomic structure of n-butanes [1]

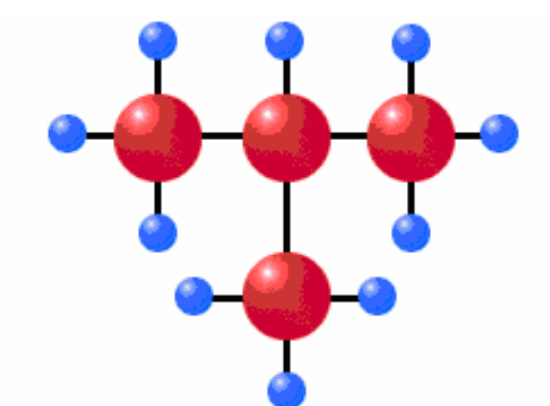


Figure 1.3: Atomic structure of iso-butanes [1]

At normal pressures and normal ambient temperatures, LPG will evaporate. Because of this, LPG is supplied in pressurized steel bottles at normal ambient temperature. In order to allow thermal expansion of the contained liquid, these bottles are not filled completely; typically, they are filled to between 80% and 85% of their capacity [1]. When pressurized

in metal containers (pressure bottles) or in tanks, LPG can be transported easily and can be used immediately for numerous applications, for example, as a fuel.



Cylinders

Toroidal

Underslung

Figure 1.4: Types of LPG tank for engine [15]

1.1.1. Specific volume, relative density

In the vapor phase, LPG exists as a heavy gas, being approximately 1.5 to 2.0 times the density of air. (propane 1.40-1.55; butane 1.90-2.10).

On liquefaction, LPG reduces considerably in volume: the ratio of gas volume to liquid volume (at temperature 15.6°C, pressure 1.016 bar) is 233 for butane; and 274 for propane.

Both gases exist as a clear liquid which is approximately half the density of water - (propane 0.5- 0.51; butane 0.57-0.58).

1.1.2. Vapor pressure

Vapor pressure is a measure of the volatility of the gas. Where vapor exists, in an enclosed system, in conjunction with the liquid phase the pressure occurring is known as the 'saturated vapor pressure'. At the boiling point, this pressure is equal to atmospheric pressure and it increases as the temperature rises. Propane, with its lower boiling point thus exerts, under identical conditions, a greater vapor pressure than butane.

The ratio between the volumes of the vaporized gas and the liquefied gas varies depending on composition, pressure and temperature, but is typically around 250:1. The pressure at which LPG becomes liquid, called its vapor pressure, likewise varies depending on composition and temperature; for example, it is approximately 2.2 bar for pure butane at 20°C, and approximately 22 bar for pure propane at 55°C. LPG is heavier than air, and

thus will flow along floors and tend to settle in low spots, such as basements. This can cause ignition or suffocation hazards if not dealt with.

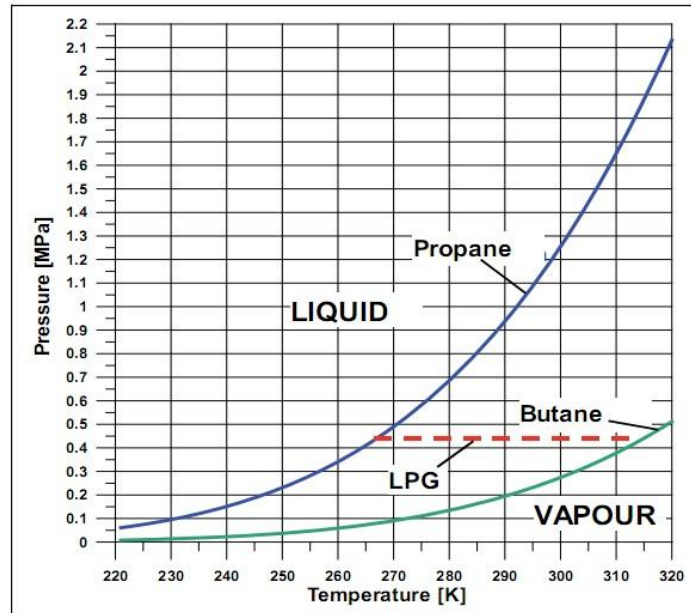


Figure 1.5: Vapor pressure of main LPG fuel components: propane and butane (dashed line represents constant value of vapor pressure for different composition of LPG fuel) [2]

1.1.3. Limits of flammability

A mixture of LPG and air is combustible within certain concentrations, known as the flammable range. This range is bounded by the lower and upper limits of flammability which are approximate 1.8 to 8.4 percent for butane and 2.4 to 9.5 percent for propane. These are approximately values of atmospheric pressure. At higher pressures, or with oxygen, the flammability limits are different.

1.1.4. Boiling points

The gases found in a commercial LPG mixture all have very low boiling points, and exist as vapor under atmospheric conditions.

Where the gases are held at a temperature at or below their boiling point, the vapor pressure will be equal or less than atmospheric pressure. Boiling point of LPG ranges from -42°C to 0°C depending on its mixture percentage of butane and propane.

Above ambient temperature, the gases exert an increasing vapor pressure thus increasing the pressure required to achieve liquefaction.

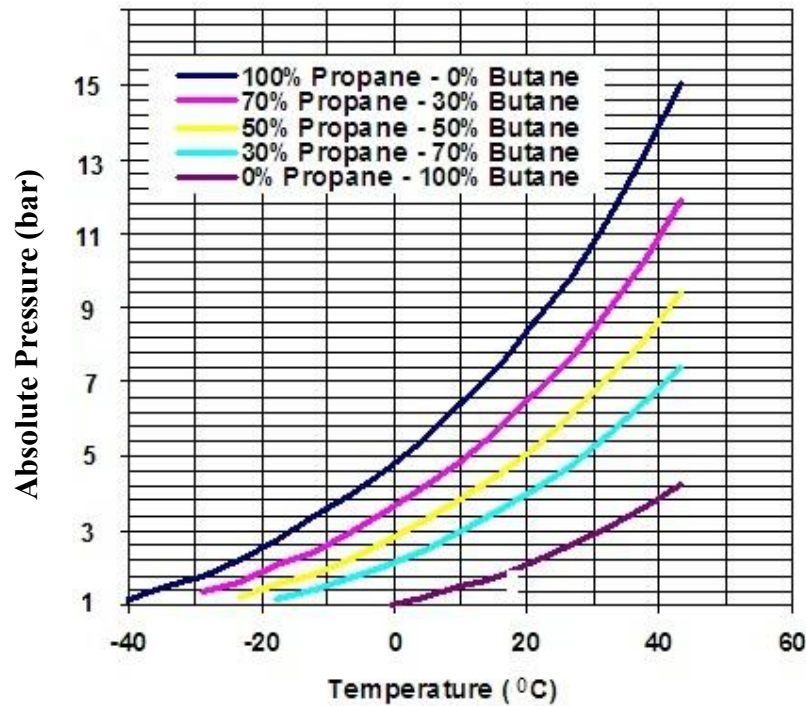


Figure 1.6: Composition of LPG fuel in p-T diagram [33]

1.1.5. Critical temperature

As the substance approaches critical temperature, the properties of its gas and liquid phases converge, resulting in only one phase at the critical point: a homogeneous supercritical fluid. The heat of vaporization is zero at and beyond this critical point, and so no distinction exists between the two phases. On the p-T diagram, the point at which critical temperature and critical pressure meet is called the critical point of the substance. Above the critical temperature, a liquid cannot be formed by an increase in pressure, even though a solid may be formed under sufficient pressure. The critical pressure is the vapor pressure at the critical temperature.

The critical point is sometimes used to specifically denote the vapor–liquid critical point of a material, above which distinct liquid and gas phases do not exist. As shown in the phase diagram above, this is the point at which the phase boundary between liquid and gas

terminates. In LPG, the critical point occurs at 369.8K and 425.2K of propane and butane respectively.

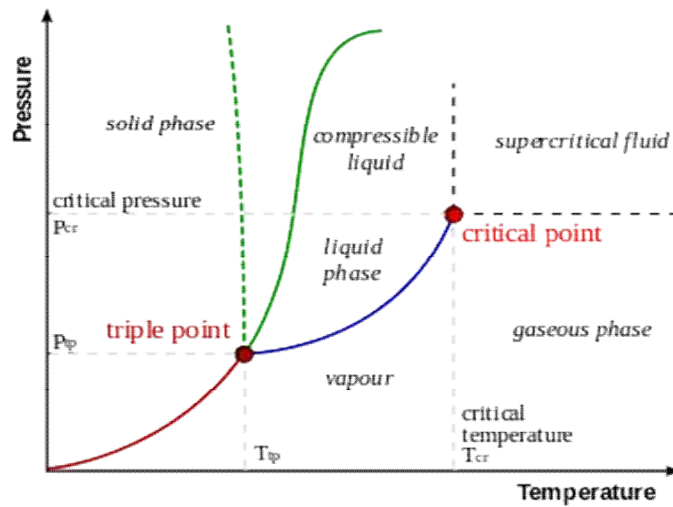


Figure 1.7: The vapor–liquid critical point in a pressure–temperature phase diagram is at the high-temperature extreme of the liquid–gas phase boundary [27]

1.1.6. Viscosity of LPG

The absolute viscosity of LPG, held as a liquid under vapor pressure, is considerably less than that of water thus requiring a very high integrity in the pressurized system if leakage is not to occur. Dynamic or absolute viscosity of propane is 0.00011 N.s/m² at temperature 300K.

Table 1.1 is sum up properties of propane and butane. Those are described above.

Table 1.1: Typical properties of LPG [16]

Properties	Unit	Butane	Propane
Formula		C ₄ H ₁₀	C ₃ H ₈
Boiling point at atmospheric pressure	°C	0	-42
Relative density of gas at 15 °C & 1bar	kg/m ³	0.57-0.58	0.50-0.51
Relative density of liquid at 15 °C	kg/m ³	1.9-2.1	1.4-1.5
Liters per tonne at 15 °C	-	1723-1760	1965-2019
Limits of flammability by volume of gas/air mixture	%	1.8-8.5	2.4-9.5
Air required for combustion (to burn 1 m ³ of gas)	m ³	30	24
Viscosity at 300 K of propane	N.s/m ²	0.00011	

1.1.7. Latent heat

The latent heat of the liquid product is the quantity of heat required to enable vaporization to occur. As such it is essential data required during the design of vaporizer systems.

When LPG vaporizes naturally the latent heat required is taken from the liquid itself, and its immediate surroundings, at the same time causing a drop in temperature. This is known as 'autorefrigeration'. Heat of evaporation of propane and butane is shown in Figure 1.8.

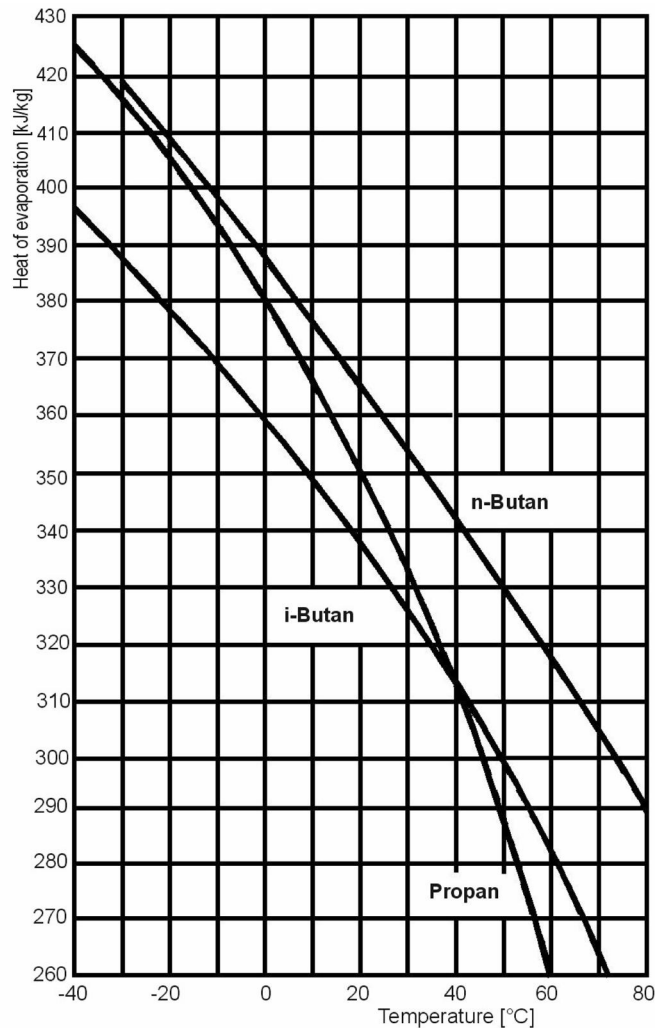


Figure 1.8: Heat of evaporation of propane and butane depend on temperature [26]

1.2. LPG as an alternative fuel for internal combustion engine.

Today, LPG is used in vehicles worldwide for its advantages for the environment and performance of the engine. However, the utilization of LPG as an engine fuel varies widely

from one country to another, depending on the cost and availability of the fuel in relation to alternative fuel, notably petrol and diesel. Table 1.2 shows the variation in the LPG fuel composition in the Europe in 1982.

Table 1.2: LPG composition (volume) in Europe in 1982 [34]

Country	Propane	Butane
Austria	50	50
Belgium	50	50
Denmark	50	50
France	35	65
Greece	20	80
Ireland	100	0
Italy	25	75
Netherlands	50	50
Spain	30	70
Sweden	95	5
United Kingdoms	100	0
Germany	90	10

1.2.1. Combustion properties

The Octane Number (ON) is a parameter that is relevant only for the use of LPG as an alternative fuel for SI engines, and represents a measurement of its antiknock capacity, i.e. the capacity to withstand strong compression without detonating, undergoing a series of anomalous combustion phenomena causing violent pressure transitions.

The Octane number of LPG is measured using the motor method. This provides a measurement (MON, Motor Octane Number) of the fuel antiknocking capacity in spark ignition engines. A sufficiently high value for MON ensures that the LPG provides an acceptable performance level in motor vehicles. Since each hydrocarbon has its own MON value, the specification leaves room for some compositional flexibility. Values of MON and ON of LPG are shown in Table 1.3.

The net calorific value (NCV) is a parameter characterizing the use of LPG as a fuel. It represents the amount of energy released by the combustion of 1 kg of product, after subtracting the heat of evaporation of any water present and the water formed during combustion. The NCV depends on the hydrogen- carbon ratio, and thus on the composition

of the LPG.

LPG defuses in air fuel mixing at lower inlet temperature than with either gasoline or diesel. This leads to easier starting, more reliable idling, smoother acceleration and more complete and efficient burning with less unburned hydrocarbons present in the exhaust. In contrast to gasoline engines, which produce high emission levels while running cold, LPG engine emissions remain similar whether the engine is cold or hot [21].

The high ignition temperature of gas compared with petroleum based fuel leads to reduced auto ignition delays, less hazardous than any other petroleum based fuel and expected to produce less CO, NOx emission and may cause less ozone formation than gasoline and diesel engines [21].

1.2.2. Mass per unit volume

Density is used for mass (or weight) to volume conversions; it may also provide an approximate indication of the composition of the LPG (or more generally of any petroleum product), and is therefore considered a volatility property.

LPG is composed of normal butane (n-butane), isobutane (i-butane) and propane. Therefore, the density of liquid phase LPG can be expressed as

$$\rho_{LPG} = \left(\frac{\omega_p}{\rho_p} + \frac{\omega_{nb}}{\rho_{nb}} + \frac{\omega_{ib}}{\rho_{ib}} \right)^{-1}$$

Values of density and temperature of LPG are shown in Figure 1.9.

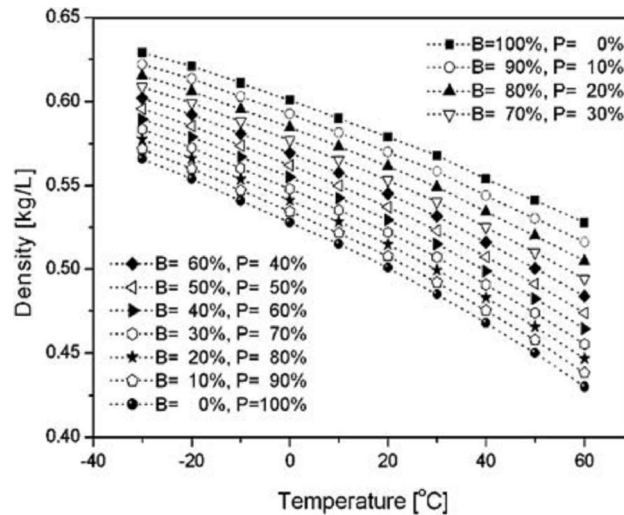


Figure 1.9: Density of LPG as a function of fuel temperature [12]

Figure 1.9 shows the density for various blends of butane and propane as a function of temperature. The density of n-butane varies from 0.528 to 0.629 kg/l, and the density of propane varies from 0.430 to 0.566 kg/l over the temperature range from -30 to 60°C. At a fuel temperature of 20°C, the density of liquid phase LPG varies from 0.501 to 0.579 kg/l [12]. The value of vapor pressure at 40°C and 10°C are extremely important for LPG. The vapor pressure at 40°C is correlated with operational safety of pressurized appliances (tanks, piping, etc.); vapor pressure at 10°C is correlated with the possibility of providing an adequate feed pressure to engines and combustion plants under all circumstances. The evaporation residue is correlated with the control of the LPG's non-volatile heavy hydrocarbon content, in order to guarantee a correct functioning of the vaporizer.

Table 1.3: Properties of LPG and gasoline 95

Fuels			Density [kg/m ³]		Heating value [MJ/kg]
	MON	RON	Liquid	Gas	
Gasoline 95	95	85	725-775		43.5
Propane	111	97	510	1.96	46.5
i-butane	99	99	-	2.51	45.57
n-butane	96	92	579	2.59	47.07
LPG (P/B=60/40)	105	95	540	2.21	46.06

1.3. Advantages and disadvantages of LPG as an engine fuel

It is because of its low maintenance costs, suitability for new and applicable technologies, beside its economic market price, and environment friendly characteristic that LPG has become a serious alternative for gasoline.

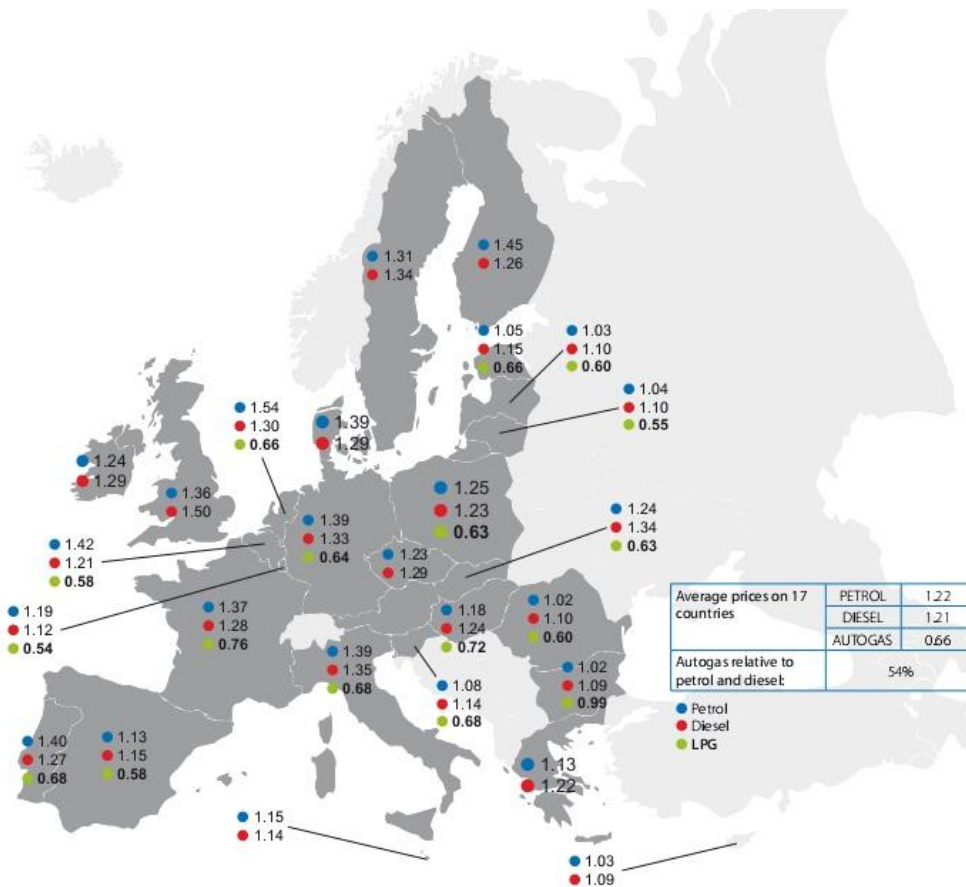


Figure 1.10: An overview of average pump prices in €/l (vat& excise duty included) in a selection of European countries in 2008 [9].

1.3.1. Advantages of LPG in comparison to conventional fuels

Emissions from LPG vehicles are significantly lower than conventionally fueled vehicles. Some of the major attractions of these fuels, in comparison with conventional liquid fuels, are due to their relatively low carbon content, causing them to burn cleanly with lower emissions of CO, CO₂, HC and NO_x. Compared to petrol, greenhouse gas emissions from LPG cars are reduced. Taking CO₂ emissions into account, real world tests show around a 15% reduction of life cycle greenhouse gas emissions (per km) for bi-fuel LPG cars as compared to petrol operation [10], placing the level of greenhouse emissions between those from petrol and diesel. Regulated emissions (per km) are reduced for LPG cars as compared to conventional fuels. Even compared to petrol, which itself is low in NO_x, the best quality LPG bi-fuel engines produce fewer NO_x emissions and virtually eliminate emissions of particulates. Particle emission from diesel engines is about 10 times higher

than gasoline engines and 100 times higher than LPG powered engines, LPG cars therefore also provide significantly lower regulated pollutants than diesel.

LPG has a typical heating value of 46.1 MJ/kg compared with 42.5 MJ/kg of fuel-oil and 43.5 MJ/kg for premium grade petrol (gasoline), therefore, improving fuel economy from engines running on LPG compared with gasoline.

LPG has a higher octane rating, pure propane Research Octane Number (RON=108), which prevents the occurrence of knocking at a high engine compression ratio (CR). Therefore, operating on LPG was more safety at a higher CR than an equivalent engine operating on gasoline. However, the advantage of higher Octane Number of LPG can only be guaranteed by having a separate ignition and injection map in the engine control module, because, the CR in a bi-fuel vehicle is usually fixed by design.

To sum up, LPG has more benefits compared to gasoline and diesel fuels and those advantages are shown in the table below:

Table 1.4: Advantages of LPG compared to gasoline and diesel fuels [35].

Advantages	It has low cold-start emissions due to its gaseous state.
	It has a lower peak pressure during combustion, which generally reduces noise and improves durability; noise levels can be less than 50% of equivalent diesel engines.
	LPG fuel systems are sealed and evaporative losses are negligible.
	It is easily transportable and offers ‘stand-alone’ storage capability with simple and self-contained LPG dispensing facilities, with minimum support infrastructure.
	LPG vehicles do not require special catalysts
	It contains negligible toxic components.
	LPG has lower particle emissions and lower noise levels relative to diesel, making it more attractive for urban areas.
	Its low emissions have low greenhouse gas effects and low NO _x precursors.
	Any increases in future demand for LPG can be easily satisfied from both natural gas fields and oil refinery sources.
	Emissions of polycyclic aromatic hydrocarbons (PAH) and aldehydes are much lower than those of diesel-fuelled vehicles.

1.3.2. Disadvantages of LPG in comparison to the conventional fuels

Conventional LPG engines have carburetor type fuel supply systems with a mixer, so it is difficult to control the air / fuel ratio precisely. Also, the same engine with LPG produces less power than one with gasoline [35] because the fuel is supplied into the cylinder as a vapor.

Some conversion technologies have no electronic control means, during different operational modes of any car, either fuel consumption increases or power of the engine decreases.

In the liquid LPG injection system, icing phenomenon occurs around the LPG injector, it is the cause of running engine irregularities and increasing concentrations of unburned hydrocarbons in exhaust gases.

Table 1.5: Disadvantages of LPG compared to gasoline and diesel fuels [35].

Disadvantages	Although LPG has a relatively high energy content per unit mass, its energy content per unit volume is lower than diesel, which explains why LPG tanks take more space than diesel fuel tanks. They are pressure vessels so that they also weigh more than diesel tanks.
	It is heavier than air, which requires appropriate handling
	Though the lower flammability limit for LPG is actually higher than the lower flammability limit for petrol, the vapor flammability limits in air are wider than those of petrol, which makes LPG ignite more easily
	It has a high expansion coefficient so that tanks can only be filled to 80% of capacity.
	LPG in liquid form can cause cold burns to the skin in case of inappropriate use.
	LPG produces less power than with gasoline
	Icing phenomenon around the LPG injector (with liquid LPG injection systems)

2. FUEL SYSTEMS FOR SI ENGINES RUNNING ON LPG

Today, although the regulations have not yet matured, LPG conversion has been spread fast by a lot of investors and private companies all over the world. Number of vehicles with LPG and thus consumption of LPG is increasing in developed countries due to economical and environmental effects of LPG, accompanied with considerable achievements in LPG conversion technologies. LPG can be used as the best alternative fuel for vehicles with aspirated and turbocharger engines. The commonest is an external mixture formation with mixer or injector, which gaseous LPG is already moving in the intake manifold or using liquid LPG injection. The engine runs on both gasoline and LPG with a switch to change the type of fuel with which engine will operate. Actually, there are four main methods to LPG/air mixture creating,

- Venturi mixing system.
- Injection gaseous LPG in the intake manifold.
- Injection liquid LPG in the intake manifold.
- Direct injection LPG in the cylinder of the engine.

Nowadays, Venturi mixing system or the first generation system is not used much in the world, It is only used in countries where vehicles are not required to meet any emission standards. This dissertation introduces three most popular LPG system.

2.1. Injection gas phase LPG into the intake manifold (gas LPG injection system)

2.1.1. Multipoint gas injection

This system is suitable for electronic fuel injection engines with oxygen sensor, catalytic converter and plastic intake manifold of both naturally aspirated and turbocharged, supercharged engines.

Multipoint gas injection is also a closed loop system as it is 'intelligent', gathering information on the fuel mixture from the oxygen sensor, acting upon it to vary the mixture as it is received [4].

Inputs from a number of sources must be provided or it cannot work, those being: Oxygen sensor signal, throttle position sensor signal, RPM signal, ambient pressure at the intake manifold.

These signals are picked up raw at source and then used by the additional gas ECU to arrive at the correct mixture for the conditions. The big difference over 'closed loop' is in the way gas is fed to the engine. It will still use one or more vaporizers and emulators but there is no single point mixer in this system. Instead, gas is injected under pressure by separate injectors placed points in the inlet manifold just before the engine inlet valves, (just as petrol is injected normally).

The multipoint injection system is much more expensive but brings huge benefits. It practically removes the potential for 'Backfiring' mentioned in both systems above, as no gas is present in the inlet manifold, only air. This system may well prove to be more fuel efficient than any of the above mixer systems [5].

2.1.2. Multipoint sequential gas injection system

This 3rd generation system has all of the attributes and benefits of the earlier multi point systems. In addition, it is super intelligent and it has the ability to inject gas in a truly sequential manner, just like the latest petrol vehicles. It achieves the latest European exhaust emission requirements with ease. This has a double meaning to the LPG motorist - A car that pollutes the least can be the most fuel efficient as less fuel is wasted [4].

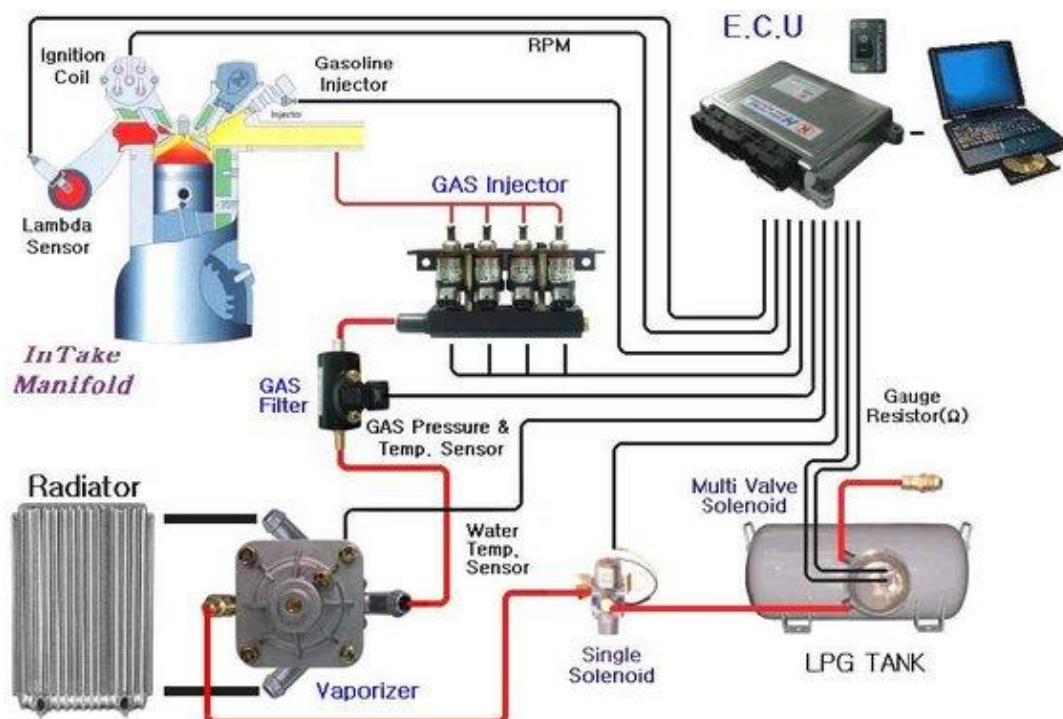


Figure 2.1: Multipoint sequential gas injection system [7].

They are suitable for sequential and non sequential electronic multi point fuel injection engines with oxygen sensor, catalytic converter and plastic inlet manifold and all turbocharged and supercharged engines.

Multipoint sequential gas injection system requires even more information from the engine but uses a lot of data from the vehicle's existing engine management instead of picking it up raw at source as the earlier system did. The additional information required is: gas temperature, gas pressure, and petrol injector pulse length.

The system also has its own ECU but this works in conjunction with petrol ECU, instead of working alongside it like the earlier non-sequential system.

The even more benefits of performance and economy are delivered by the new system, along with one or two useful bonuses. The new system will 'sense' if gas pressure is low and switch back to petrol before the gas tank runs dry - a very useful trick. It will even give an audible warning to tell that, it has done this [5].

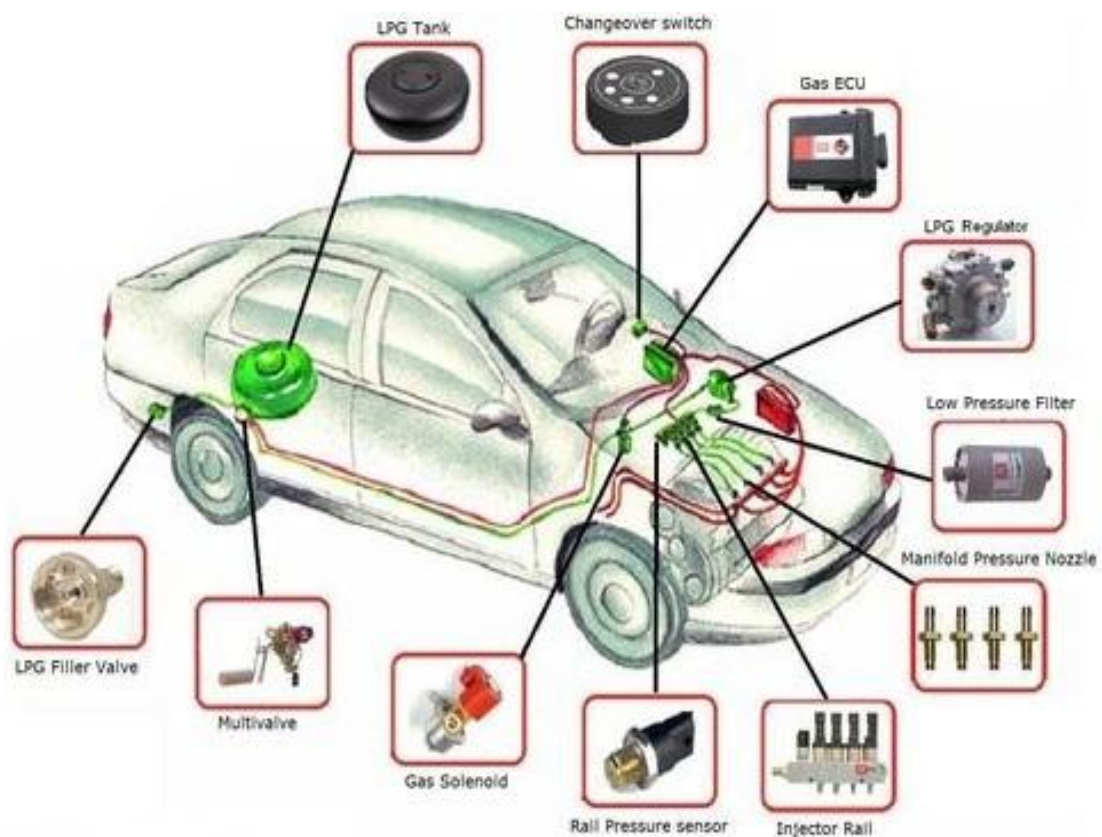


Figure 2.2: Components of multipoint sequential gas injection system in the a car [4] [7].

2.2. Injection of liquid LPG into the intake manifold (liquid phase LPG injection system).

These are suitable for use on the same vehicles as the fully sequential multipoint LPG injection systems, meaning they are suitable for most electronic fuel injected vehicles. These systems are also fully sequential multipoint LPG injection systems but instead of injecting LPG in gaseous form, they inject LPG in liquid phase in much the same way as a petrol injection system. These systems are nowhere near as common as the gaseous injection systems but are fitted by certain vehicle manufacturers on some models of vehicle as factory fitted LPG systems, rather than by aftermarket installers such as ourselves.

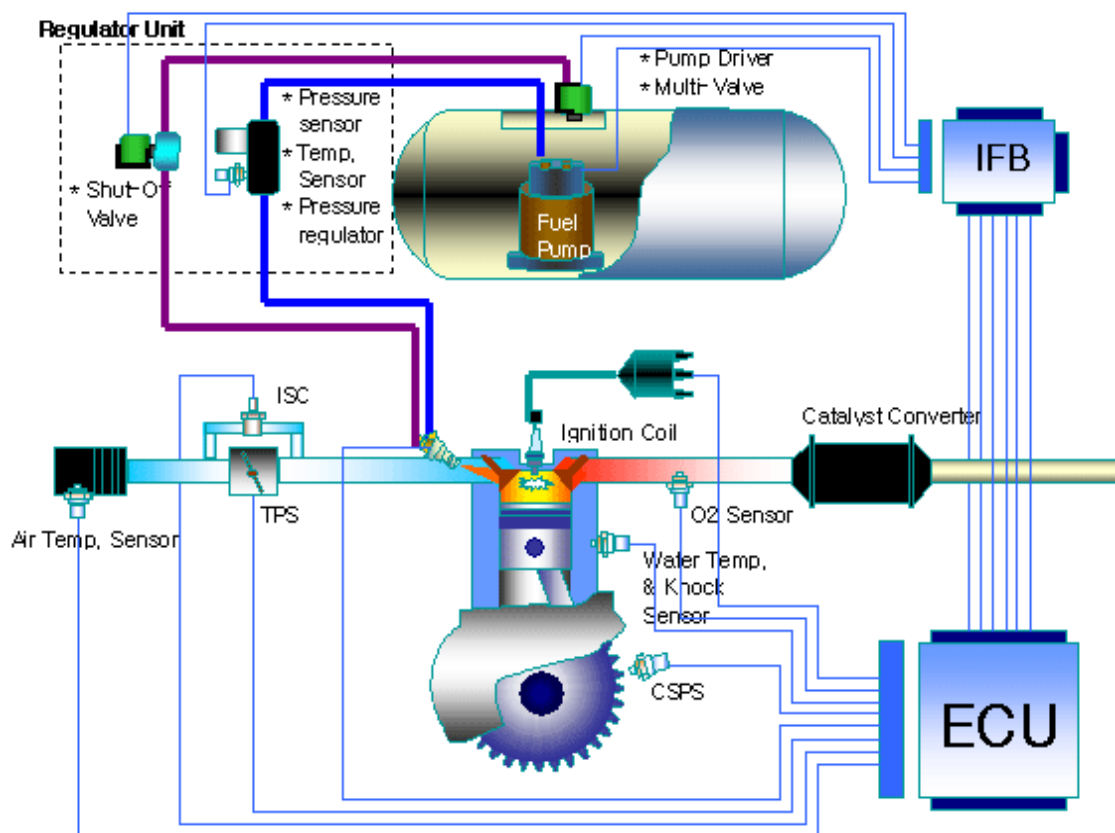


Figure 2.3: Liquid phase LPG injection system [3]

Advantages: Injecting LPG in the liquid phase for vehicle manufacturers is beneficial in that no separate LPG brain is required - the normal petrol ECU can control the liquid LPG injectors directly. This is because the main role of the LPG brain on gaseous LPG

injection systems can compensate for the varying LPG pressure and temperature, and low different flow rate of gaseous fuel rather than liquid fuel. As liquid LPG fuel systems do not need to allow these factors, none of these factors apply, so the petrol brain is capable of driving the LPG injectors. Another advantage for vehicle manufacturers of installing a liquid LPG injection system is that they do not have to consider the mounting location of a vaporizer (the part that turns high pressure liquid LPG into lower pressure gaseous LPG), additional water piping to heat the reducer, or need to consider the wiring loom and ancillary components that a gaseous LPG injection needs such as pressure and temperature sensors [4].

Disadvantages: Liquid LPG injection systems problem is they require a high pressure pump to be mounted in the LPG tank, because the liquid LPG injectors need a pressure that is higher and more constant than the pressure in the LPG tank. The high pressure LPG pump mounted in the tank is very expensive.

LPG expansion and vaporization which the heat requires for evaporation of the LPG and because of LPG boiling point is low ($-40 - 0^{\circ}\text{C}$), the temperature around the outside of the outlet nozzle is dropped under 0°C . This explains for formation of ice around the outlet nozzle. Engines with the liquid LPG injection system will operate irregularly and there will be increasing concentrations of unburned hydrocarbons in exhaust gases [3].

2.3. Direct injection LPG in the cylinder of the engine.

This is the latest generation of automotive LPG fuel systems. It is exclusive for direct injection engines that inject fuel in the combustion chamber at high pressure. This provides many advantages allowing better fuel consumption and lower exhaust emissions. The environment inside the combustion chamber is quite hostile (extreme temperatures and pressures) [3]. The petrol injector is designed to withstand these conditions by flowing petrol through the component to prevent overheating.

The advantage of this system is that it does not require interventions in the intake manifold of the engine (which negatively affects volume efficiency of the engine). Another advantage of direct injection system is exact extreme fuel injection, which can lower the CO_2 emissions by 20%. Furthermore, vehicles equipped with this system easily meet the Euro 5 emission standards [5].

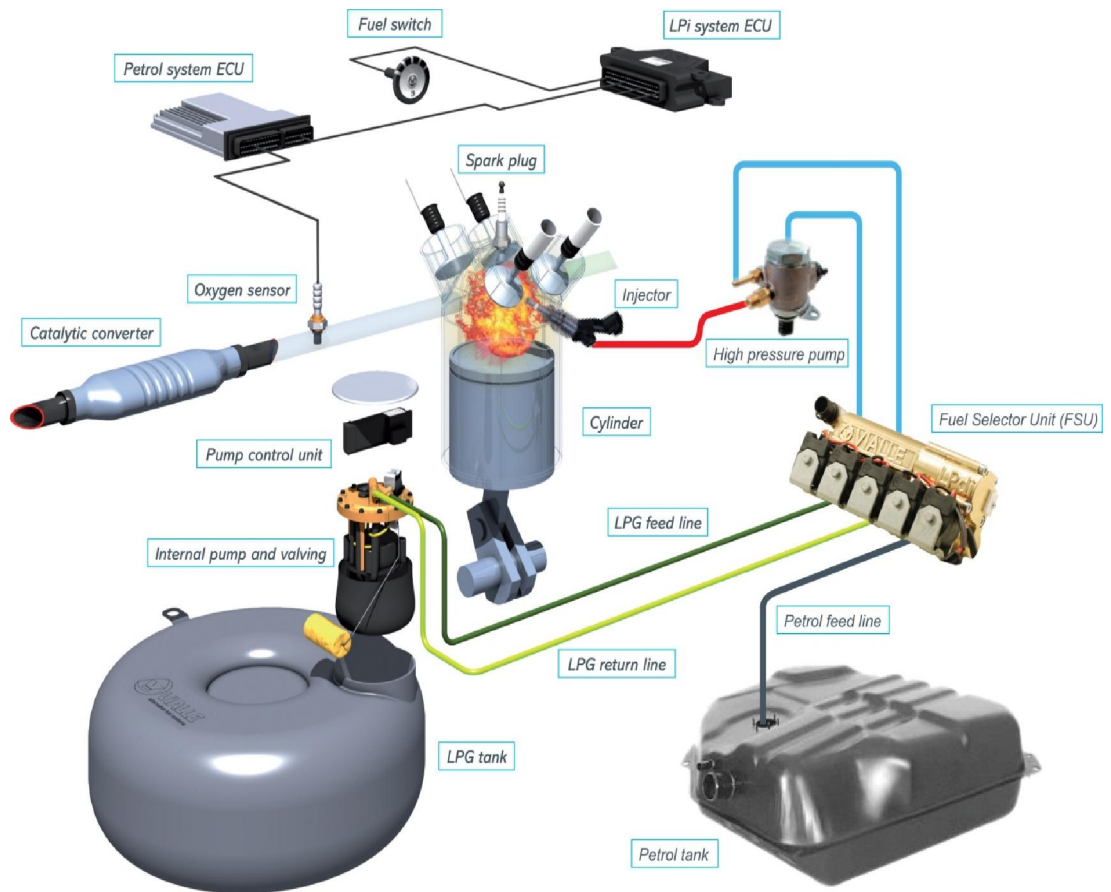


Figure 2.4: Liquid LPG direct injection system [6]

3. PARAMETERS OF THE SI ENGINE RUNNING ON LPG

3.1. Environmental impact (exhaust emission of LPG engines and petrol engines)

LPG is composed of predominantly simple hydrocarbon compounds and LPG is free of lead and most additives and contains very little sulfur. So LPG-powered vehicles produce less pollutants in their exhausts (hydrocarbon compounds, nitrogen oxides, sulfur oxides, air toxics) in comparison with gasoline fueled vehicles. For example, they are about 60% less CO, 30% less HC and 20% less NO_x in comparison with gasoline [36]. These results have also been confirmed by different published works (Snelgrove et al., 1996; Klausmeier and Billick, 1993; Wu et., 1996; Newkirk., 1996; Celik., 2006; Cevik., 1998; Diaz, 2000). Ristovski. (2005)[10]. Comparisons of engine running on LPG and petrol are shown in Table 3.1 [11].

Table 3.1: Environmental Impact of LPG, Petrol. [11]

(Remarks: “+”: represents better than LPG, “0”: represents more or less equal to LPG, “-”: represents worse than LPG)

	LPG	Petrol
Regulated Exhaust Components	base	
CO	base	-
HC	base	-
NO _x	base	-/0
Unregulated Exhaust Components		
NO ₂	base	-
SO ₂	base	-
Benzene	base	0
Formaldehyde	base	-
Other Impact on the Environment		
Acidification	base	-
Global warming	base	-

Emission research results from different model of vehicles. LPG engines have less carbon monoxide and hydrocarbon compounds than petrol engines in the exhaust pipe of four

models, but LPG engines have more nitrogen oxides than petrol engines in three models. They are shown in Table 3.2 and Figure 3.1 [11].

Table 3.2: Emissions of passenger cars on LPG and Petrol (grams per km) [11]

	CO	HC	NO _x
LPG			
Opel Vectra 2.0 16V	0.28	0.08	0.15
BMW 318I	0.74	0.11	0.10
Toyota Carina E 1.6 Xli	0.80	0.13	0.15
Renault Laguna 2.0	0.53	0.07	0.05
Honda Accord 2.0 iS	1.25	0.22	0.37
Petrol			
Opel Vectra 2.0 16V	0.06	0.03	0.10
BMW 318I	0.89	0.16	0.10
Toyota Carina E 1.6 Xli	1.21	0.15	0.11
Renault Laguna 2.0	0.70	0.11	0.05
Honda Accord 2.0 iS	1.48	0.24	0.24

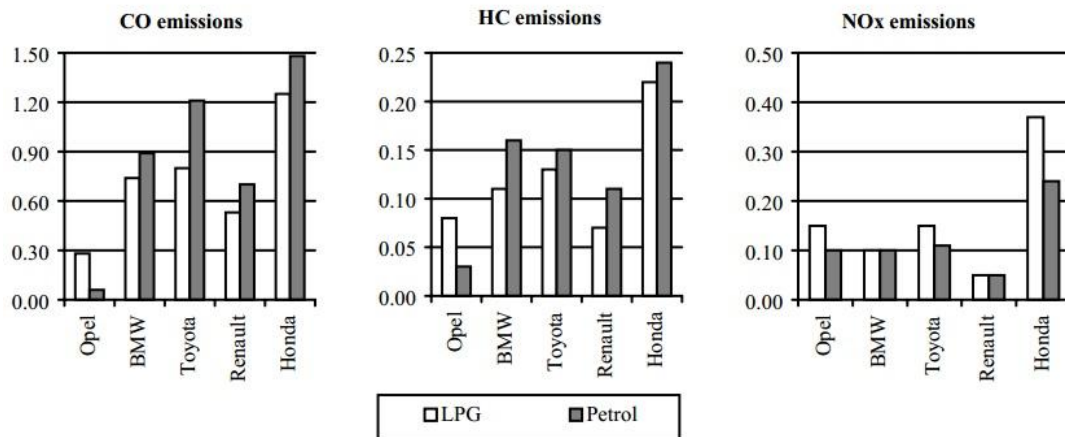


Figure 3.1: Emissions of passenger cars on LPG and petrol (grams per km) [11]

3.2. Efficiency and performance.

Efficiency and performance of LPG are similar to those of petrol depending on the measure. The results of various tests are consolidated in Table 3.3.

Remarks:

+: A range of various efficiency or performance tests results which is better than LPG

0: A range of various efficiency or performance tests results which is more or less equal to LPG.

- : A range of various efficiency or performance tests results, which is worse than LPG.

Table 3.3. An indication of the relative efficiency and performance of LPG and petrol [11].

	LPG	Petrol
Compression ratio	Base	-/0
Traveled distance on 1 kg of fuel (km)	Base	-
Traveled distance on 1 liter of fuel (km)	Base	+
Maximum power (kW)	Base	+/0
Maximum torque (Nm)	Base	0

3.3. The reason of decrease power of LPG engines

As analyzed in the section 1, the LPG is a very suitable fuel for internal combustion engines.

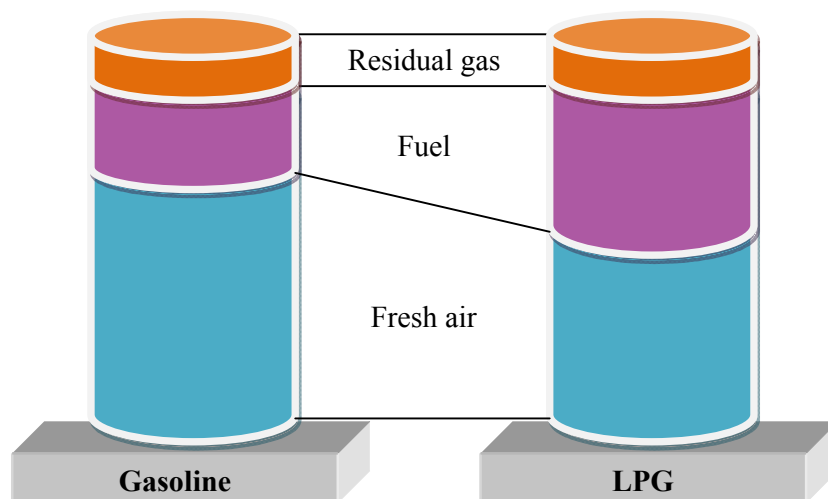


Figure 3.2: Schematic of volumetric comparison of the fresh cylinder charge components in the engine between gasoline fuel and gas fuel. (These images are for illustration purposes only).

As a rule, the fuel system is generally based on the external formation of the mixture, bringing the gas fuel (in the case of the LPG, the evaporated fuel) into the sucked-in (filling) air by means of the carburetor or injector. Different properties of fuels to make different energy contents of new fuel/air mixtures with gasoline or LPG, resulting in a decline of engine power when the engine is operated on LPG (gas fuel contains a large volume in the mixture, so the amount of air in the cylinder will be reduced).

The relative change of the value p_e in the condition of full load after the conversion of the petrol engine ($\lambda=1$) to the LPG is shown by the simplified relation (in the condition of the equal values of the volumetric efficiency and the overall efficiency of both the engines) [8]:

$$\frac{p_{e/LPG}}{p_{e/PF}} = \frac{(A_{T/GF} \cdot r_{air} + r_{PF}) \cdot H_{L/LPG} \cdot T_{BDC/PF}}{(A_{T/LPG} \cdot r_{air} + r_{LPG}) \cdot H_{L/PF} \cdot T_{BDC/LPG}} \quad (3.1)$$

After replacing values in the table in the formula (3.1), Computation result will be:

$$\frac{p_{e/LPG}}{p_{e/PF}} = 0.925 \quad (3.2)$$

Values of parameters in the formula show in the table follow:

Table 3.4: Parameters of fuels and air.

	Abbreviate	Values
Theoretical consumption of air for petrol fuel	$A_{T/PF}$	14.5 kg/kg
Theoretical consumption of air for LPG fuel	$A_{T/LPG}$	15.6 kg/kg
Individual constant of gas for air	r_{air}	287 J/kg.K
Individual constant of gas for evaporated of gasoline fuel	r_{PF}	76 J/kg.K
Individual constant of gas for evaporated of LPG	r_{LPG}	168 J/kg.K
Heating value (low) for gasoline fuel	$H_{L/PF}$	43.5 MJ/kg
Heating value (low) for LPG	$H_{L/LPG}$	46.1 MJ/kg
Temperature of the cylinder charge at the BDC for evaporating gasoline	$T_{BDC/PF}$	335 K
Temperature of the cylinder charge at the BDC for evaporated gaseous LPG	$T_{BDC/LPG}$	350 K
Mean effective pressure of the engine working cycle	p_e	?

It is shown that, the theoretical power reduce about 7,5%. The better solution in case of using LPG is a multipoint injection of liquid LPG into the intake ports in the cylinder head or in the intake manifold. LPG provides lower temperatures at the end of filling cylinder against running with petrol. The opposite previous case using this injection gets a rise of specific filling fresh air in the cylinder. Injection of liquid LPG decreases the temperature of the cylinder at the end of the intake stroke on value $T_{BDC/LPG-inj} \approx 325$ K (heat of evaporation LPG at $t = 20^0\text{C}$ is $L_{LPG} \cong 360$ kJ/kg): next relative change of ratio p_e will be:

$$\frac{P_{e/LPG}}{P_{e/PF}} = (0.98 \rightarrow 1.05) \quad (3.3)$$

The results show that an engine with injection of liquid LPG has the power as the same engine running on petrol fuel. However, a risk of freezing of the injectors due to very fast evaporation injected LPG – see Figure 3.3. It therefore demands special alterations on injectors and well-considered the development incorporation of the injectors in the intake manifold.

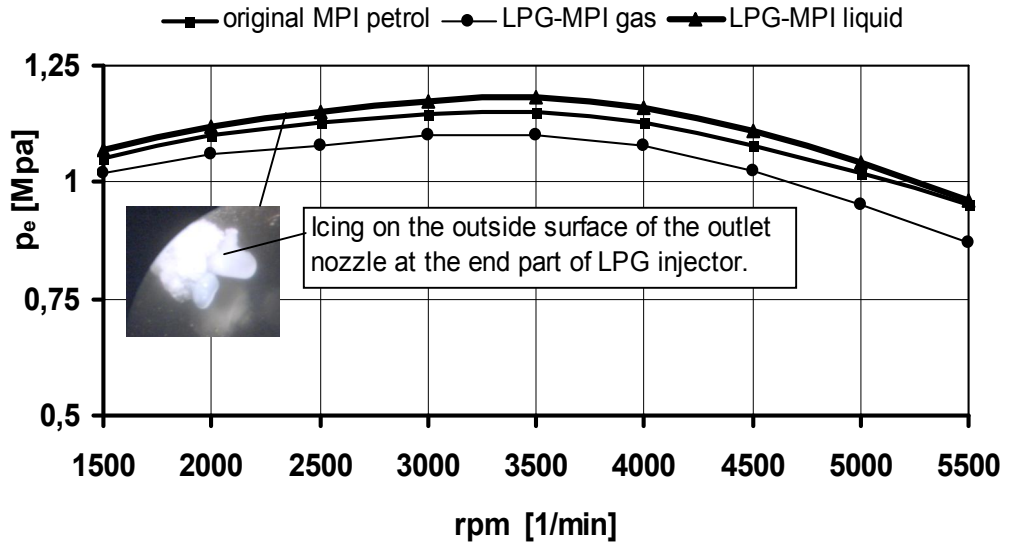


Figure 3.3: The courses of the mean effective pressure of the engine working cycle on speed characteristic at full load of the SI engine running on petrol or LPG. The input of the gaseous fuel for the mixture forming in the intake manifold reduces the engine power (lower curve) to the engine running on petrol (middle curve). The engine power somewhat increases using the mixture forming by liquid LPG injection into the intake manifold (upper curve). The icing fractures off from the outside of the outlet nozzle (inserted picture) is the risk for the trouble-free engine running (misfire chance). [14]

4. THE MIXTURE FORMATION IN THE LIQUID LPG INJECTION SYSTEM.

The air and fuel mixture formation (preparation) represents an important part of the engine working cycle which influences the mixture behavior with controlled ignition and the resulting combustion process. The mixture composition has effects on engine parameters such as maximum power, fuel consumption, emissions, combustion rate and temperature. LPG powered engines can be just like any other spark ignition engines, in principle, there are two concepts of the mixture preparation: internal and external.

The external mixture formation represents a simplest concept. The fuel injector is placed in the intake air manifold. This option has advantages in terms of its easier installation and better homogeneity of the mixture. An LPG automobile operated engine can be equipped with a fuel system incorporating a gas and air mixer in the engine intake manifold or with gas injection into the engine intake by means of solenoids sequentially controlled for each cylinder. The mixer in the engine induction causes a pressure loss, and as a result, less suitable compared to LPG liquid injectors.

The mixture quantity available to the working cycle is smaller compared to the internal mixture formation. The disadvantage of the shorter time available for mixture formation associated with the internal mixture formation can be compensated with higher injection pressures during the compression stroke, eventually also by increasing the turbulence of the cylinder charge. The requirement for higher energy ignition system and a possible increase in the cycle-to-cycle variation speak against the internal mixture formation concept.

The internal mixture formation with the liquid LPG fuel injected directly into a working cylinder space is a more complex concept to develop and construct. The separation of fuel from air during the cylinder charge exchange eliminates backfires in the induction system, the achievable heat value increases and consequently, the engine power grows. Internal mixture preparation also allows a layered air-fuel mixture, thus lowering the fuel consumption and the production of harmful compounds within the exhaust gases. Direct injection (DI) is believed to be one of the key strategies for maximizing the thermal efficiency of SI engines and meet the ever-tightening emissions regulations. Depending on the injector inlet pressure two implementations of the concept can be distinguished: one

using low-pressure injection and the other involving high pressure injection. Low-pressure injection with gas pressure below 2 MPa requires a longer duration and at high load the injection commencement must occur during the induction stroke, i.e. at the time when the inlet valve is open. High pressure injection with gas pressure between 10 and 12 MPa currently represents the most up to date and efficient concept of an internal mixture formation eliminating adverse combustion anomalies and benefiting from a stratified mixture formation in combination with lean mixture.

4.1. Problems analysis of an engine with liquid LPG MPI system.

Traditionally, LPG is used as a vapor because it is normally stored in a space saving saturated state and then vaporized in the fuel system in order to accurately meter the fuel in one phase. A liquid LPG fuel system offers power gains over vaporized fuel introduction due to the ability to use the heat of vaporization from the vaporizing fuel to cool the intake charge and improve the volumetric efficiency of the engine. However, when LPG is injected into the intake manifold, the fuel will absorb heat from the surroundings as the heat of vaporization. After that the temperature of the surface the outlet nozzle will be under 0°C . This is a reason for the icing phenomenon around external surface of the injector nozzle. Icing will fracture smaller parts and moving to engine cylinder leads to engine running is not stable, HC misfire in the engine make higher HC concentration at the exhaust manifold.

Recently, studies have been carried out for injecting the fuel directly into the combustion chamber to meet low emission standard and high efficiency. Varied methods have been used in practical gasoline engines. However, a large amount of unburnt hydrocarbon emission is also a problem with GDI engines, when they operate near the stoichiometric mixing condition.

4.1.1. Fundamentals of fuel injection.

Quantities of injected fuel through an orifice of injector is calculated by the Bernoulli equation. The assumption of incompressible flow, the discharge coefficient is calculated by experimental injection. Quantities of LPG injection are determined as a function of LPG: density, injection pressure difference, flow coefficient, area of outlet nozzle.

$$\dot{m}_{LPG/liq} = \mu_{EV} \cdot S_{EV} \cdot \sqrt{2 \cdot \rho_{LPG/liq} \cdot \Delta p} \quad (4.1)$$

Where

μ_{EV} - flow coefficient

S_{EV} - area of outlet

$\rho_{LPG/liq}$ - density of liquid fuel.

$\Delta p = p_{up} - p_{down}$ - difference pressure.

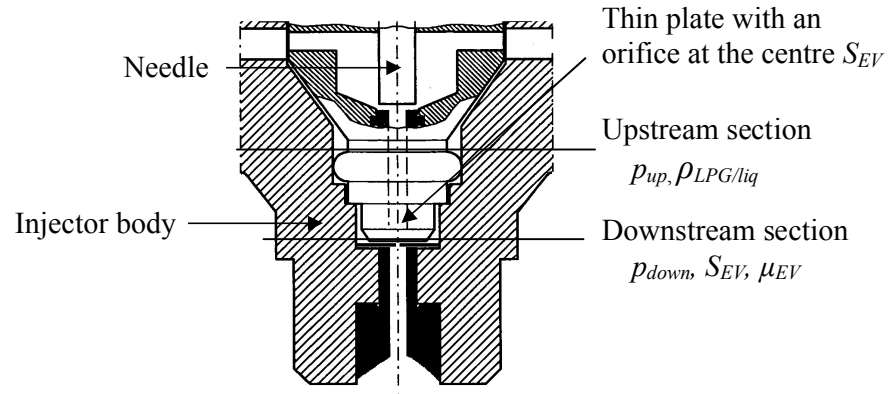


Figure 4.1: Cross section view of LPG injector

4.1.2. Analysis of problems at the LPG injectors

Liquid phase LPG injection research programs have started since 2006 in the laboratory of the Department of Engines and Vehicles Faculty of Mechanical Engineering, Technical University of Liberec. The experiment was conducted on an SI engine. Images and icing sprays around the outlet nozzle was taken in the intake manifold with various geometries, size and materials of the end part of the injector. Some of them are described in the following:

- The injector is a tube shape with an inner channel diameter of about 1 mm, it is connected directly to the electromagnetic valve and fixed in the intake manifold (Figure.4.2). The advantage is a very simple structure and a minimum reduction of the flow cross section of the air intake manifold. The end part of the injector was made of metal or plastic. The disadvantage is the formation of ice on a large scale (with the metal EP was icing on a large part - this is the result of different thermal conductivity of the EP material: plastic has much lower thermal conductivity than metal)

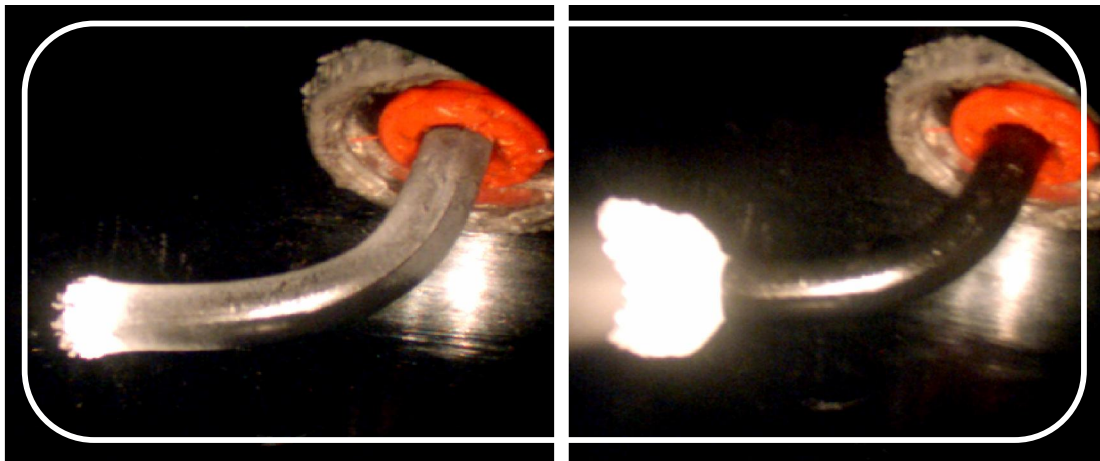


Figure 4.2: At the idle and low load (picture left), icing forms on the plastic end part of the injector, and when the load was increasing then the size of ice at EP is increasing rapidly [23].

- The end part of injector with the metal cover, which reduces the amount of the icing insulation EP from the air in the intake manifold. A disadvantage is the complicated structure and a relatively large reduction in the flow cross section of the air intake manifold, which explains for small reduction of the engine power. Icing occurs at the top of the injector at the outlet nozzle. Currently, this type of liquid phase LPG injectors is used in commercial fuel systems for injecting the mixture of liquid LPG for vehicle engines.



Figure 4.3: Ice formed on the top metallic EP and ability of icing breaking off is moving into the engine cylinder, causing of irregular engine running. This is reflected in "highest" increased emissions of unburned hydrocarbons [23].

- The best solution would be injecting liquid LPG original injectors for gasoline. To reduce the risk of overheating in the LPG injectors (in terms of the critical temperature LPG) is necessary to increase the pressure in the fuel rail (Common Rail).

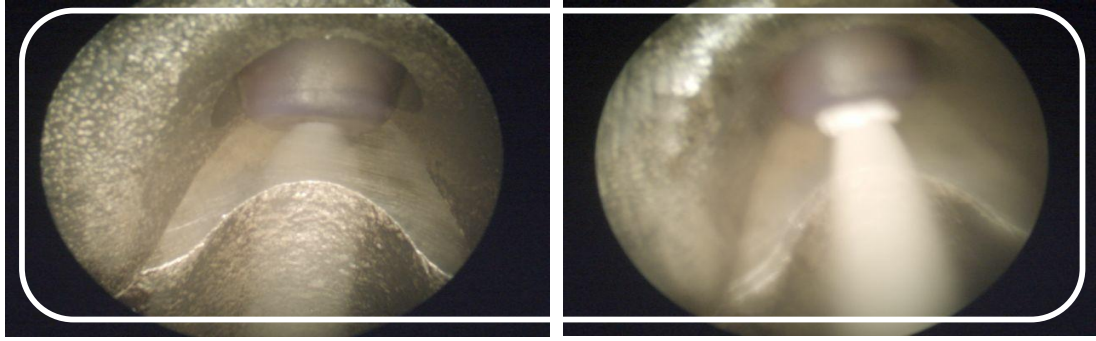


Figure 4.4: Injection of liquid phase LPG by petrol injector with 18 bars - pressure in the fuel rail. At idle (left) icing around the top of the injector did not arise and at higher loads (right), icing around on the top of the injectors had smaller size than in previous cases [23].

The course of unburnt hydrocarbon emission during operation of the test engine on gasoline fuel and the LPG injector with geometries in Figure 4.2 and 4.3 are shown in Figure 4.5. Highest and irregular increased emissions of unburnt hydrocarbons is probably due to small debris of icing were misfiring in the engine combustion chamber.

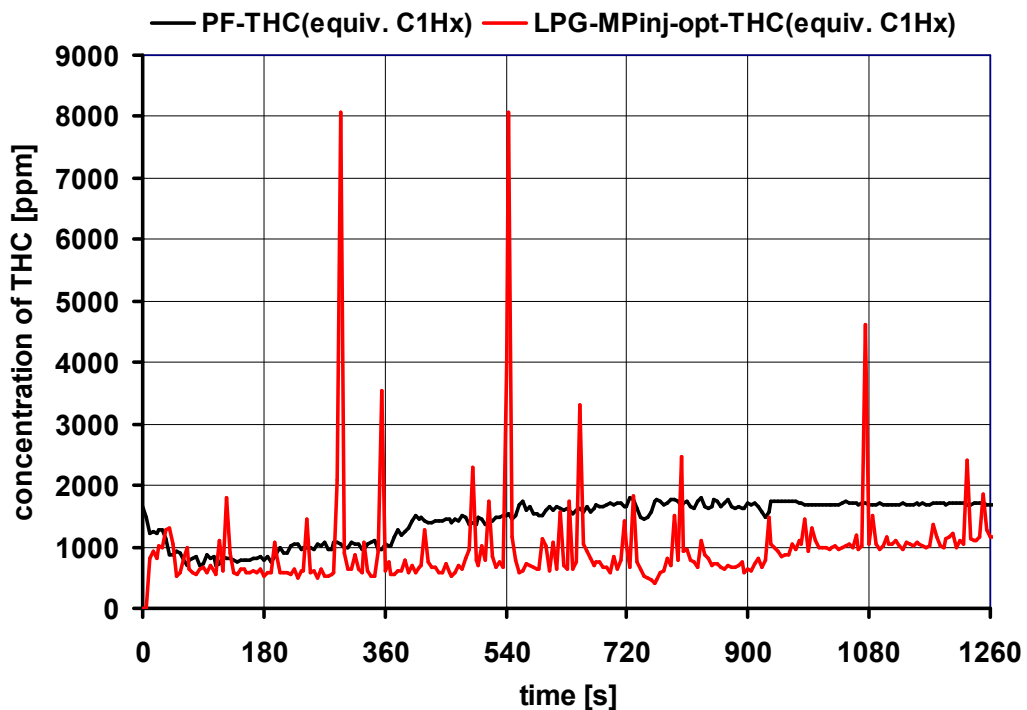


Figure 4.5: Concentration of THC measurement engine of the testing SI engine with the liquid LPG injection in external speed characteristics (data acquisition analyzer with an interval of 5 seconds) with original λ regulation. And the comparison with the THC pattern from the petrol-operated engine measurements. When operating on LPG appear randomly high concentrations of HC apparently as a result of a possible "icing" in the intake manifold during rapid evaporation of injected LPG [6].

4.1.3. Analysis of next problems of liquid LPG injection

▪ Influence of the fuel temperature

The fuel density is largely affected by the LPG temperature, which is influenced by ambient temperature and heat transfer from the engine compartment. As a result, the injected LPG quantity varies with the fuel temperature. In order to analyze the influence of fuel temperature on the injected fuel quantity, the fuel injection rate at an arbitrary fuel temperature is expressed as [12]

$$\dot{m}_{LPG/i} = \dot{m}_{LPG/base} \cdot F_{LPG,\rho(T)} \quad (4.2)$$

The temperature correction factor $F_{LPG,\rho(T)}$ is defined as

$$F_{LPG,\rho(T)} = \sqrt{\frac{\rho_{LPG/i}}{\rho_{LPG/base}}} \quad (4.3)$$

The figure 4.6 shows the temperature correction factors for propane and butane at various fuel temperatures. The temperature correction factor increases with decreasing fuel temperatures. The rate of change in the propane temperature correction factor is steeper than that of butane –Figure 4.7.

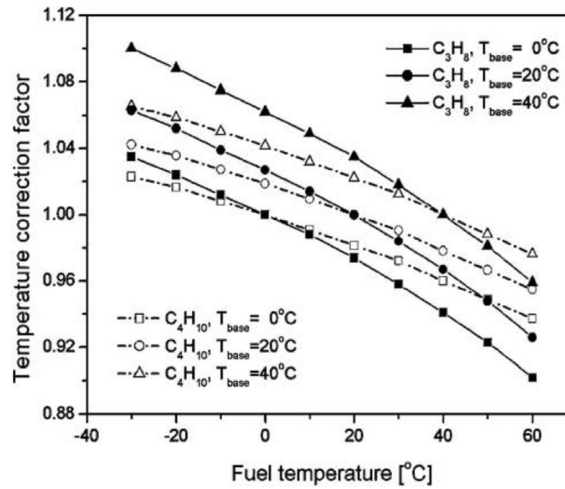


Figure 4.6: Temperature correction factor for propane and butane [12]

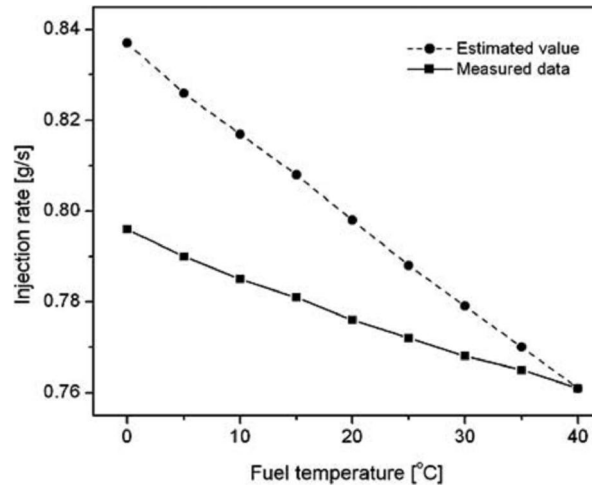


Figure 4.7. Injection rate as a function of fuel temperature [12]

▪ Influence of the injection pressure

The injection pressure, which is different from the LPG fuel rail pressure and the intake port pressure, varies with the engine operating conditions. Therefore, the amount of injected fuel fluctuates according to the injection pressure. In this case, the fuel injection rate at an arbitrary injection pressure is expressed as

$$\dot{m}_{LPG/i} = \dot{m}_{LPG/base} \cdot F_{LPG,\Delta p} \quad (4.4)$$

The pressure correction factor $F_{LPG,\Delta p}$ is defined as

$$F_{LPG,\Delta p} = \sqrt{\frac{\Delta p_{LPG/i}}{\Delta p_{LPG/base}}} \quad (4.5)$$

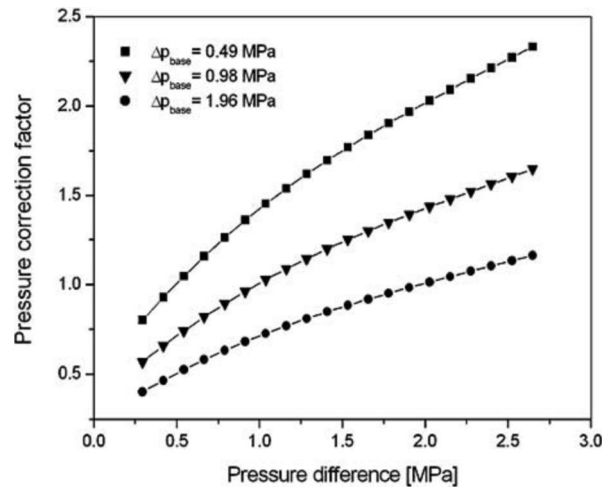


Figure 4.8: Pressure correction factor as function of pressure difference [12]

Figure 4.8 shows how the pressure correction factor changes with injection pressure based on three pressure differences. The pressure correction factor increase as the pressure difference increases. The higher the pressure difference, the lower is the rate of the change in the pressure correction factor.

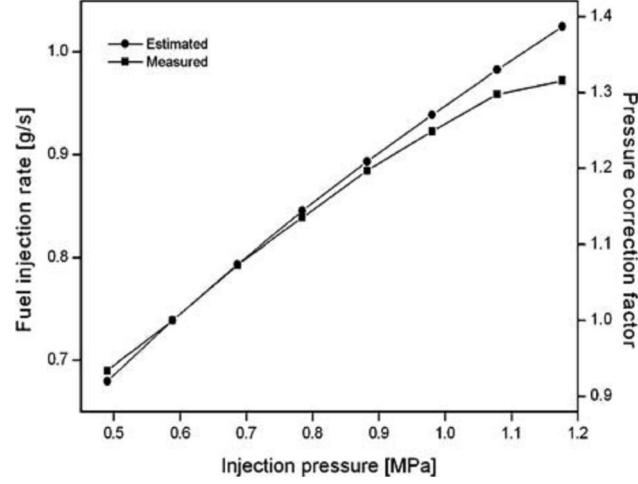


Figure 4.9: Fuel injection rate and pressure correction factor as functions of injection pressure [12].

■ Influence of the driving voltage

The injected fuel quantities under arbitrary and standard driving voltages are described as

$$m_{LPG/V_i} = \dot{m}_{LPG/V_i} \cdot t_{LPG/V_i} \quad \text{And} \quad m_{LPG/V_{base}} = \dot{m}_{LPG/V_i} \cdot t_{LPG/V_{base}}$$

As a result, the injection duration at an arbitrary driving voltage is expressed as

$$t_{LPG/V_i} = \frac{\dot{m}_{LPG/V_{base}}}{\dot{m}_{LPG/V_i}} \cdot t_{LPG/base} \quad (4.6)$$

If the voltage correction factor is defined as

$$F_{LPG/V} = \frac{\dot{m}_{LPG/V_i}}{\dot{m}_{LPG/V_{base}}} \quad (4.7)$$

Then we have equalled

$$t_{LPG/V_i} = \frac{t_{LPG/base}}{F_{LPG/V}} \quad (4.8)$$

Figure 4.10 shows the voltage correction factor as a function of driving voltage. The voltage correction factor has an increasing tendency according to the increase in the driving voltage.

Those problems in this section are compensated in the electronically controlled fuel systems ECU according to data from the lambda probe and "map" the richness of the mixture depending on the operating mode engine. ECU adjusts the required amount of injected LPG by changing the time of injection, as shown in section 4.2.

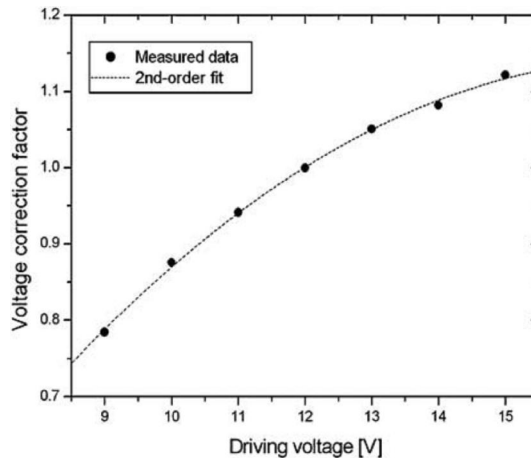


Figure 4.10. Voltage correction factor as a function of driving voltage [12]

4.2. Fuel injection duration and amount of LPG injected.

The amount of LPG injected is directly related to the volumetric efficiency. Comparison of quantity of injection of gaseous and liquid LPG injection system will give one of the reasons why liquid LPG injection has higher volumetric efficiency.

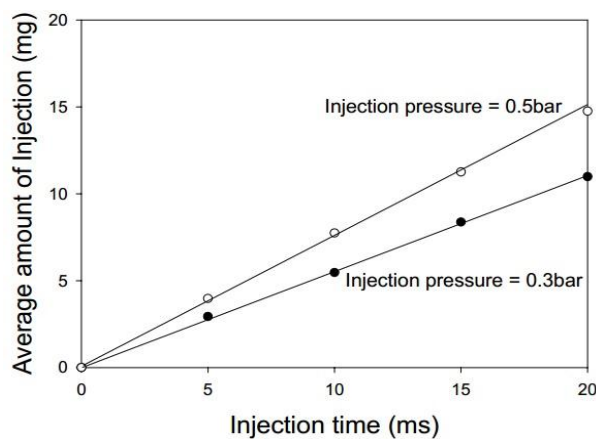


Figure 4.11: The average amounts of gaseous LPG injection [20].

Injection duration is an important parameter in terms of engine load changes. Average injected fuel amounts were calculated as a function of the injection pressure and duration. Normally, liquid LPG injection has higher pressure so the comparison must be concerned with this difference. The average amounts of injection are shown in Figure 4.11 compared to the case of gaseous injection pressure of 0.3 bar, the amount of injection increased about 35% when the gaseous injection pressure increased up to 0.5 bar [12]. Figure 4.12 shows the high amount of injection in the same injection times of course with difference injection pressure.

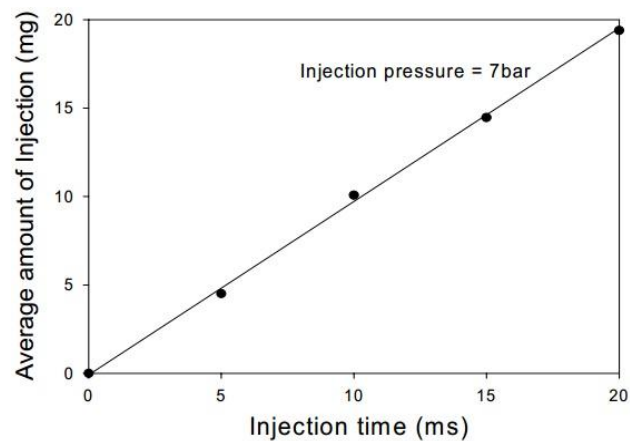


Figure 4.12: The average amounts of liquid LPG injection [20].

5. AIMS OF DISSERTATION

5.1. Motivation

The increasing cost of gasoline and diesel fuels in recent years accompanied by the stringent regulations regarding exhaust emissions have stimulated interests in alternative fuels for automotive engines. LPG has been one of the highly considered alternative fuels for internal combustion engines with a low cost, low pollutant emissions and characteristically adaptable to engine operation [24]. When operating with LPG, engines tend to operate at leaner mixtures resulting in economy of engines running on LPG. However, the use of LPG in externally air fuel mixing spark ignition engines, i.e. carburetor or gas LPG injection, results in reduced power and limited engine upper speed [24]. These are the results of reduced volumetric efficiency due to displaced air in the intake manifold and lower burning velocity respectively. To mitigate the problem, LPG injected in phase liquid into the intake manifold. LPG is kept liquefied until it reaches the outlet nozzle of injector and evaporates partially in the intake manifold, this fuel system gives higher volumetric efficiency than gas injection system. There is an additional benefit from charge cooling. The liquid partly vaporizes in the manifold and the vapor expands. Some of the energy required for the latent heat of vaporization and the boundary work of expansion is supplied from the inducted air. Consequently this air is cooled; the mixture density increases and the mass of the mixture (and hence the total heating value of the mixture) inducted per cycle increases, hence the engine torque increases. A secondary benefit is that the knock is less likely in the cooler mixture so the spark can be advanced further, increasing torque. The spark advance due to cooling adds to the advance due to the higher octane rating (RON) of LPG relative to gasoline [25].

Although injection of liquid phase LPG into intake manifold provide an excellent system for LPG fuel, problems still remain to be solved with this system, i.e. icing around the surface of the outlet nozzle of LPG injector. The formation icing derived from LPG expansion, evaporates quickly and dramatically lowering pressure.

To solve this problem, scientists have studied a variety of methods to prevent icing around outlet nozzle in recent years. Most of them focused on changing the shape of the injector body or changing materials in their designs but those changes are not effective as expected. Some others use electric heat in the intake manifold with the hope temperature helps to

increase LPG evaporator icing easier. However, this might cause volume efficiency decrease and lead to reducing of engine power.

High ability in applications of LPG liquid phase injection systems for vehicles in the Vietnam is also a motivation of dissertation working. Vietnam is densely populated with 89 million people. Air pollution in Vietnam is considered a serious problem, the air quality of Vietnam's urban centers has been degraded with the pollution reaching alarming levels in some areas, many areas of environmental pollution problems have been at an alarming rate. In major cities, road motor vehicles are the main culprit causing air pollution problems, accounts for 70-80 percent in total of pollutions [41]. Vietnam Stemming from the viewpoint that prioritizing the development of road traffic is to create the premise and motivation for socio-economic development, satisfying requirements for industrialization and modernization. Orienting vehicle development in the plan is that by 2020, there will be 3.2–3.5 million automobiles, 57% of which is cars, 14% is buses, and 29% is trucks. Besides, there will be 36 million motorbikes by 2020 [41]. Meanwhile, air pollution will become bigger and more serious. So an LPG phase injection system for vehicles is one of the best solutions to solving the environmental problems by vehicles in the recent future in the Vietnam.

5.2. Objectives of the dissertation

The aim of the dissertation is a theoretical and experimental research process in the channel of the end part of the LPG injector, which will be devoted to the study of changes of liquid phase LPG injection in the channel from the electromagnetic valve to the outlet nozzle of the EP and mass flow out into the intake manifold after that create LPG – air mixture formation before moving to the cylinder. The study will also focus on the result of experiments on the hazard of icing around the outlet nozzle of the EP. To achieve these objectives, the study will perform:

1. Description of the processes in the channel of the EP of the LPG injector. Analyses of thermal processes with physical properties of LPG and a simplified logic sequence of computational processes and relationships to build the computational model.
2. Experimental research on the properties of the EP of the injector: Measuring the pressure of LPG in the channel and the temperature near the outlet nozzle, analysis of

measurement results and use of measurement for a more accurate description of processes in the channel of the EP injector and the computational model.

3. The simplified calculation model for assessing the effect of operating parameters, the geometry of the EP and size of the channel to the course of LPG in the channel and mass flow through an outlet nozzle into the intake manifold.

6. THEORETICAL BASES

6.1. LPG liquid injection system – the basic form

Injecting the LPG in liquid form requires a certain system pressure. This system pressure is released by the diaphragm pump in the tank. This pump pumps the liquid LPG fuel via the coupling block to the LPG injectors (see Figure 6.1). The pressure regulator keeps the system pressure at 5 bar above the tank pressure. For example: Pressure of LPG in the tank is 5,5 bar, that means pressure at the electromagnetic valve of LPG injector has a value of 10.5 bar.

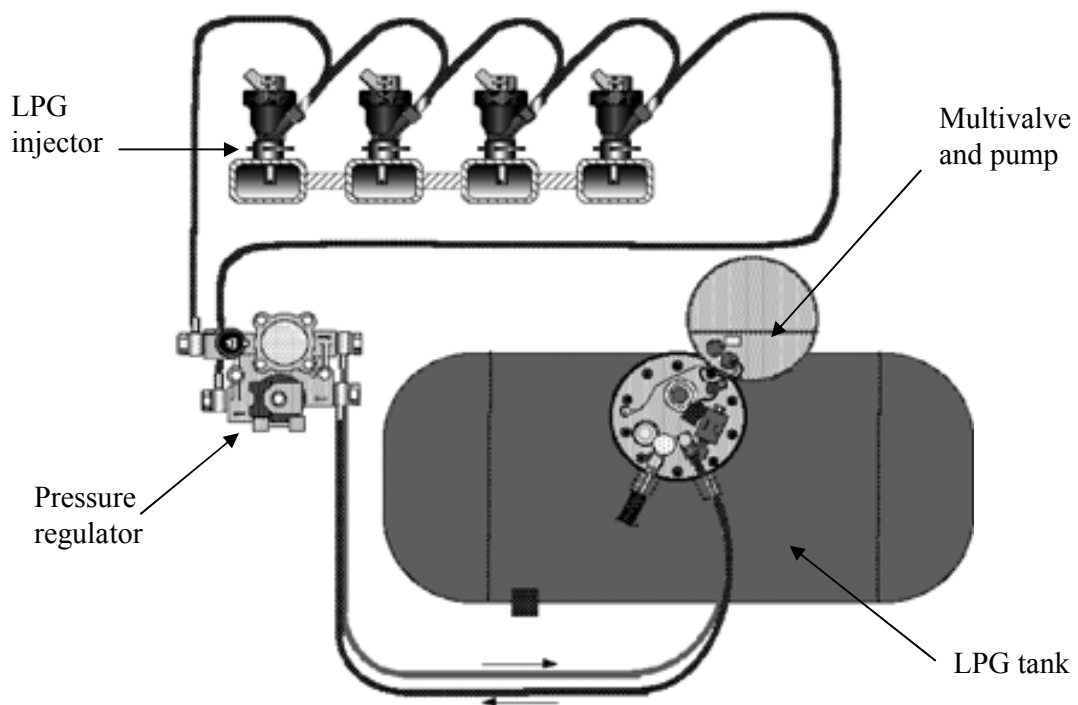


Figure 6.1: Schema of liquid LPG fuel injection system [28]

The LPG injector is assembled by the electromagnetic valve and the end part with the channel for LPG leading to the outlet nozzle (Figure.6.2). The LPG pressure extremely drops in the channel, the intensive evaporation of the LPG in the channel changes liquid phase to a gaseous phase and before the outlet nozzle there is the damp steam of LPG with very low temperature. This situation is illustrated by the diagrams in Figure 6.3.

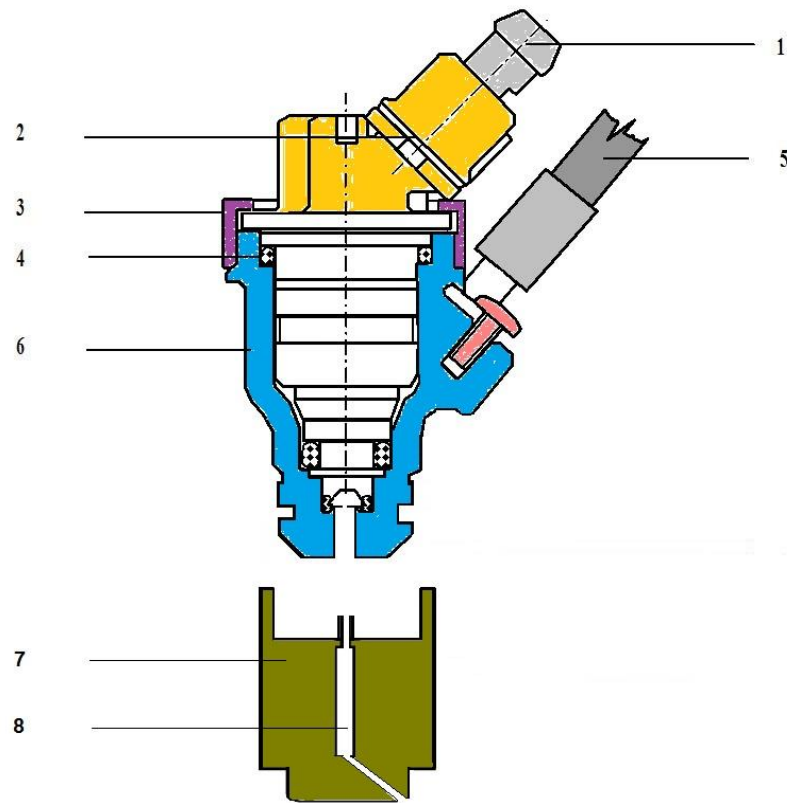


Figure 6.2: Scheme of LPG liquid phase injector: 1-electrical connection, 2-injector body, 3-ring fixing the injector to body, 4-o ring, 5-LPG fuel supply and LPG return to tank, 6-injector housing, 7-the end part of injector, 8-the channel of the end part.

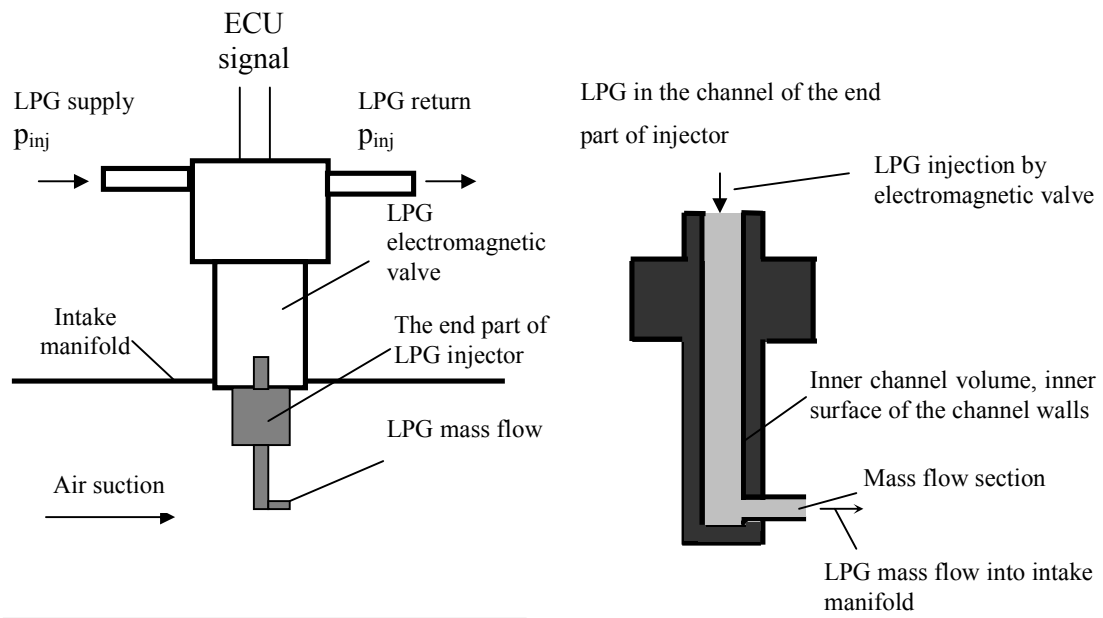


Figure 6.3: Schema of the liquid LPG injectors in the intake manifold and schematic internal structure of the end part of the LPG injector.

6.2. Theoretical analysis of process in the end part of the LPG injector, liquid phase LPG injection into the intake manifold.

Theoretical analysis of process relies on thermal processes with physical properties of LPG. Thank to a simplified logic sequence of each calculative sample and relationships to create the computational model.

6.2.1. Theoretical analysis of LPG course in the channel and effects of surrounding environment.

At the time when LPG is not injected into the channel, the pressure of the channel is equal to ambient pressure. After solenoid electromagnetic valve injector opened, the fuel charge of the liquid phase LPG is injected into the channel a quantity element of fuel $\Delta m_{LPG/liq}$. This LPG quantity will expand and evaporate and in the channel there are combined stay gaseous LPG phase and liquid LPG phase (very small droplets).

To simplify, it is assumed that the full volume of the channel will be the state of damp steam homogeneous – The mixture of gaseous phase LPG and liquid phase LPG in the channel is simulated on the scheme of Figure 6.4: the gaseous phase represents gray filling the full volume of the channel, the liquid phase points are very small droplets dispersed in the gas phase throughout the volume of the channel (black points).

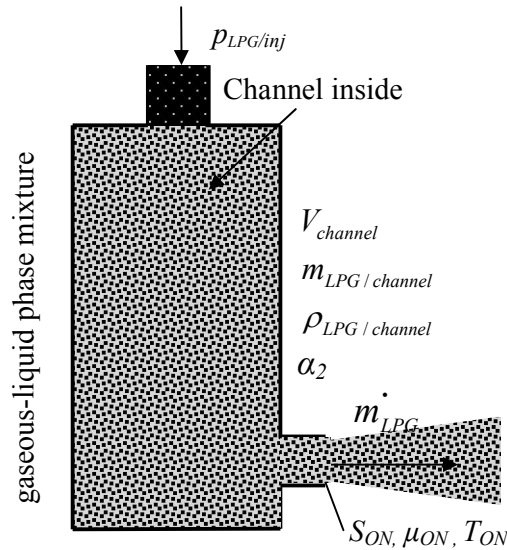


Figure 6.4: Diagram of the gas-liquid LPG homogeneous mixture in the channel.

Density of LPG in the channel is calculated by equation:

$$\rho_{LPG/channel} = \frac{m_{LPG/channel}}{V_{channel}} \quad (6.1)$$

Where

$m_{LPG/channel}$: Mass of LPG in the channel [kg].

$V_{channel}$: Channel volume [m³].

The density of the LPG damp steam before the outlet nozzle, can be understood as the density of the saturated steam (gas) LPG and density of LPG droplets dispersed in the channel:

$$\rho_{LPG/channel} = \rho_{LPG/gas/channel} + \rho_{LPG/liq/channel} \quad (6.2)$$

Where

$\rho_{LPG/gas/channel}$: Density of LPG in gas phase in the channel [kg/m³].

$\rho_{LPG/liq/channel}$: Density of LPG in liquid phase in the channel [kg/m³].

The density of the saturated steam LPG depends on pressure and temperature in the channel:

$$\rho_{LPG/gas/channel} = \frac{p_{LPG/channel}}{r_{LPG} \cdot T_{LPG/channel}} \quad (6.3)$$

Where:

$p_{LPG/channel}$: LPG pressure in the channel [Pa]

r_{LPG} : Individual gas constant of LPG [J/kg.K].

$T_{LPG/channel}$: LPG temperature in the channel [K].

The density of the liquid phase in a channel is dispersed droplets of LPG in the full volume of the channel. Vapor LPG amount in the channel is impossible to determine using the equation above, because the temperature of LPG in the channel before the outlet nozzle can be determined by the thermal balance.

The evaporated part of LPG (i.e. saturated steam) is an important parameter in the thermal balance and the calculative process is needed to determine the proportion of evaporation of LPG in the channel. On the assumption that the indicator of the fraction of vaporized LPG is the difference between standard density ($\rho_{LPG/liq} = 550 \text{ kg/m}^3$) and the density of LPG gas-liquid mixture phase in the channel ($\rho_{LPG/channel}$). It can be described to the relationship (simplified)

$$x \cdot \rho_{LPG/liq} \approx \rho_{LPG/liq} - \rho_{LPG/channel} \quad (6.4)$$

Another expression of the same relationship is

$$x \approx \left(1 - \frac{\rho_{LPG/channel}}{\rho_{LPG/liq}} \right) \quad (6.5)$$

The parameter x indicates saturation damp steam or vapor quality, which is defined as the ratio of saturated steam in damp steam or vapor LPG mass $m_{LPG/gas}$ and mixture mass $m_{LPG/gas} + m_{LPG/liq}$ (gas and liquid LPG). The actual value of the density of damp steam LPG is influenced by the dynamics of the evaporation. So that, equation (6.5) above is only a rough approximate estimate of the proportion of vaporized LPG in the channel. For thermal balance, the proportion of vaporized LPG in a channel defined simply modified the relationship for the density of damp steam LPG. We can estimate (for the next step of calculation) the vapor quality x of LPG by the equation:

$$x = \frac{m_{LPG/gas}}{m_{LPG/gas} + m_{LPG/liq}} = k_{evap} \cdot \left(1 - \frac{\rho_{LPG/channel}}{\rho_{LPG/liq}} \right) \quad (6.6)$$

The equation of vapor quality contains a correction factor evaporation $k_{evap} \leq 1$, whose values will be determined by subsequent calibration of the model calculation of LPG pressure course in the channel of the end part of LPG injector according to measurement.

The thermal balance for the damp steam LPG in the volume channel before the outlet nozzle of the each computational sample (for the time interval $\Delta\tau$) contains:

- The heat ΔQ_{begin} in the liquid and gas phase LPG in the volume of channel before outlet nozzle at the start of the computational sample $\Delta\tau$.

$$\Delta Q_{begin} = m_{LPG/gas/begin} \cdot c_{p/LPG/gas} \cdot T_{LPG/begin} + m_{LPG/liq/begin} \cdot c_{p/LPG/liq} \cdot T_{LPG/begin} \quad (6.7)$$

Where

$m_{LPG/gas/begin}$: Gas LPG mass at start of sample [kg].

$m_{LPG/liq/begin}$: Gas LPG mass at start of sample [kg].

$c_{p/LPG/gas}$: Specific heat at constant pressure of gas LPG [J/kg.K].

$c_{p/LPG/liq}$: Specific heat at constant pressure of liquid LPG [J/kg.K].

$T_{LPG/begin}$: LPG temperature in the channel at start of a sample [K].

- The heat ΔQ_{inj} of the liquid LPG injected to channel volume before the outlet nozzle in the quantity element $\Delta m_{LPG/liq}$ at the start of each computational sample (actual sample inside channel).

$$\Delta Q_{inj} = \Delta m_{LPG/liq/inj} \cdot c_{p/LPG/liq} \cdot T_{LPG/inj} \quad (6.8)$$

Where

$\Delta m_{LPG/liq/inj}$: Quantity of liquid LPG injected into the channel [kg].

$c_{p/LPG/liq}$: Specific heat at constant pressure of liquid LPG [J/kg.K].

$T_{LPG/inj}$: Injection temperature of liquid LPG [K].

The quantity $\Delta m_{LPG/liq/inj}$ determines by the Bernoulliho equation

$$\Delta m_{LPG/liq/inj} = \mu_{EV} \cdot S_{EV} \cdot \sqrt{2 \cdot \rho_{LPG/liq} \cdot (p_{LPG/liq} - p_{LPG/channel})} \cdot \Delta \tau \quad (6.9)$$

Where

$\Delta m_{LPG/liq/inj}$: The quantity element of liquid LPG injected into channel [kg].

$p_{LPG/liq}$: Injection pressure at electromagnetic valve [Pa].

$p_{LPG/channel}$: LPG pressure in the channel [Pa].

μ_{EV} : Flow coefficient at the electromagnetic valve.

S_{EV} : Area of orifice below electromagnetic valve [m²].

$\Delta \tau$: Interval of liquid LPG quantity [s].

- After LPG liquid injected quantity element $\Delta m_{LPG/liq/inj}$, density of liquid and gas LPG in the channel will be determined. The estimation of the vapor quality of the damp steam in the channel volume before mass flow through an outlet nozzle from the total mass of LPG in the channel volume is at the equation (6.5). The difference between gas LPG mass in the channel $m_{LPG/gas/channel}$ in the current and previous step was a parameter for determine of LPG vapor mass in the current step (actual sample inside channel). The heat for LPG evaporation ΔQ_{evap} at computational sample thereby is determined in the current step.

$$\Delta Q_{evap} = m_{LPG/evap} \cdot L_{LPG} \quad (6.10)$$

Where

$m_{LPG/evap}$: Mass of LPG evaporated in a calculative sample [kg].

L_{LPG} : Specific latent heat of LPG vaporization [J/kg].

- Heat balance of the current step effects by the heat transfer, where heat conducting from the walls of the channel to LPG filling in the channel. It is calculated as the heat transfer from the environment (ambient) outside of the end part of the injector to LPG filling in the channel using classical relations and simplifying assumptions. Due to specific conditions of very intense evaporation of LPG in the channel, which changes as a boiling in the full volume of the channel, the problem is determining the heat transfer coefficient between the

channel walls and LPG filling in the channel, the temperature of the wall and the coefficient of heat transfer there are estimated. It explained as below:

+ Heat is transfer from the outside of the wall of the end part of injector to LPG filling in the channel as the result of several heat transfer processes and their specific conditions: heat conduction from the environment into the outside surface of walls and heat transfer from the walls of the channel in LPG filling in the channel. The situation is shown in the schematic diagram in Figure 6.5.

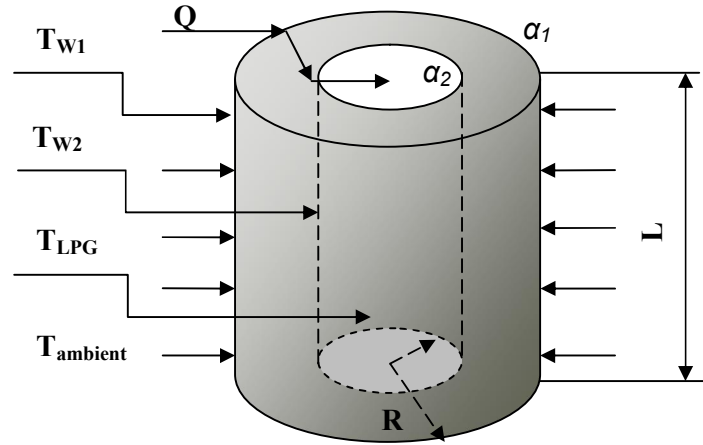


Figure 6.5: Heat transfer from outside wall of the EP to LPG in the channel.

+ Heat transfer from ambient to the LPG filling in the channel can be described as heat conduction. For each calculative sample, filling of LPG in the channel will be in the time interval $\Delta\tau$ applied to the current step filling LPG heat quantity that determines the equation

$$\Delta Q_{transfer} = 2 \cdot \pi \cdot L \cdot k \cdot (T_{amb} - T_{LPG/channel}) \cdot \Delta\tau \quad (6.11)$$

Where

k [W/m.K]: overall heat transfer coefficient for cylinder.

$$k = \frac{1}{\frac{1}{\alpha_1 \cdot R} + \frac{1}{\lambda} \ln \frac{R}{r} + \frac{1}{\alpha_2 \cdot r}} \quad (6.12)$$

L : The length of the EP [m].

R, r : Radius outside and inside of the EP [m].

λ : Thermal conductivity of the EP material [W/m.K].

α_1, α_2 : Heat transfer coefficient at outside and inside surface of material [W/m²K].

T_{amb} : Ambient temperature [K].

$T_{LPG/channel}$: Average temperature of LPG in the channel [K].

Parameters $R, r, L, \lambda, \alpha_1, \alpha_2$ shown on Figure 6.5, depend on structure and material in the design of the EP, value of heat transfer coefficient α_1 is estimated with sufficient reliability (when the air flow over the wall surface can be estimated $\alpha_1 \cong 30 \div 50 \text{ W/m}^2\text{K}$). The value of heat transfer coefficient α_2 is influenced by the LPG phase in the channel: very intense evaporation of LPG in the channel is a bubble boiling over the volume of the channel in which the value of heat transfer coefficient on the inside wall surface is a change parameter. Possibly, effects of heat transfer is not considerable, for purpose to simplify in calculative process, the value of α_2 is calculated like a function which depends on ratio of injected quantity in samples and total of mass LPG in each working cycle. The basic (maximum) value of heat transfer coefficient reach $\alpha_2 \cong 10^4 \div 10^5 \text{ W/m}^2\text{K}$ [31], thermal conductivity of aluminum alloy (used in design of EP) is $\lambda = 145 \text{ W/m.K}$.

The equations (6.7), (6.8), (6.10) and (6.11) for the thermal balance for LPG inside volume before the outlet nozzle (i.e. heat in the LPG at start of computational step, the heat of the injected $\Delta m_{LPG/liq}$, heat of evaporation of the next LPG part, heat transfer from the wall to LPG and the temperature change of the liquid and gas phase LPG in the channel volume before the outlet nozzle - BON) determine the new temperature T_{BON} of the damp steam LPG at the end of the computational sample.

$$\Delta Q_{begin} + \Delta Q_{inj} + \Delta Q_{transfer} - \Delta Q_{evap} = \Delta Q_{BON} \quad (6.13)$$

Solving this equation to deploy descriptions above, we have an equation below:

$$\begin{aligned} & m_{LPG/gas/begin} \cdot c_{p/LPG/gas} \cdot T_{LPG/begin} + m_{LPG/liq/begin} \cdot c_{p/LPG/liq} \cdot T_{LPG/begin} + \\ & + \Delta m_{LPG/liq/inj} \cdot c_{p/LPG/liq} \cdot T_{LPG/inj} + 2 \cdot \pi \cdot L \cdot k \cdot (T_{amb} - T_{LPG/channel}) \cdot \Delta \tau - \\ & - m_{LPG/evap} \cdot L_{LPG} = m_{LPG/liq/BON} \cdot c_{p/LPG/liq} \cdot T_{BON} + m_{LPG/gas/BON} \cdot c_{p/LPG/gas} \cdot T_{BON} \end{aligned} \quad (6.14)$$

Where

T_{BON} : Temperature of damp steam at the end of the computational sample – before outlet nozzle [K]

$m_{LPG/liq/BON}$: Mass of liquid LPG at the end of the computational sample [kg]

$m_{LPG/gas/BON}$: Mass of gas LPG at the end of the computational sample [kg]

From equation (6.14) determine for temperature before outlet nozzle T_{BON} in the following equation:

$$T_{BON} = \frac{m_{LPG/gas/begin} \cdot c_{p/LPG/gas} \cdot T_{LPG/begin} + m_{LPG/liq/begin} \cdot c_{p/LPG/liq} \cdot T_{LPG/begin}}{m_{LPG/liq/BON} \cdot c_{p/LPG/liq} + m_{LPG/gas/BON} \cdot c_{p/LPG/gas}} + \frac{\Delta m_{LPG/liq/inj} \cdot c_{p/LPG/liq} \cdot T_{LPG/inj} + 2 \cdot \pi \cdot L \cdot k \cdot (T_{amb} - T_{LPG/channel}) \cdot \Delta \tau - m_{LPG/evap} \cdot L_{LPG}}{m_{LPG/liq/BON} \cdot c_{p/LPG/liq} + m_{LPG/gas/BON} \cdot c_{p/LPG/gas}} \quad (6.15)$$

The pressure of the damp steam LPG is determined by the calculated temperature of the damp steam LPG (simple conversion for the reflected composition of LPG – ratio propane/butane). From a figure of vapor pressure of main LPG fuel components according to temperature, we can determine the pressure of LPG by an equivalent equation (with compositional mixture propane/butane =50/50):

$$p = 3.437 + 0.108 \cdot T + 0.001 \cdot T^2 + 0.000008 \cdot T^3 \quad (6.16)$$

Where p : LPG pressure [bar]

T : LPG temperature [$^{\circ}\text{C}$]

The elementary quantities of LPG flow out as gas (compressible fluid) from the outlet nozzle to the intake manifold at the end of each computational sample: Damp steam LPG mass flow into the intake air is solved as isentropic gas discharge, the gas properties have the saturated steam of LPG only, outflow is calculated with the respecting to critical expansion ratio (for gaseous LPG the $\beta_{crit} = 0,54$). The saturated steam carries away the droplets of the LPG damp steam (it includes the vapor quality x in the equation). The elementary quantities of LPG outflows from the outlet nozzle at computational sample then will be:

$$\Delta m_{LPG/ON} = \mu_{ON} \cdot \frac{S_{ON}}{x} \cdot \sqrt{\frac{2 \cdot \kappa_{LPG}}{\kappa_{LPG} - 1} \cdot \frac{p_{LPG/channel}^2}{r_{LPG} \cdot T_{LPG/channel}} \cdot \left(\frac{p_{int}}{p_{LPG/channel}} \right)^{\frac{2}{\kappa_{LPG}}} \cdot \left[1 - \left(\frac{p_{int}}{p_{LPG/channel}} \right)^{\frac{\kappa_{LPG}-1}{\kappa_{LPG}}} \right]} \cdot \Delta \tau \quad (6.17)$$

Where:

$\Delta m_{LPG/ON}$: The quantity element of LPG mass flow into the intake manifold [kg]

μ_{ON} : Flow coefficient at outlet nozzle of the EP.

S_{ON} : Area of outlet nozzle [m^2].

κ_{LPG} : Specific heat capacities ratio of LPG

r_{LPG} : Individual gas constant of LPG [J/kg.K].

$T_{LPG/channel}$: LPG temperature in the channel [K].

$p_{LPG/channel}$: LPG temperature in the channel [Pa].

p_{int} : Pressure in the intake manifold [Pa].

$\Delta \tau$: An interval of the quantity element [s].

After discharge (mass flow), at the end of computational sample, after outflow quantities $\Delta m_{LPG/ON}$, the residual amount LPG keeps the pressure $p_{LPG/channel}$, temperature $T_{LPG/channel}$ and vapor quality x of the damp steam on the same values like before outflow. The model calculation continues identical procedures: supply the next elementary quantities $\Delta m_{LPG/liq}$ to channel volume and so forth. The calculation procedures are replicated up to the full LPG charge injection to channel volume before outlet nozzle and they are ended at the outflow the full LPG charge from the nozzle into the intake manifold.

The process of damp steam injection LPG into the intake manifold is explained in detail in the following part.

Damp steam LPG mass flows into the intake manifold is supposed to be isentropic compressible. Gas properties have only saturated steam, the mass flow rate $\dot{m}_{LPG/gas/ON}$ [kg/s] of the nozzle determines the equation:

$$\dot{m}_{LPG/gas/ON} = \mu_{ON} \cdot S_{ON} \cdot w_{LPG/gas/ON} \cdot \rho_{LPG/gas/ON} \quad (6.18)$$

Discharge velocity of LPG $w_{LPG/gas/ON}$ [m/s] at the outlet nozzle determines the relationship (for isentropic expansion of the gas discharge)

$$w_{LPG/gas/ON} = \sqrt{2 \cdot r_{LPG} \cdot T_{LPG/channel}} \cdot \sqrt{\frac{\kappa_{LPG}}{\kappa_{LPG} - 1} \cdot \left[1 - \left(\frac{p_{int}}{p_{LPG/channel}} \right)^{\frac{\kappa_{LPG}-1}{\kappa_{LPG}}} \right]} \quad (6.19)$$

LPG mass flow at the outlet nozzle to be calculated on the average value of the pressure of LPG in the channel ($p_{LPG/channel}$), specified pressure of LPG in the channel in the previous sample and the pressure of LPG in the channel for the current sample (i.e. flow elemental quantities $\Delta m_{LPG/liq}$ for the current sample is determined by the temperature of LPG in the channel for the current sample - see description above). Discharge velocity $w_{LPG/gas/ON}$ is calculated by the pressure ratio of intake manifold p_{int} and LPG $p_{LPG/channel}$ in the channel before outlet nozzle. In the calculation process is respecting to critical expansion ratio β_{crit} .

- If the ratio $\frac{p_{int}}{p_{LPG/channel}} \geq \beta_{crit}$ then the discharge (flow) velocity $w_{LPG/gas/ON}$ will be determined by the equation (6.19).
- If the ratio $\frac{p_{int}}{p_{LPG/channel}} < \beta_{krit}$ then the discharge velocity $w_{LPG/gas/ON}$ will be determined by flow rate critical.

The value β_{crit} is calculated from ideal gas properties

$$\beta_{crit} = \left(\frac{2}{\kappa + 1} \right)^{\frac{\kappa}{\kappa - 1}} \quad (6.20)$$

LPG (composition: propane/butane = 50/50) has properties: $\kappa_{LPG}=1.33$, $r_{LPG}=165$ J/kg.K, $\beta_{crit}=0.54$.

Density of LPG in gas phase flow out through the outlet nozzle is calculated, which depends on the relation.

$$\rho_{LPG/gas/ON} = \rho_{LPG/gas/channel} \cdot \left(\frac{p_{int}}{p_{LPG/channel}} \right)^{\frac{1}{\kappa_{LPG}}} \quad (6.21)$$

Density of gas LPG in the channel:

$$\rho_{LPG/gas/channel} = \frac{p_{LPG/channel}}{r_{LPG} \cdot T_{LPG/channel}} \quad (6.22)$$

Substituting some variables of equations (6.19), (6.21) and (6.22) into equation (6.18) to calculate the mass flow rate $\dot{m}_{LPG/gas/ON}$ (for the proposed adiabatic - isentropic expansion of the gas at the outlet nozzle). We will have an equation

$$\dot{m}_{LPG/gas/ON} = \mu_{ON} \cdot S_{ON} \cdot \sqrt{\frac{2 \cdot \kappa_{LPG}}{\kappa_{LPG} - 1} \cdot \frac{p_{LPG/channel}^2}{r_{LPG} \cdot T_{LPG/channel}} \cdot \left(\frac{p_{int}}{p_{LPG/channel}} \right)^{\frac{2}{\kappa_{LPG}}} \cdot \left[1 - \left(\frac{p_{int}}{p_{LPG/channel}} \right)^{\frac{\kappa_{LPG}-1}{\kappa_{LPG}}} \right]} \quad (6.23)$$

At the outlet nozzle, in the mass flow (discharge) process, the saturated steam (vapor LPG) needed to carry LPG droplets in the liquid gas mixture, this quantity of LPG liquid (droplets) depends on vapor quality x in the channel. The quantity elements of LPG outflows from the nozzle into the intake manifold at computational sample then will be

$$\Delta m_{LPG/ON} = \frac{1}{x} \cdot \dot{m}_{LPG/gas/ON} \cdot \Delta \tau \quad (6.24)$$

LPG saturated steam temperature at the outlet nozzle $T_{LPG/gas/ON}$ is explained in the equation of isentropic process.

$$T_{LPG/gas/ON} = T_{LPG/gas/channel} \cdot \left(\frac{p_{int}}{p_{LPG/channel}} \right)^{\frac{\kappa_{LPG}-1}{\kappa_{LPG}}} \quad (6.25)$$

If the expansion process of saturated steam in the channel reaches a critical value β_{crit} then the temperature of saturated steam LPG at outlet nozzle $T_{LPG/gas/ON}$ will equal a critical temperature T_{crit} .

$$T_{LPG/gas/ON} = T_{crit} = T_{LPG/gas/channel} \cdot \beta_{crit}^{\frac{\kappa_{LPG}-1}{\kappa_{LPG}}} \quad (6.26)$$

The discharge (flow) velocity of saturated steam LPG $w_{LPG/gas/ON}$ from the outlet nozzle is determined in equation (6.19), in the expansion process at the outlet nozzle reaches a critical value then flow velocity according to critical temperature T_{crit} .

$$w_{LPG/gas/ON} = w_{crit} = \sqrt{\kappa_{LPG} \cdot r_{LPG} \cdot T_{crit}} \quad (6.27)$$

If the overall rate of expansion of saturated steam LPG is lower than β_{crit} , the first part of the expansion will be used to discharge from the outlet nozzle and the other (remaining) part of the expansion of LPG pressure at the outlet nozzle $p_{LPG/gas/ON} = \beta_{crit} \cdot p_{LPG/gas/channel}$ to pressure of intake manifold p_{int} will take place in the intake manifold, while there is also a change in temperature $T_{LPG/gas/int}$:

$$T_{LPG/gas/int} = T_{LPG/gas/ON} \cdot \left(\frac{p_{int}}{p_{LPG/gas/ON}} \right)^{\frac{\kappa_{LPG}-1}{\kappa_{LPG}}} \quad (6.28)$$

The expansion of the LPG saturation steam from the channel through the outlet nozzle into the intake manifold is shown in a thermal T-s diagram in figure 6.6.

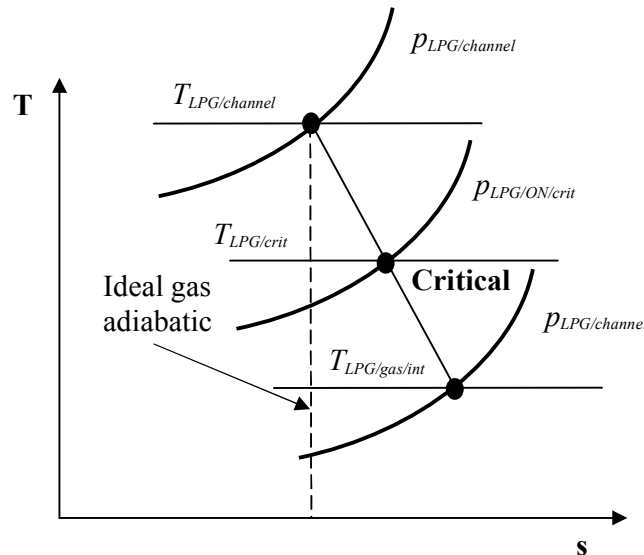


Figure 6.6: T-s diagram of the expansion of the LPG saturation steam.

6.2.2. Estimative calculation of the fresh mixture temperature in the intake manifold

The elemental quantities of saturated steam LPG with their temperature and elemental quantities of liquid phase (with temperature damp steam LPG in the channel and subsequent evaporation in the intake manifold) of the samples during the injection and producing a fresh mixture in the intake manifold. The thermal balance can estimate the temperature of the fresh mixture in the intake manifold:

The amount of fresh mixture $M_{FM/1}$ (for LPG injected mass per working cycle):

$$M_{FM/1} = \sum_1^n \Delta m_{LPG/liq/inj} + M_{air/1} \quad (6.29)$$

Where:

$M_{FM/1}$: Amount of fresh mixture in the working cycle [kg].

$M_{air/1}$: Amount of fresh air in the working cycle [kg].

$\Delta m_{LPG/liq/inj}$: The quantity element of liquid LPG injected [kg]

n : Numbers of the sample (according to injection duration and time interval $\Delta \tau$)

The amount of fresh air in the working cycle $M_{air/1}$ is calculated by the formula:

$$M_{air/1} = \lambda \cdot A_{theor} \cdot \sum_1^n \Delta m_{LPG/liq} \quad (6.30)$$

Where:

A_{theor} : Theoretical consumption of air for LPG fuel [kg/kg].

λ : Excess-air ratio

Heat of saturated steam injected LPG:

$$\sum_1^n \Delta m_{LPG/gas/ON} \cdot c_{p/LPG/gas} \cdot T_{LPG/channel} \quad (6.31)$$

Where

$\Delta m_{LPG/gas/ON}$: The quantity element of gas phase LPG at the outlet nozzle [kg].

$c_{p/LPG/gas}$: Specific gas at constant pressure of LPG [J/kg.K]

$T_{LPG/channel}$: Temperature of gas LPG in the channel [K].

Heat of injected liquid phase LPG:

$$\sum_1^n (\Delta m_{LPG/liq/ON} \cdot c_{LPG/liq} \cdot T_{LPG/channel} - \Delta m_{LPG/liq/ON} \cdot L_{LPG}) \quad (6.32)$$

Where

$\Delta m_{LPG/liq/ON}$: The quantity element of liquid phase LPG at the outlet nozzle [kg].

$c_{p/LPG/liq}$: Specific heat at constant pressure of liquid LPG [J/kg.K]

$T_{LPG/channel}$: Temperature of gas LPG in the channel [K].

L_{LPG} : Specific latent heat of LPG [J/kg]

The discharge of LPG into the intake manifold, the temperature of LPG after expansion is lower than the temperature of the LPG in the channel, high speed, causes turbulence and after termination turbulence kinetic energy after the LPG outlet changes to heat energy, and therefore can be simply calculated the thermal balance temperature of LPG in the channel before LPG discharge into the suction pipe.

Heat of air:

$$M_{air/\lambda} \cdot c_{p/air} \cdot T_{air} \quad (6.33)$$

Where

$c_{p/air}$: Specific heat at constant pressure of air [J/kg.K]

T_{air} : Temperature of air [K].

Heat balance of LPG fuel - air mixture in the intake manifold after finishing of injection

$$\begin{aligned} & \sum_1^n \Delta m_{LPG/gas/ON} \cdot c_{p/LPG/gas} \cdot T_{LPG/channel} + \sum_1^n \Delta m_{LPG/liq/ON} \cdot c_{LPG/liq} \cdot T_{LPG/channel} - \sum_1^n \Delta m_{LPG/liq/ON} \cdot L_{LPG} + \\ & + M_{air/\lambda} \cdot c_{p/air} \cdot T_{air} = \sum_1^n \Delta m_{LPG/liq+gas} \cdot c_{LPG/gas} \cdot T_{FM} + M_{air/\lambda} \cdot c_{p/air} \cdot T_{FM} \end{aligned} \quad (6.34)$$

From equation (6.34), we will infer an equation for estimating of fresh mixture temperature of each cycle

$$T_{FM} = \frac{\sum_1^n \Delta m_{LPG/gas/ON} \cdot c_{p/LPG/gas} \cdot T_{LPG/channel} + \sum_1^n (\Delta m_{LPG/liq/ON} \cdot c_{LPG/liq} \cdot T_{LPG/channel} - \Delta m_{LPG/liq/ON} \cdot L_{LPG}) + M_{air/\lambda} \cdot c_{p/air} \cdot T_{air}}{\sum_1^n \Delta m_{LPG/liq+gas} \cdot c_{LPG/gas} + M_{air/\lambda} \cdot c_{p/air}} \quad (6.35)$$

7. EXPERIMENTS

The experimental research program has been conducted in the laboratory of the Vehicles and Engines Department, Mechanical Engineering Faculty, Technical University of Liberec. The experimental work was performed on a device that had done in a Master thesis [6].

7.1. Experimental devices

The basis of the experimental equipment includes a model suction manifold - plexiglas square tube, This tube had a hole for fixing of LPG injector. The intake manifold is connected to the diesel engine Dawoo-Avia (DA), which is used to simulate the airflow in the engine intake and guarantee safety to the drainage and burning of a mixture of air-LPG. Figure 7.1 shows a schematic diagram of the experimental set-up to measure pressure in the channel and temperature at the tip of the EP.

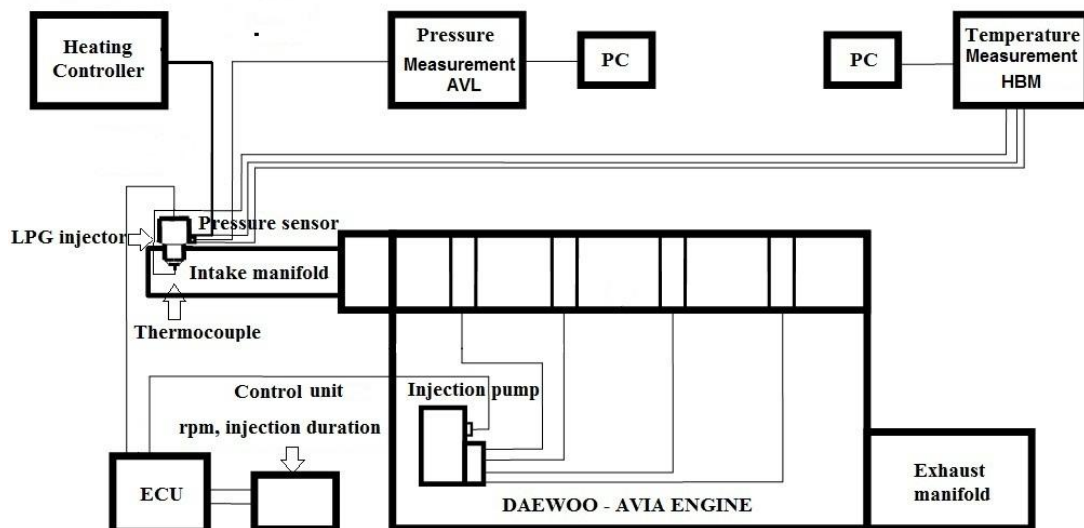


Figure 7.1: Schema of experimental test bench.

The engine is a standard turbocharger, when using the engine for experiments with liquid injection LPG filling turbocharger was not connected to the intake manifold. The diesel engine was operated at idle. This solution was chosen for two reasons:

- DA engine was used for the simulation of flow in the model intake manifold injector LPG: the rate of intake air in the intake manifold model is adjusted by changing its position [6].

- DA engine sucked mixtures of air and LPG, which is running as a bi-fuel, exhaust gases from the engine are discharged through the exhaust pipe outside the laboratory) [6].

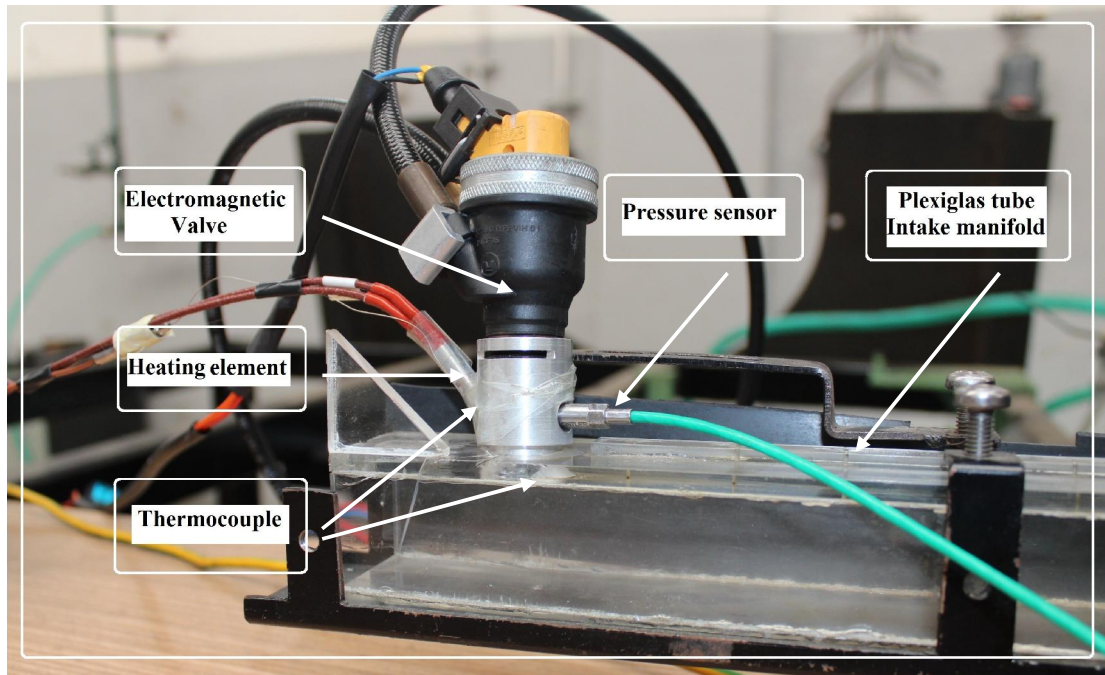


Figure 7.2: Model of plexiglas tube (connected to the intake manifold) and position of the LPG injector nozzle.

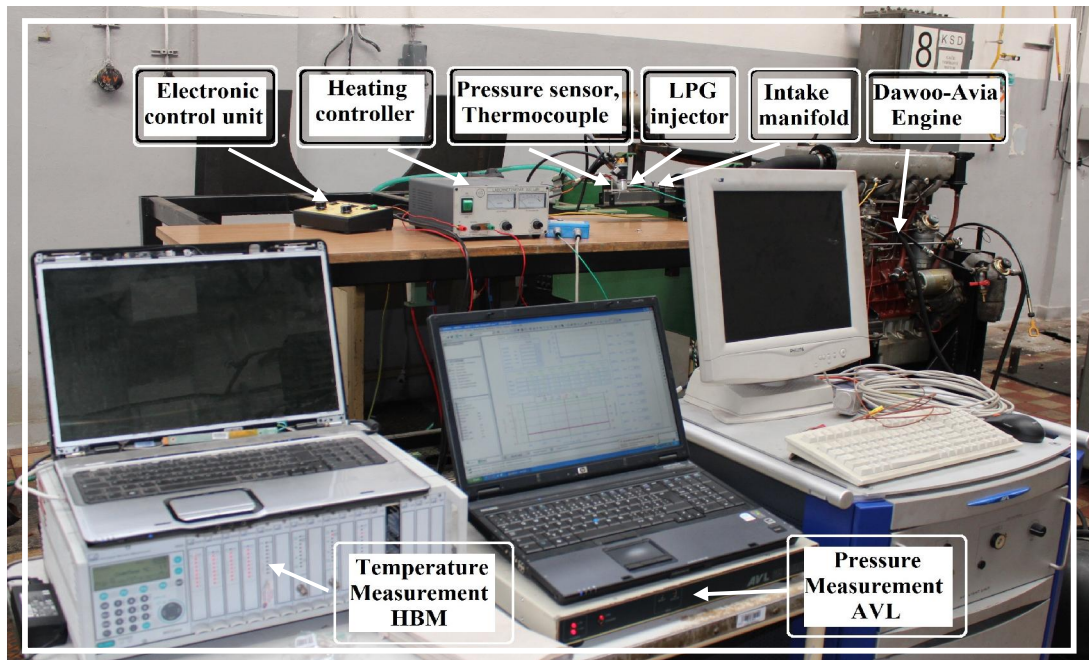


Figure 7.3: Test engine and experimental devices

The end part of the injector was fixed into the intake manifold, which was attached to LPG injector. The injector was controlled by a special control unit, which was managed by injection frequency (engine speed) and duration of injection (engine load). The arrangement of the measuring station is shown in Figure 7.2 and Figure 7.3.

The electromagnetic injection valve was placed in the holder, which was embedded in the model of the manifold. Tightness between the injector and the end part of the injector (EP) by a ring clamp, The diameter of orifice S_{EV} is 0.25 mm. (It was shown in Figure 4.1).

The end part of the injector (see Figure 7.4) was designed with different diameters of 2 channels. Channel 1 (the vertical part) had a diameter of 1.6 mm and the channel 2 had of diameter of 1,3 mm. In particular, the EP is designed with 1 hole passing through the body of the EP itself, where a heating element was installed. Heat flux was controlled by a temperature controller (Statron type 2230–13.8V/10A). A precision temperature controller used a current or voltage source (the values of the temperature of the electric resistor depend on a variety of voltage and current). The heating element in the EP is primarily to increase the temperature in the part of the outlet nozzle. Structure and sketch drawing of the EP are shown in Figure 7.4 and values of dimension are shown in Appendix 1. Design the EP was prepared for experimental research, testing the EP is not intended for normal operation.

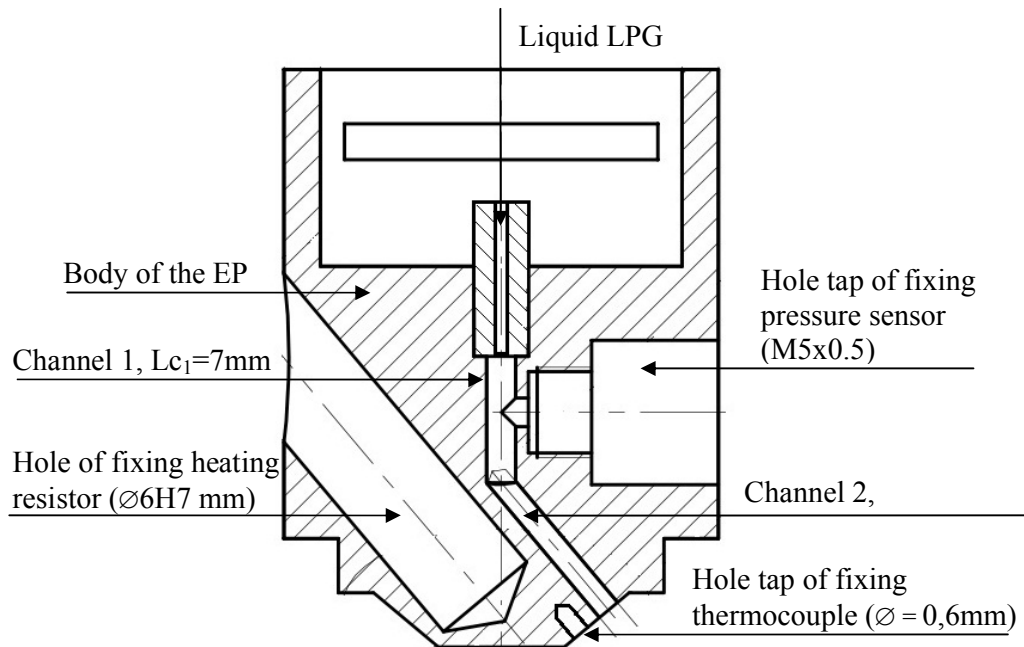


Figure 7.4: Structure and sketch drawing of the EP.

7.2. Data acquisition systems

The purpose of the experiment was to determine the pressure of LPG in the channel of the end part of the injector and temperature at the outlet nozzle of the EP, in order to find the causes and solutions to reduce or prevent icing around the outlet nozzle of the EP.

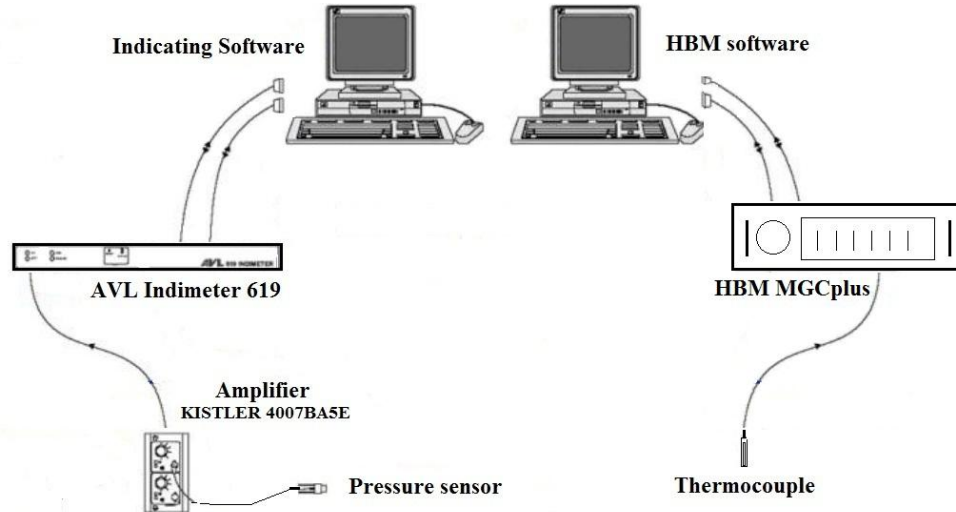


Figure 7.5: Diagram of measurement pressure and temperature of channel, the tip of the EP [18].

A measuring chain was used for measurement of LPG in the channel using absolute pressure sensor piezoresistive Kistler 4007BA5F. Data was collected in AVL test and measurement. Signal from pressure transducer was lead through a charge amplifier to the acquisition device, AVL Indimeter 619. In addition, signal of the crankshaft rotation angle and signal of top dead center (TDC) led to the same device. AVL IndiCom, indicating software were used in this experiment.

The temperature of the end part of nozzle body was measured by micro thermocouple OMEGA type K and it was connected to HBM MGCplus logger test and measurement. Using interfaces such as Ethernet or USB, data were sent to an external computer.

7.3. Measurement program and result of experiments.

Measuring the pressure of LPG in the channel of the end part of the LPG injector and the temperature, near the outlet nozzle was performed in the settings of the control unit injector LPG for three modes of the valve opening time (injection duration) of the EV and 3 frequency injection, corresponding 4 strokes engine speed $n = 1000, 3000$ and 5000rpm .

Measurements were performed with the end part of the injector in Figure 7.4 and Appendix 1

- Conditions of measurements were performed at an ambient temperature of 18°C in the laboratory. LPG pressure in the pressure tank was 5.5 bar, injection pressure (the pressure at the injectors LPG) was 10.5 bar.
- In the hole M5x0.5 was mounted with piezoresistive pressure sensors, range 5 bar, compensation in the temperature range 25-180°C at the reference temperature of 25°C).
- In the hole of diameter $\varnothing = 0,6$ mm was mounted with the sheathed micro thermocouple.
- In the hole $\varnothing 6H7$ mm was inserted the heating element (measurements were performed both without heating and by controlled heating of the end part of the LPG injector near the outlet nozzle at a temperature of about 5°C).

All the measurements showed that the pressure course in the channel of the end part of the LPG injector was influenced by the temperature of the end part of the injector. Injector temperature was measured at only one point: In the measurement at the mode of without heating, the temperature state of the EP was determined as coolly consequence LPG vaporized in the channel. The temperature near channel is probably similar to the temperature measured on the EP bottom beside outlet nozzle. When measuring with heating elements, hot elements will transfer heat to EP and temperature at the outlet nozzle will be higher.

Measurement of LPG course in the channel in normal conditions (without heating) was used to test the computational model and a more accurate description and calculation of processes in the channel of the end part of the LPG injector. The measurement results are presented in the graphs in Figures 7.6 to 7.13.

7.3.1. Experiments without heating elements

Measurements were performed that has not the heating element at the end part of injector or without heating (in Figures these measurements are termed "normal")

The graph in Figure 7.6 shows a comparison of LPG pressure course in the channel of the end part of injector with difference of injection duration $\Delta\tau = 2, 6$ and 10ms. Both engine speeds were at 3000rpm and values of geometry and dimension of the EP as described in Figure 7.4 and Appendix 1.

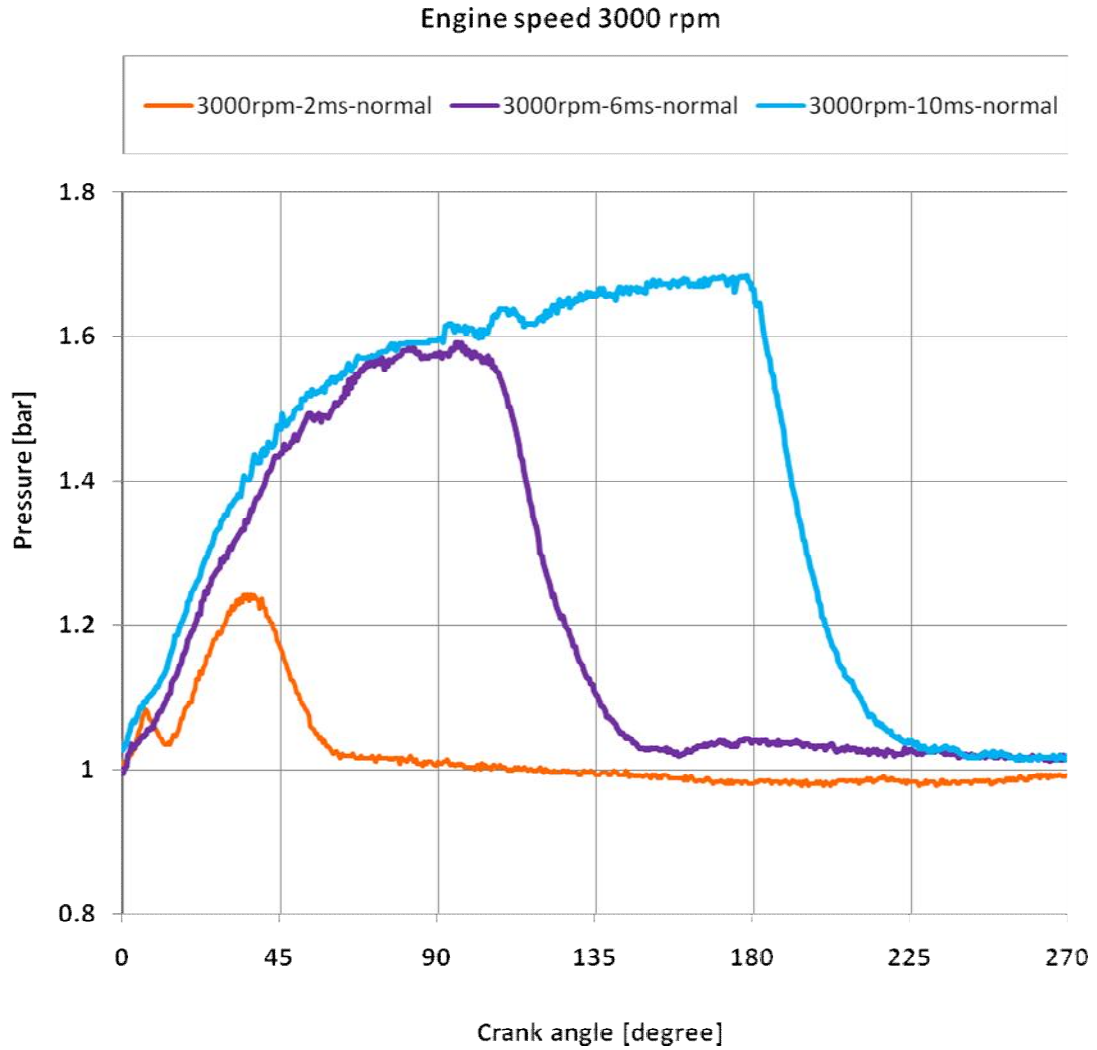


Figure 7.6: LPG pressure course depends on variations of injection durations 2 ms, 6 ms and 10 ms at the engine speed of 3000 rpm.

As shown clearly, pressure in the channel will increase when injection duration increases, because the injection duration increases due to the increase of quantities of LPG injected into the channel, and the pressure of LPG in the channel also grows up correspondingly.

In the experiment, icing phenomenon occurs most often around the tip of EP with higher of injection duration.

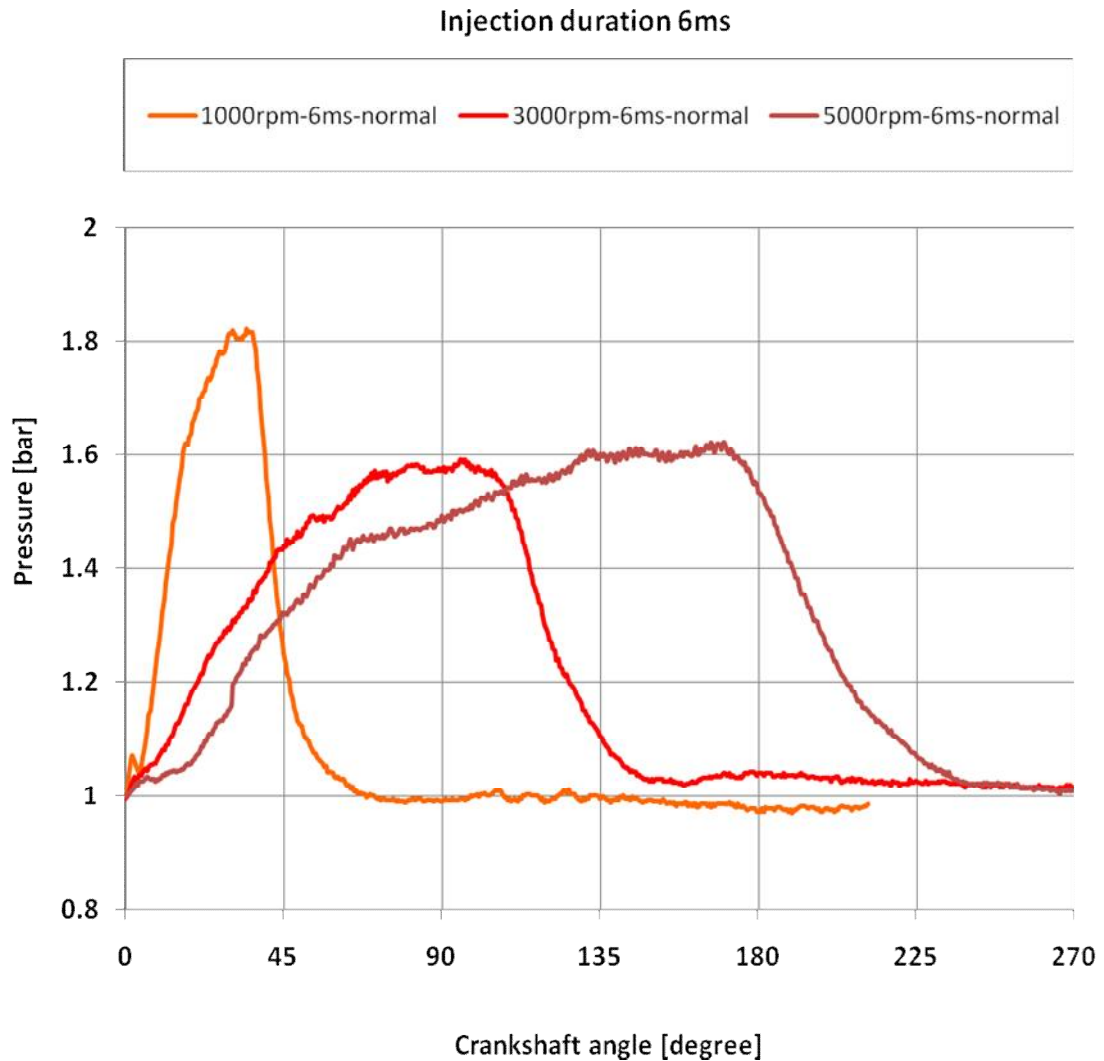


Figure 7.7. LPG pressure courses depend on variations of engine speeds 1000, 3000 and 5000 rpm at the injection duration of 6 ms.

Graph in Figure 7.7 shows the variation in pressure of LPG in the channel over the crankshaft angle at injection duration 6 ms. It is clear to perceive from the figure that maximum pressure of all engine speed is equal at a value. However, at an engine speed of 1000 rpm pressure maximum value is higher than that at speeds of 3000 and 5000 rpm. Higher maximum air pressure at 1000 rpm is due to the higher temperatures of the EP (see Figure 7.9).

The increases of engine speed lead to an increase of mass flow (discharge) duration, that means degrees of crank angle in injection duration will be higher.

Similarly, with an increase of injection duration and engine speeds the icing phenomenon increases significantly. Icing forms during the experimental process is shown in Figure 7.8.

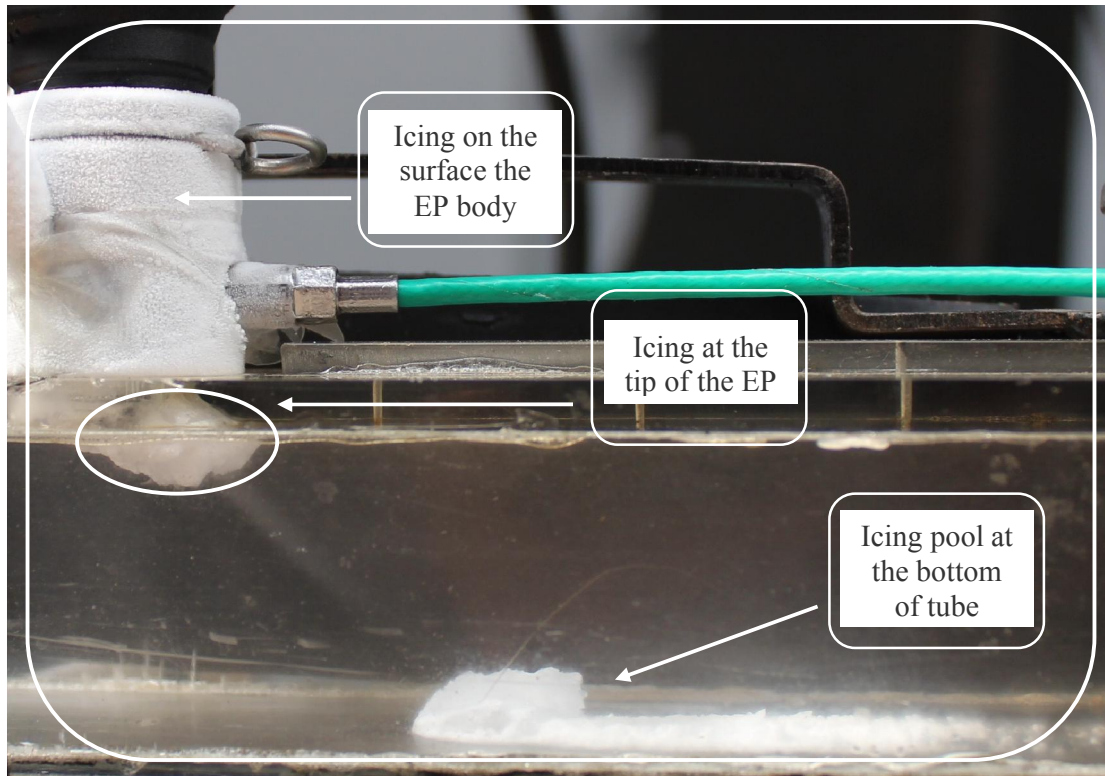


Figure 7.8: Icing at the tip of the EP and the surface of the EP body in the experimental process. At 1000 rpm and small quantities injected of LPG into the channel, Icing was beginning to appear at the tip and the surface outside of the EP. They would thicker when increasing of engine speeds and quantities of LPG injected. On the other hand, icing also took form an “icing pool” inside of the intake manifold.

7.3.2. Experiment with heating elements

Results of experiment with heating elements are shown in the graph from Figure 7.9 to 7.13, temperatures near the outlet nozzle in experimental models are exposed in circles. Those circles have colors to similar each variant of the mode of experiment process.

Subscripts in graphs: “normal” is in the case of measurement without heating and “reg.5C” is shown regulation of temperature near the outlet nozzle a approximate value of 5⁰C in the case of measurement with heating at the end part of the injector.

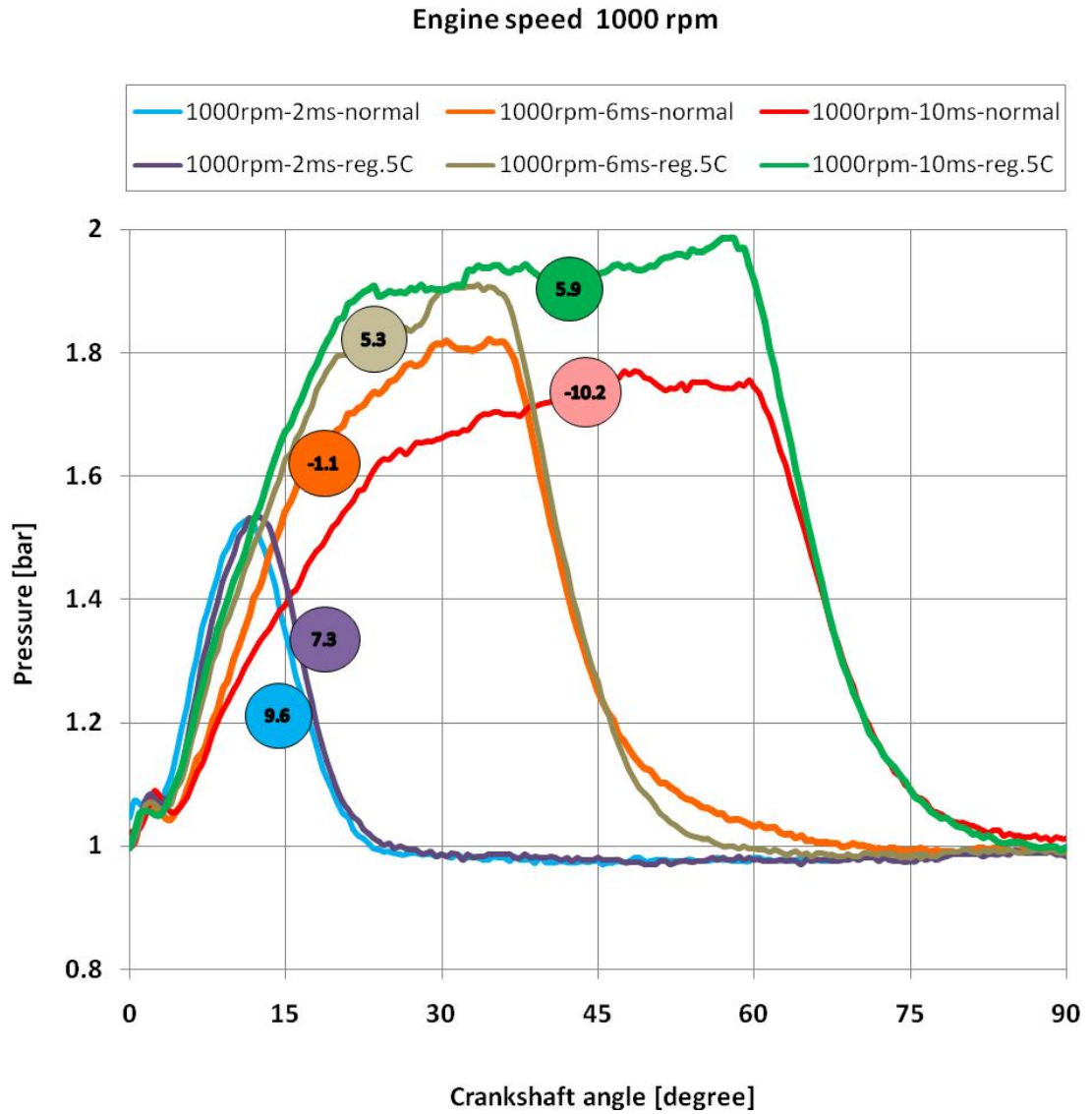


Figure 7.9: Measurement in a mode of engine speed 1000 rpm, while the amount of LPG injected was very small causing a decrease of temperature in the end part of the LPG injector by about 10°C. With the increase of LPG injected amount, the temperature in the part of the outlet nozzle of the channel decreases by more than 30°C. The heating elements of LPG injectors had an effect on increasing the pressure in the channel of the EP.

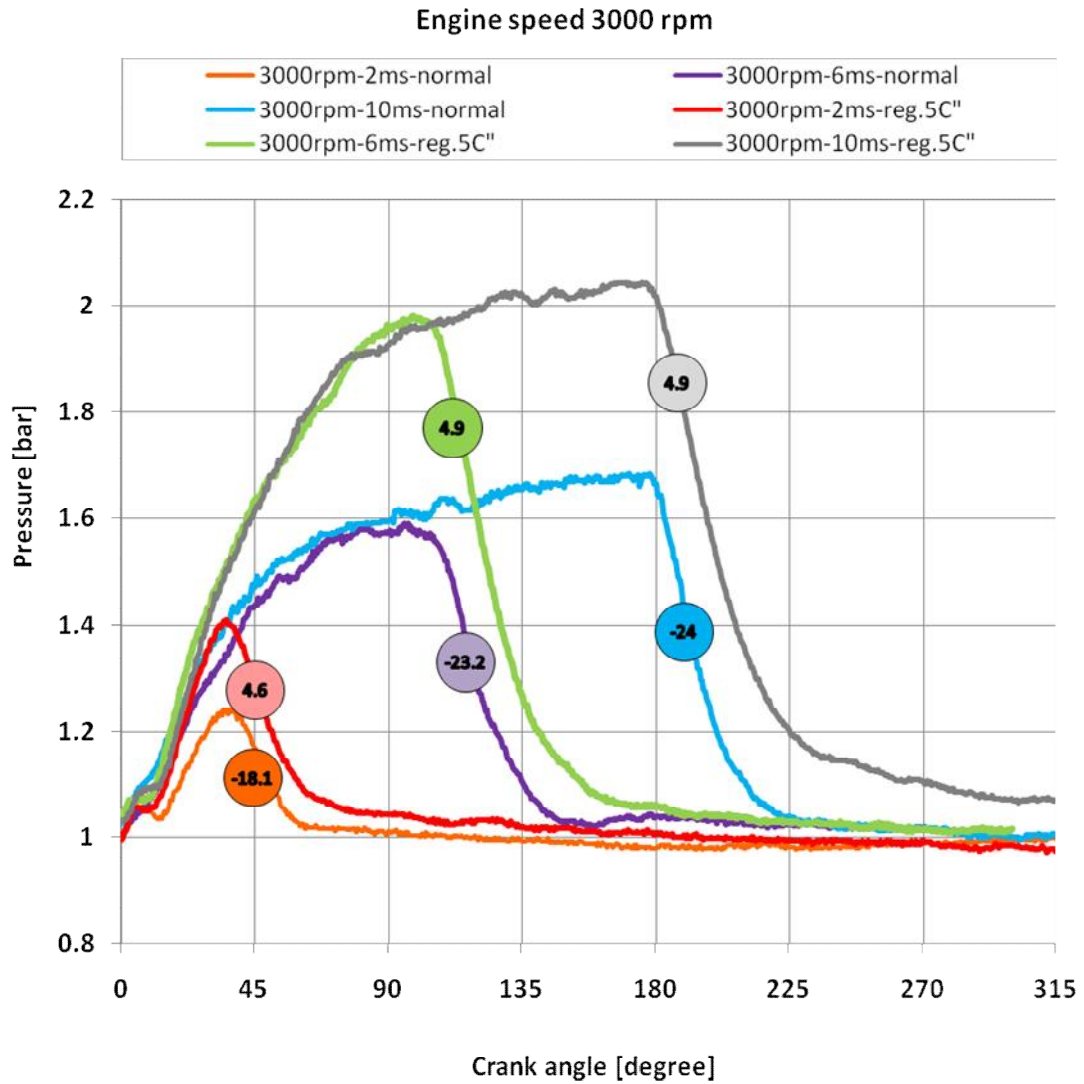


Figure 7.10: Measurement in the mode of medium speed 3000rpm, with all of LPG injected amount, pressure course in the channel of the end part of the injector influenced by a significant temperature drop in the EP of the injector. Heating elements at the end part of the injector are a reason of higher LPG pressure in the channel. The extension of time for mass flow of LPG into the intake manifold was probably due to an increase in density of damp steam LPG in the channel (increasing the value of vapor quality “ x ” and thus decreases the mass flow of LPG through an outlet nozzle into the intake manifold – according to equation (6.24) in section 6). Pressure measuring (especially evident in the region around zero) might be affected by cold temperature while the pressure sensor was exposed to very low temperature over a long period of time (temperature drift).

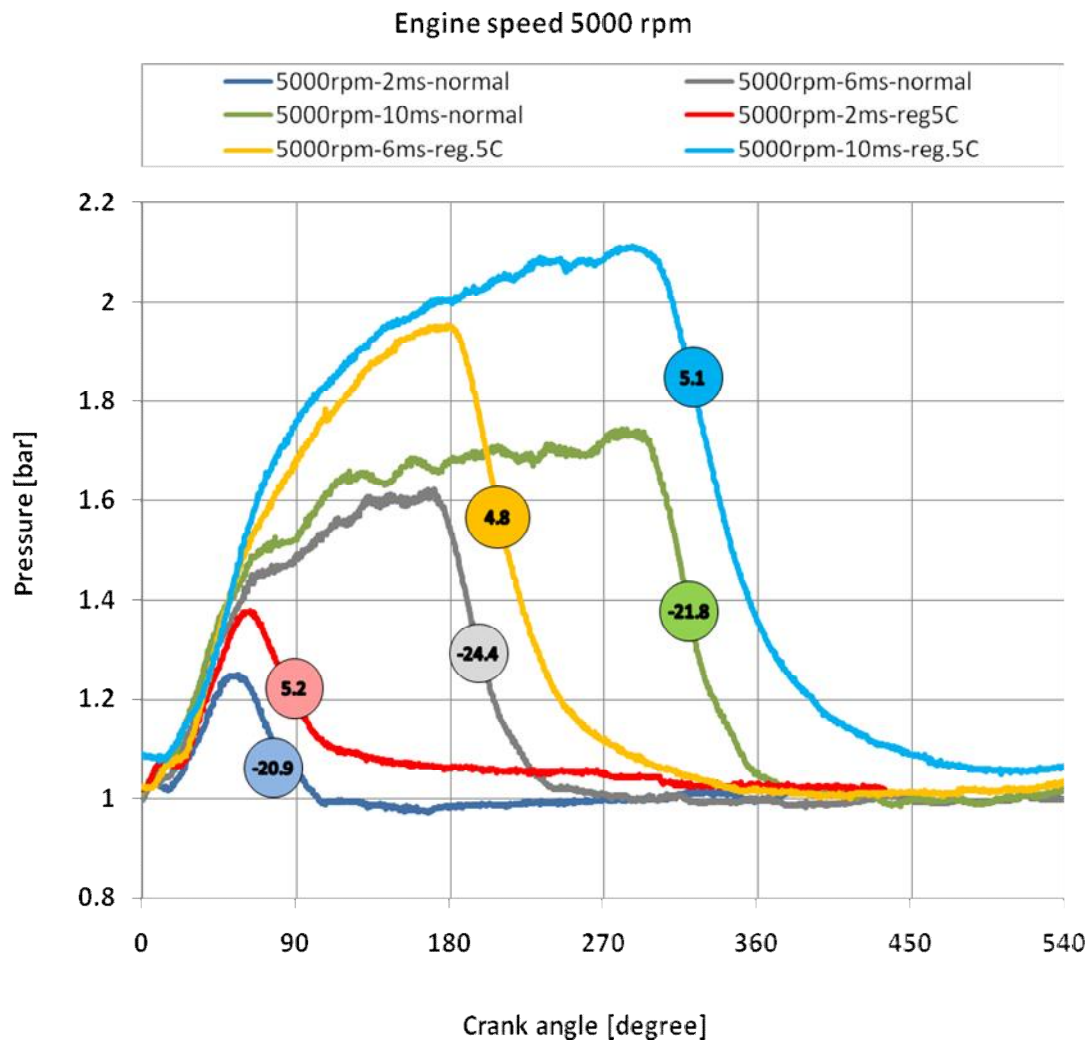


Figure 7.11: In the high speed mode of the engine with an LPG pressure course in the channel of the EP of the injector similar to that in the medium engine speeds, both in terms of maximum pressure and temperature of the EP of the injector that the pressure in the channel is influenced by temperature of heating element.

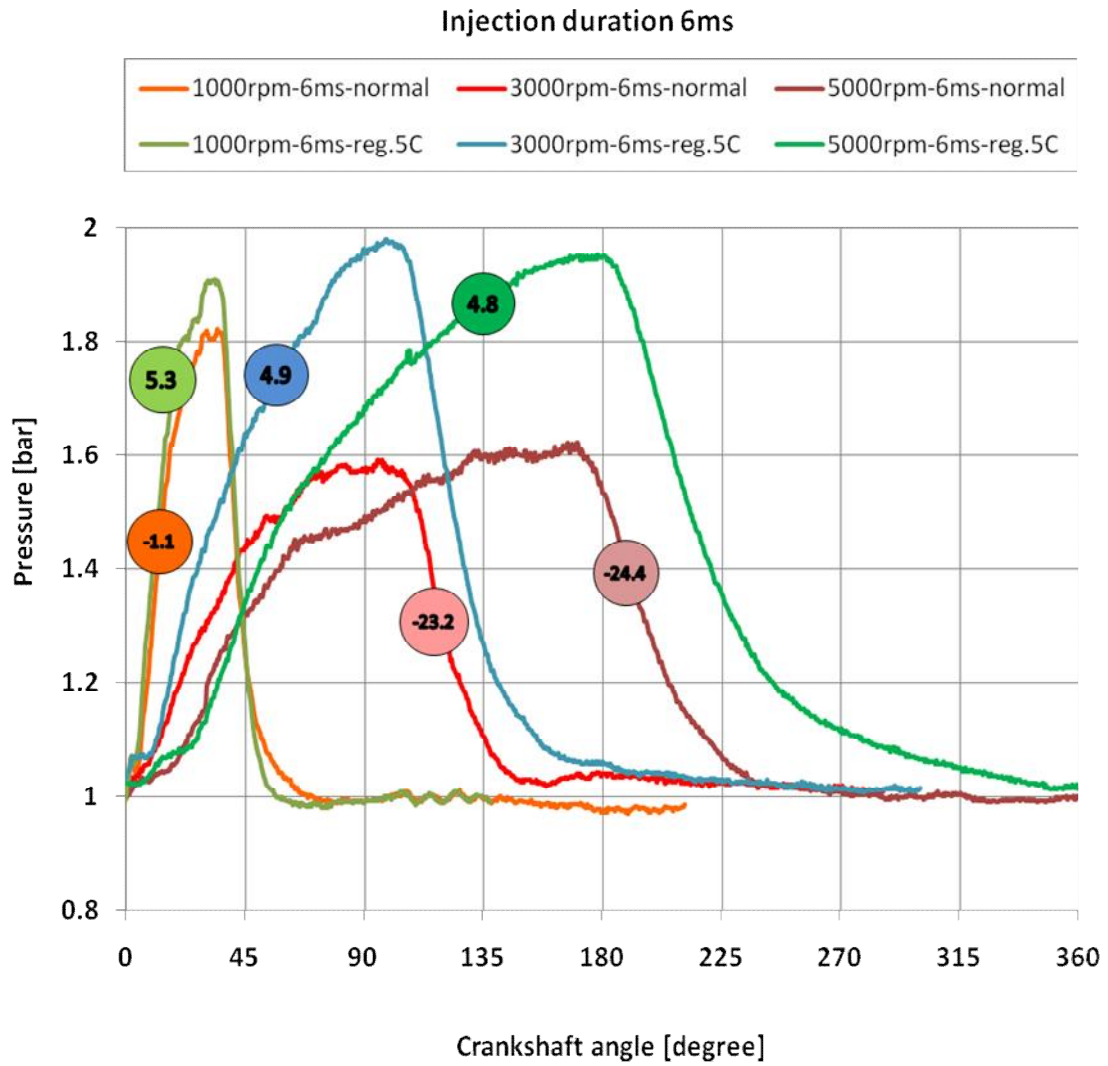


Figure 7.12: Comparison of measured LPG pressure course in the channel of the end part of the injector for injection of the same duration of LPG (at the medium amount of LPG injection) in the low, medium and high speed.

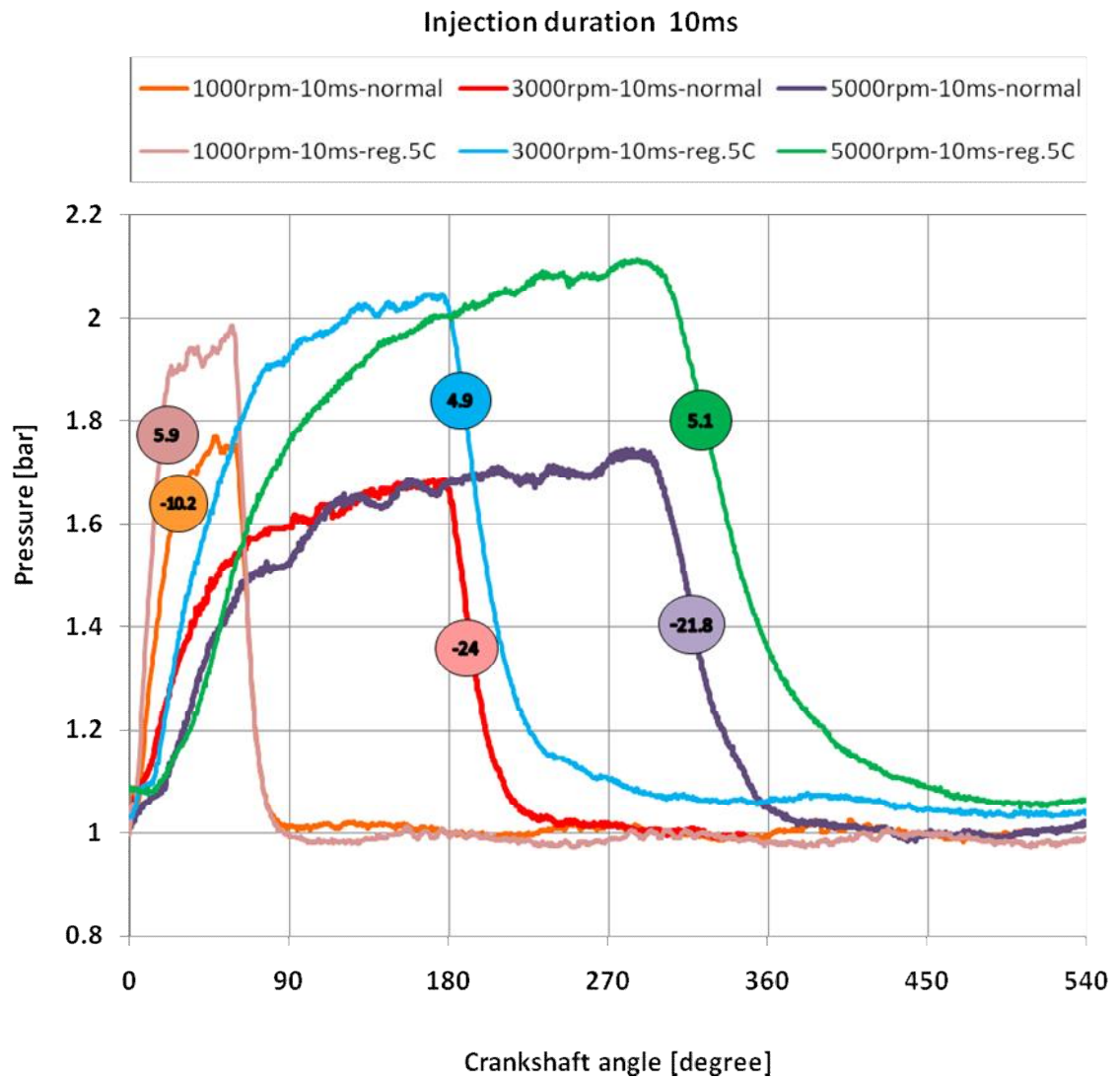


Figure 7.13: Comparison of measured LPG pressure course in the channel of the end part of the injector for injection of the same duration of LPG (at the higher amount of LPG injection) in the low, medium and high speed.

All the experimental results of LPG pressure course in the channel of the end part of injector have been shown in the graph above. To sum up effects of heating element as the temperature of the EP near the outlet nozzle, duration of discharge damps steam LPG into the intake manifold, maximum pressure in the channel, power of electric heating in all modes of experiment will describe further in Figures 7.14 - 7.18

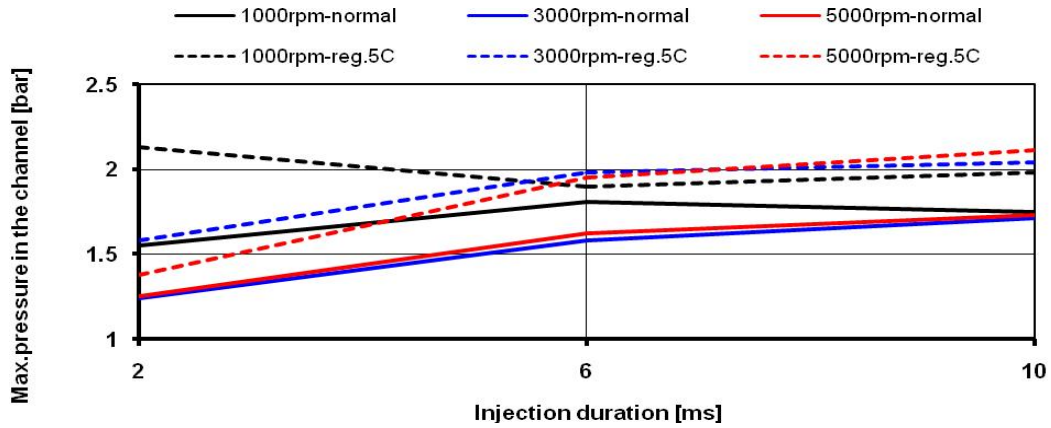


Figure 7.14: Maximum pressure of damp steam LPG in the channel of the EP depending on the time of opening the EV injectors (injected amount) at various engine speeds and different temperature modes of the end part of the injector.

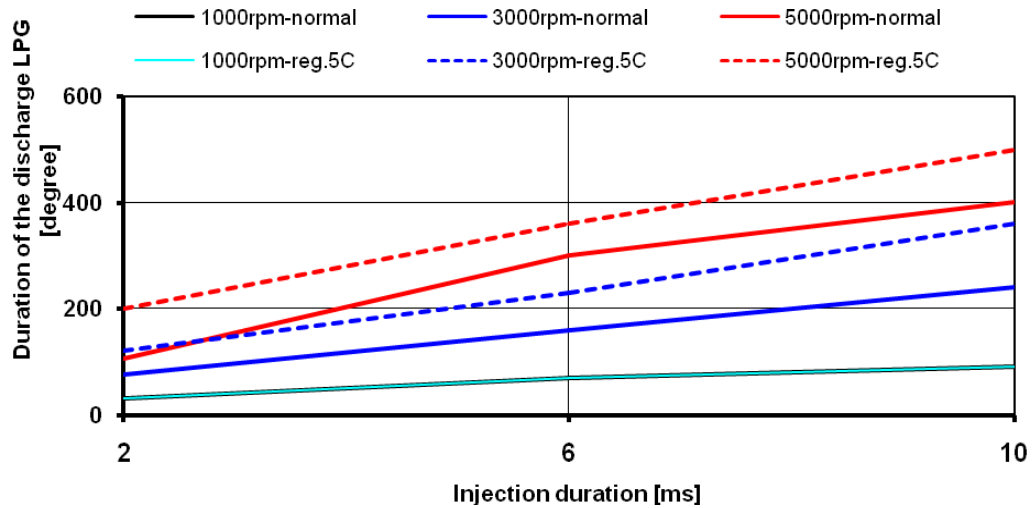


Figure 7.15: Duration of discharge damps steam LPG from the channel of the EP of the injector depending on the time of opening the EV injectors (injected amount) at various engine speeds and measurements without heating at the EP of the injector. Duration of discharge is not changing practically when measured in a mode of 1000 rpm and in both of case: without heating and heating.

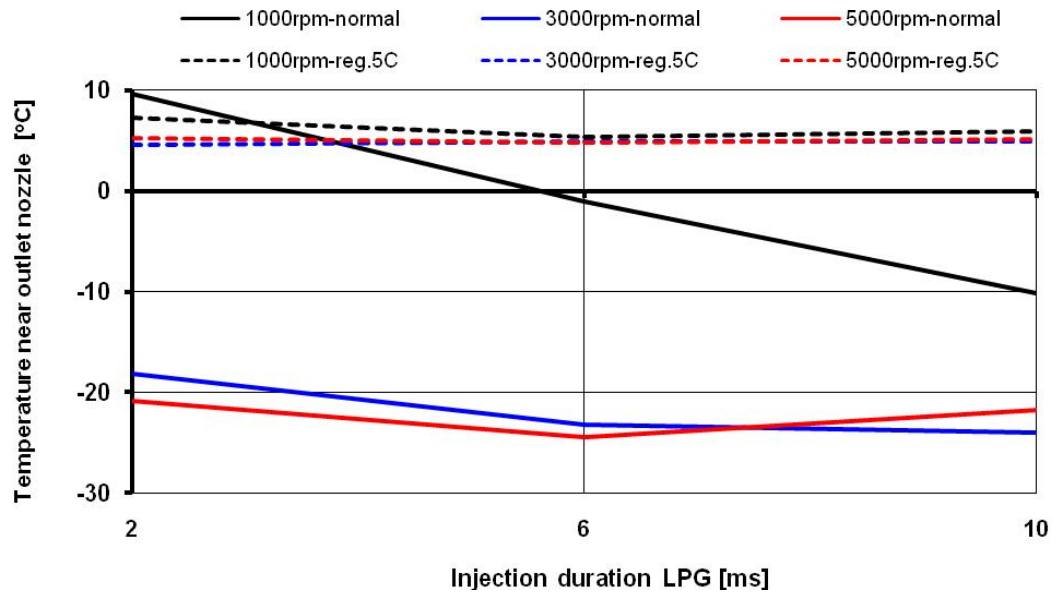


Figure 7.16: Temperature near the outlet nozzle of the EP as the temperature of damp steam LPG from the channel at the outlet nozzle. That depend on the injection duration (time of opening the EV injector - injected amount) at various engine speeds and measurements without heating at the EP of the injector and heating elements controlled at 5°C near the outlet nozzle.

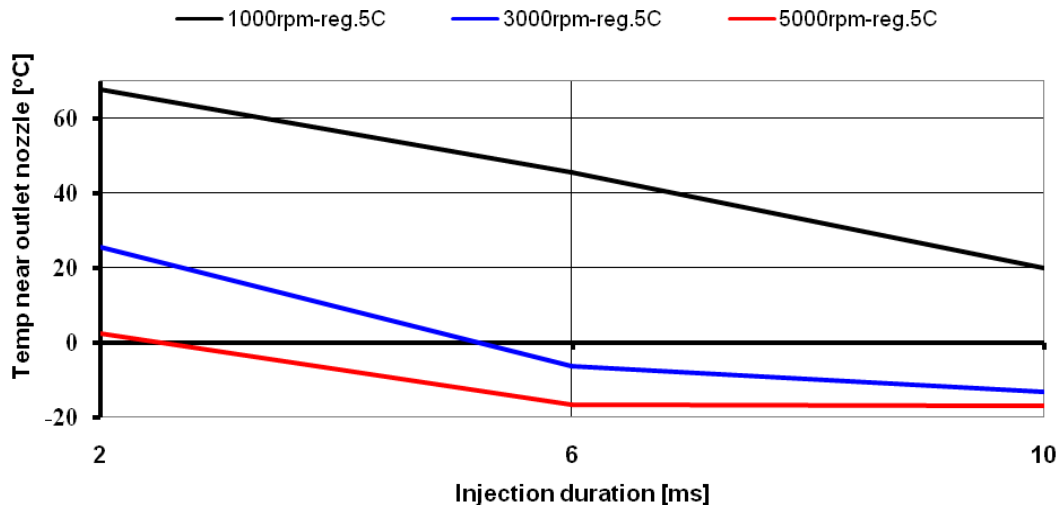


Figure 7.17: The temperature near the end of the injector outlet nozzle as the temperature of damp steam LPG from the channel, depending on the time of opening EV injectors (injected amount) at various engine speeds and measurements with hot heating elements at the EP of the injector by power of heating of 10 W (power of heating elements is 20W, the heating element is the end of the injector inserted only 50%).

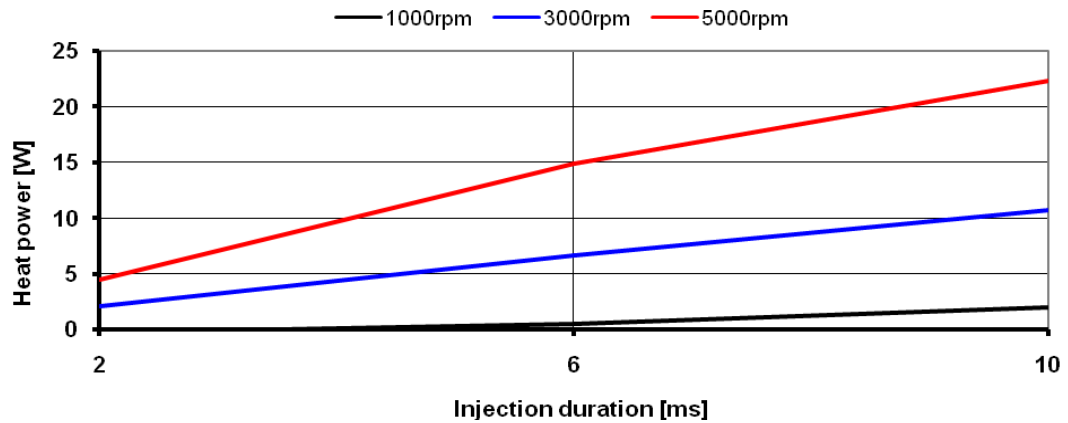


Figure 7.18: Power of the heating element in the EP required to achieve a temperature of about 5°C near the outlet nozzle of the end part of the injector, LPG damp steam from the channel depending on the injection duration (time of opening the EV injector - injected amount) at various engine speeds and various temperature modes on the terminal of the injector.

Note: Calculated estimate allow power of heating that measured by temperature without heating and heating with an element at voltage controlling of 12V (20W- power input), and for heating at the end part of the injector is used only 50% (the heating element inserted only half in the hole of the EP) - see Figure 7.19 and the heating portion with the outlet nozzle is estimated recovered only 40% majority of the heating element is high thermal conductivity material, and it transfers heat to full of the EP.

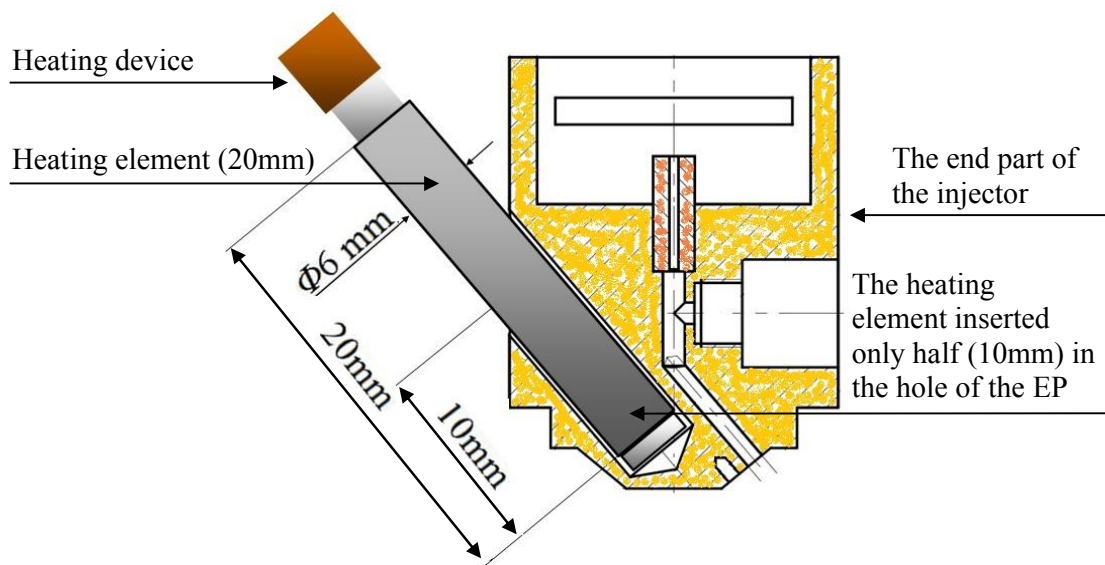


Figure 7.19: The heating element inserted into the hole of the EP.

8. COMPUTATIONAL SOLUTION OF LIQUID LPG INJECTION INTO INTAKE MANIFOLD.

8.1. The basic geometric parameters of the end part of LPG injector.

The end part of injector (EP) was designed with geometry shown in Appendix 1. The EP had two main parts, channels and the body of the EP. Channels include the channel 1 (the vertical part) with the length (L_{c1}), the diameter (Φ_{c1}) and the channel 2 with the length (L_{c2}), the diameter (Φ_{c2}). For the purpose of calculating heat transfer from outside wall to channel, the body of the EP was a significant concern and it had also two main parts for calculation. The first part (Figure 8.1c) had a length L_{b1} , a thickness δ_1 and the second part was the extension of the EP, which was fixed to plexiglas tube. This part had a length L_e (Figure 8.1d).

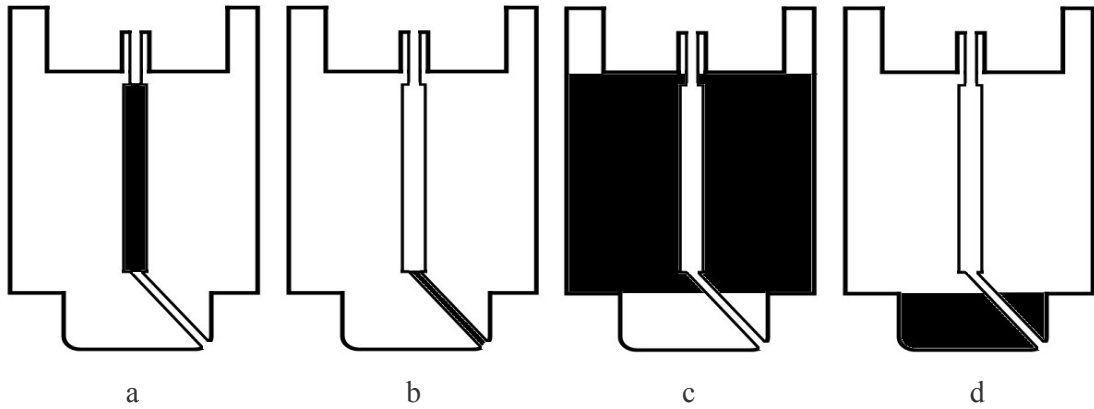


Figure 8.1: Geometry and components (bold type) of the EP

a, channel 1 (L_{c1}), (Φ_{c1}); b, channel 2 (L_{c2}), (Φ_{c2}); c, body L_{b1} , δ_1 ; d. extends body L_e

8.2. Sample and step of calculation.

The calculation of the course of LPG in the channel was divided into many samples. Time interval for one sample was $\Delta\tau = 0.2$ ms, because the interval was very small and the goals were to simplify the calculation process, each sample was divided into several different steps. The first moment when LPG had not been injected into the channel, this time the pressure in the channel was equal to the inlet pressure (1bar). Shortly after this time the solenoid electromagnetic valve opened, quantities of liquid LPG injection with a volume component (Figure 8.2.b). LPG would absorb the heat, expansion and vapor in the channel. Both liquid and the vapor composition of LPG were flowing through the outlet nozzle into

the intake manifold. After flowing into the intake manifold, the LPG residual amount and new LPG injected began to take shape for the next calculation sample. Figure 8.2 showed steps of one sample.

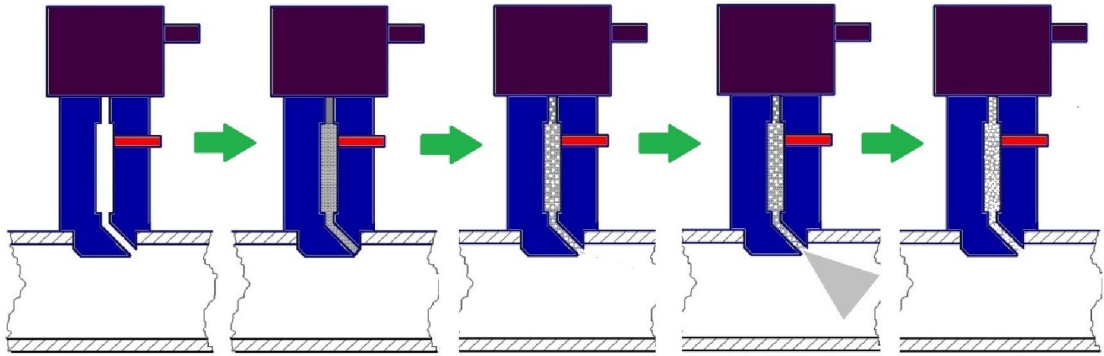


Figure 8.2: Steps of each sample for calculating the course LPG in the channel

a, LPG is emptied into the channel; b, LPG is injected into the channel (1st step); c, LPG expansion and vaporization in the channel (2nd step); d, Discharge (flow) LPG (gas and liquid phase) (3rd step); e, LPG remains after the mass flow (4th step).

8.3. Structure of the computational model

Computational program was created in an Excel sheet. The Calculative program based on the description of thermodynamic processes LPG in the channel, the calculation process and analysis were presented in sections 6. A program to calculate the predicted results for the parameters of pressure, temperature, density, mass flow rate of movement and vapor of LPG in the channel at the top and outlet nozzle of the EP by the selection of input parameters such as size, geometry of the EP, the length, the diameter of the channel, temperature injection, pressure injection, injection duration etc. This could be the basis for the optimum design based EP on the optimal output parameters.

The program has established computational work form and is designed primarily for the study of processes in the channel of the end part of the injector. The calculation program is built for the study of liquid LPG injection without heating at the end part of the injector.

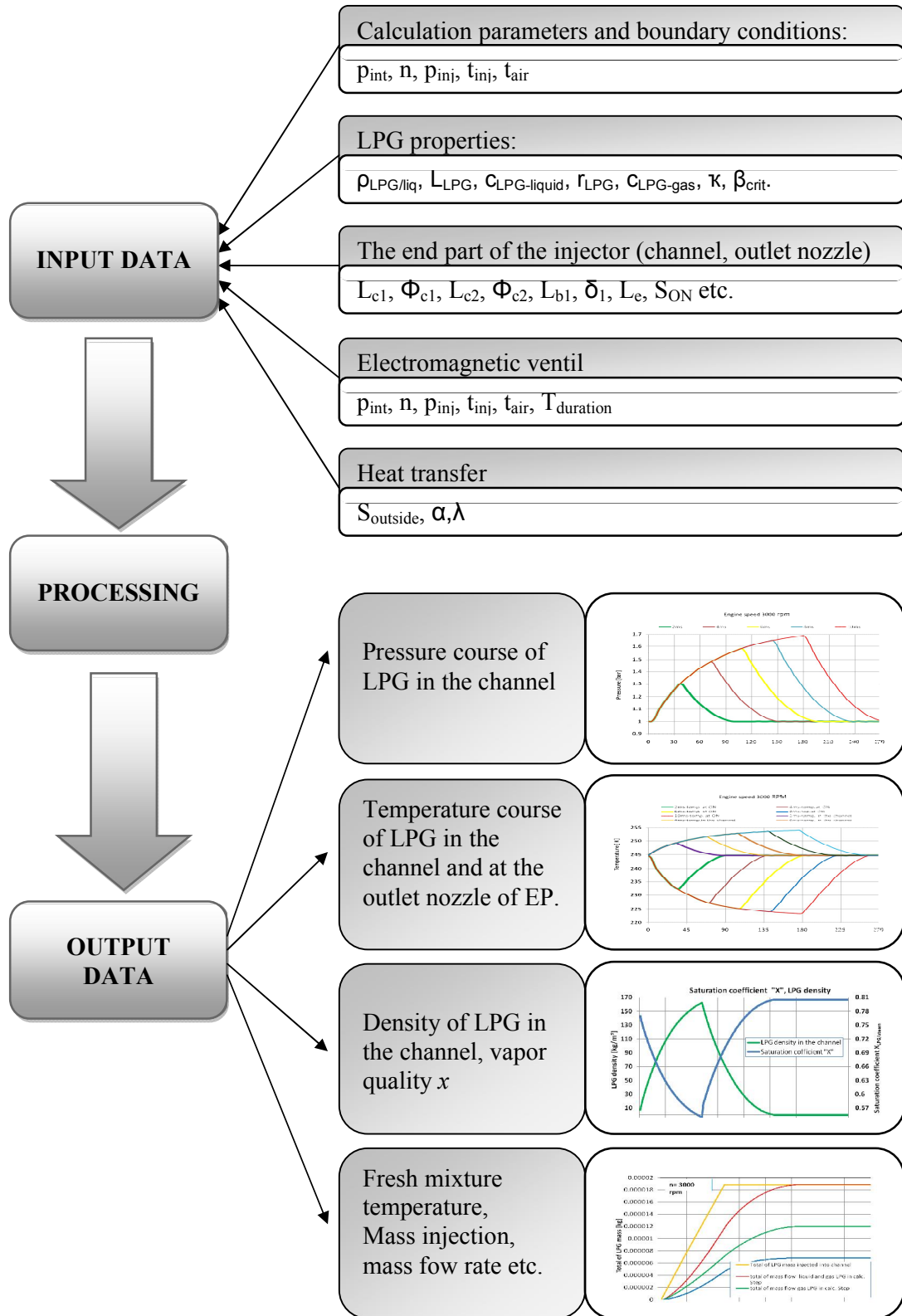


Figure 8.3: Diagram input and output parameters of calculation program.

8.4. Calibration of the computational model, calculative results and discussions

The results of the calculation program will expose by graphs with the variants of the input parameters. The calculation program demonstrates the accuracy of the theoretical description of the processes in the channel of the end part of the injector. Calculations are used an Excel spreadsheet and simplifications (constant LPG properties, the constant k_{evap} evaporation parameter, etc.). Therefore, computational program has limitations and it can not general validity for universal use, but it has potential for further development in the next work in the future.

Calculation program is not designed to control the temperature of the end part of injector (outlet nozzle) in the case of the additional heating element.

8.4.1. Pressure course of LPG in the channel.

LPG pressure course in the channel is a basic parameter for calculating the LPG temperature in the channel and at the outlet nozzle of the EP. The calculation can verify the influence of channel dimensions in the course of LPG pressure in the channel and the interval of LPG flow into the intake manifold.

Pressure course in the channel of the end part of injector variants illustrates how LPG in the channel varies. It depends on many factors such as: the speed engine, injection duration, volume of channel, heat transfer from the outside wall of injector to LPG in the channel, diameter of outlet nozzle, material of the EP, etc. All of the parameters were imported in the calculation program as input data from this program. Result of LPG pressure course in the channel depends on some important parameters displayed in Figures 8.4 to 8.8.

Graph in Figure 8.4 shows comparisons of LPG pressure course in the channel of the end part of injector with different injection durations $\Delta\tau = 2$ ms, 6 ms and 10 ms, and comparison of LPG pressure course in the channel of experimental and computational model too. Both engine speeds were at the 3000 rpm and the same values of geometry and dimension of the end part of the injector, the length of channel 1 ($L_{c1} = 7$ mm), diameter of channel 1 ($\Phi_{c1} = 1.6$ mm), the length of channel 2 ($L_{c2} = 10$ mm), diameter of channel 2 ($\Phi_{c2} = 1.3$ mm), outlet nozzle of injector ($\Phi_{ON} = 1.3$ mm), outside diameter of the EP ($\Phi_{out} = 24$ mm), material of the EP was aluminum alloy with same thermal conductivity. However, the values of evaporative coefficient " k_{evap} " are adjusted for calculation suitable

to result of an experiment with the notion that, k_{evap} is inversely proportional to the density of LPG in the channel. This means that while the higher of the LPG injected amount k_{evap} will be decreased and inverse. In the excel sheet, values of evaporative coefficient $k_{evap} = 0.83, 0.82$ and 0.80 correspond with injection durations $\Delta\tau = 2$ ms, 6ms and 10 ms.

It is shown clearly that pressure in the channel will increase when injection duration increases, because the injection duration increased due to quantity of LPG injected into the channel also increase, the pressure of LPG in the channel grew up correspondingly. The graph also indicates a similar result of experimental measure and the computational model. Subscripts in graphs: “Comp.model” is in the case of calculative result by the computational model and “Experiment” is in the case of measure result in experiments.

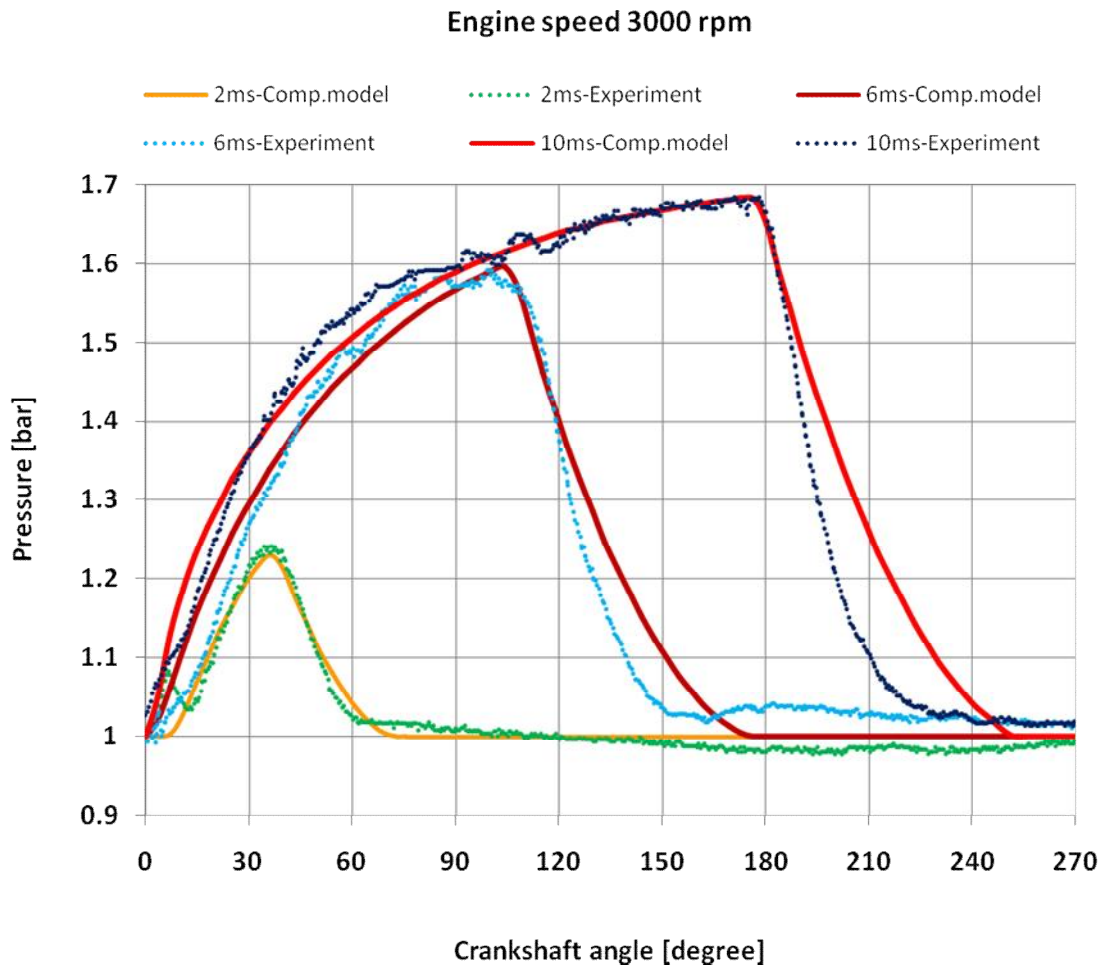


Figure 8.4: LPG pressure course depends on variations of injection durations $\Delta\tau = 6$ ms, 8ms and 10 ms and comparison theories of computation model and result of measurement in the Lab (at the engine speed of 3000 rpm).

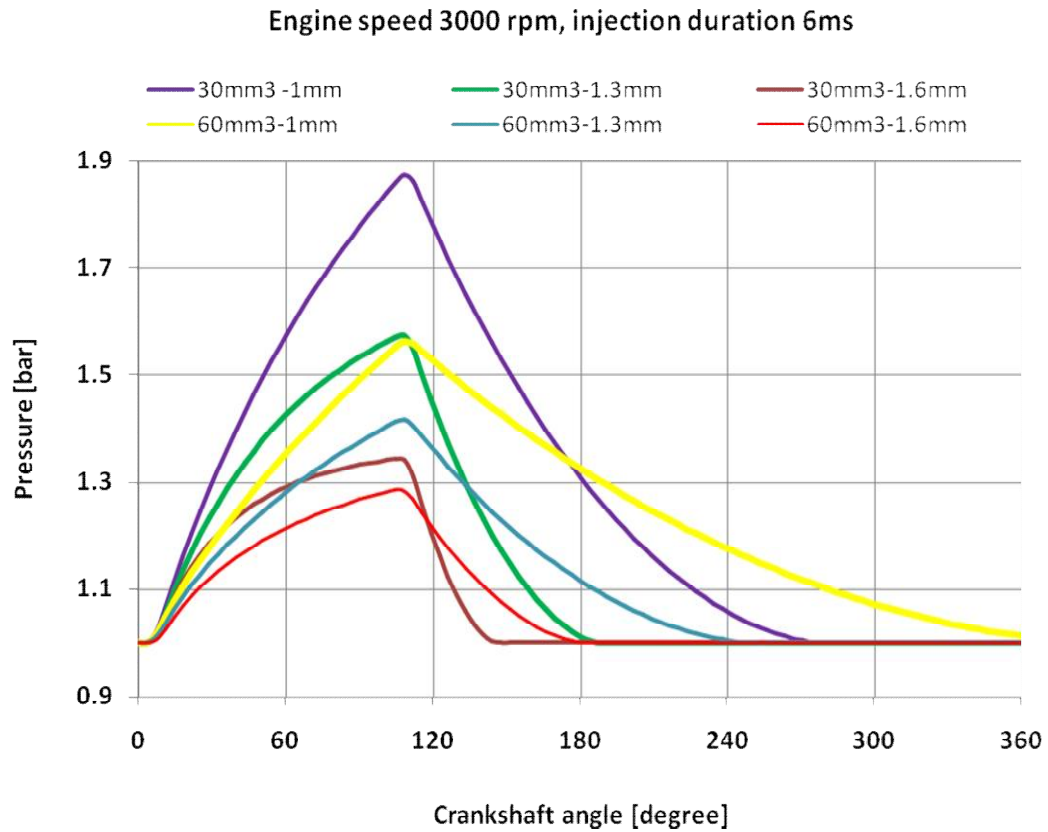


Figure 8.5: LPG pressure course depends on variations of channels volume and diameters of the outlet nozzle (at an engine speed 3000 rpm, injection duration 6 ms). Increasing the volume of the channel due to the extension of the LPG flow from the channel is the result of greater saturation vapor LPG in the channel (ie. higher values of vapor quality x)

Figure 8.5 displays the relationship between the pressure of LPG in the channel on the crankshaft angle of the engine at engine speed 3000rpm, injection duration 6 ms and different channel volume, diameter of the outlet nozzle of the EP. Variant values of channel volume total are 30 mm^3 and 60 mm^3 , the values of the outlet nozzle of variants in turn 1 mm, 1.3 mm, 1.6 mm. Generally, it is clear to perceive from the figure that the smaller the volume and diameter of the nozzle, the higher pressure maximum of LPG in the channel. Pressure in the channel is decreasing rapidly to atmosphere pressure with bigger diameter of outlet nozzle. On the contrary, in the volumetric comparison, If the volume has higher of value, LPG maximum pressure in the channel will smaller and duration of LPG flow from the channel into the intake manifold will increase.

Those are of great importance for the design of the end part of the LPG injector. Dimensions of the channel in the EP are to be minimized such that the flow cross section

and the outlet nozzle of the channel to ensure the duration of LPG flow from the channel into the intake manifold is short. That means LPG in the channel is empty with sufficient time to start the next cycle of LPG injection.

8.4.2. Temperature course of LPG in the channel and at outlet nozzle.

Temperature is the most important parameter of the computational model. From temperature course in the channel, we will calculate the temperature course at the outlet nozzle of the EP. Values of course of LPG temperature at the outlet nozzle are determined by the argument of adiabatic process from inner of channel to outlet nozzle. The temperature course of LPG is shown in Figures 8.6 and 8.7.

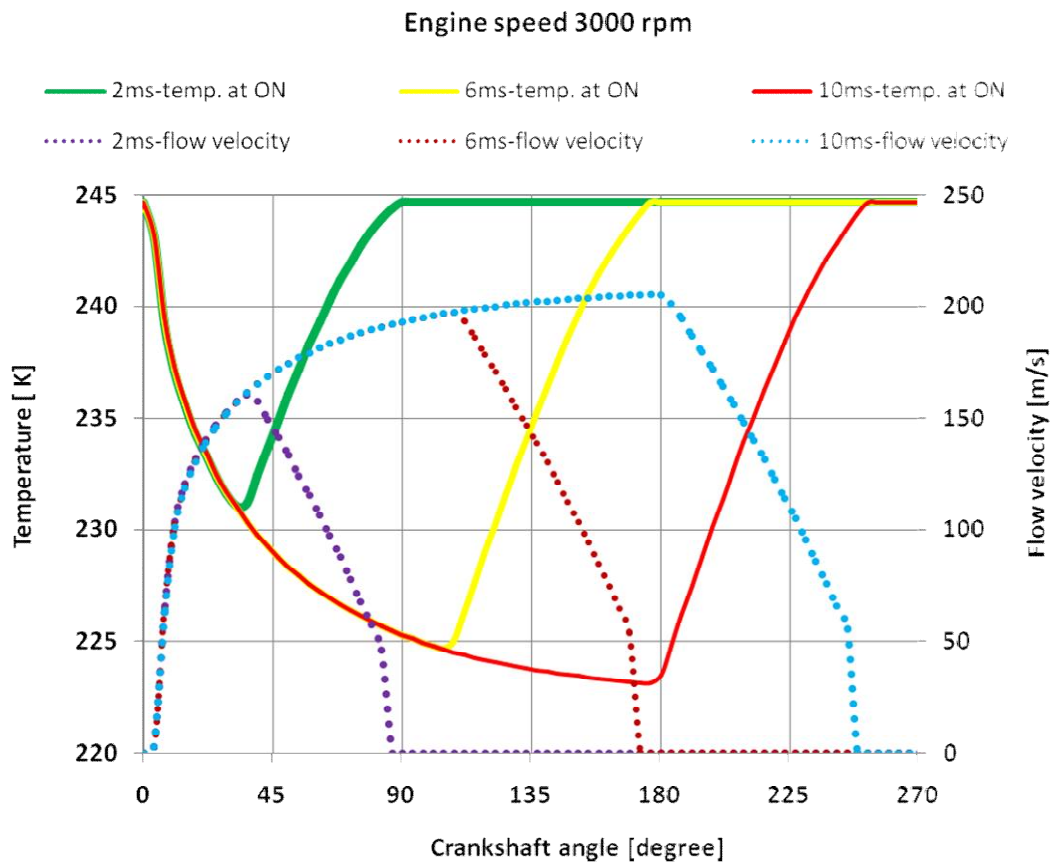


Figure 8.6: LPG temperature course and flow velocity of LPG depend on variations of injection durations at engine speed 3000 rpm. The flow velocity of LPG at the outlet nozzle is a result of the use of enthalpy gradient, that is converted to kinetic energy of LPG flowing.

Figure 8.7 shows a comparison of the temperature course at the same engine speed 3000 rpm and same parameters of input data. The course of temperature is similar the course of pressure. That means the maximum temperature value will increase and the course of temperature in the channel (higher 245K) will be longer when injection duration increases. There seems to have a difference in the temperature course at the outlet nozzle. Temperature in the channel and temperature at the outlet nozzle are contrasted, the higher the temperature in the channel, the lower the temperature at the outlet nozzle.

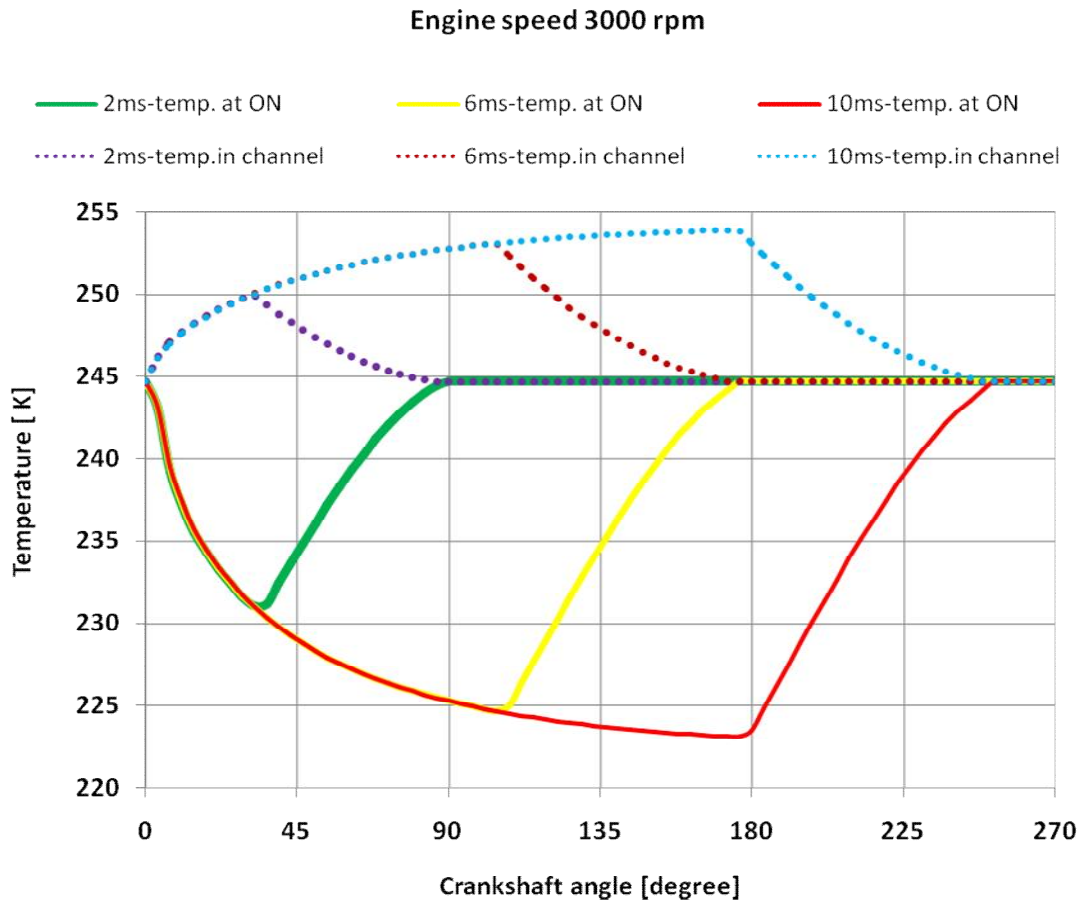


Figure 8.7: LPG temperature course in the channel and LPG temperature at the outlet nozzle depend on variations of the injection duration when engine speed is the same value of 3000 rpm.

The temperature at the outlet nozzle of the EP has a great signification in the design to minimize icing but it also means for temperature of formation mixture in the intake manifold. As analysis in section 4, the engine performance of MPI liquid LPG injection is increased by reducing the temperature of LPG in the intake manifold or by increasing the volumetric efficiency.

8.4.3. Density of LPG, vapor quality.

Density course of LPG and vapor quality or saturation coefficient x were drawn from computational programs. They are shown in Figure 8.8. Value of density is the highest at maximum pressure in the channel, when the quality of fuel in the channel is the maximum value and it will go down to zero while fuel in the channel is empty with the equilibrium of pressure in the channel and in the intake manifold.

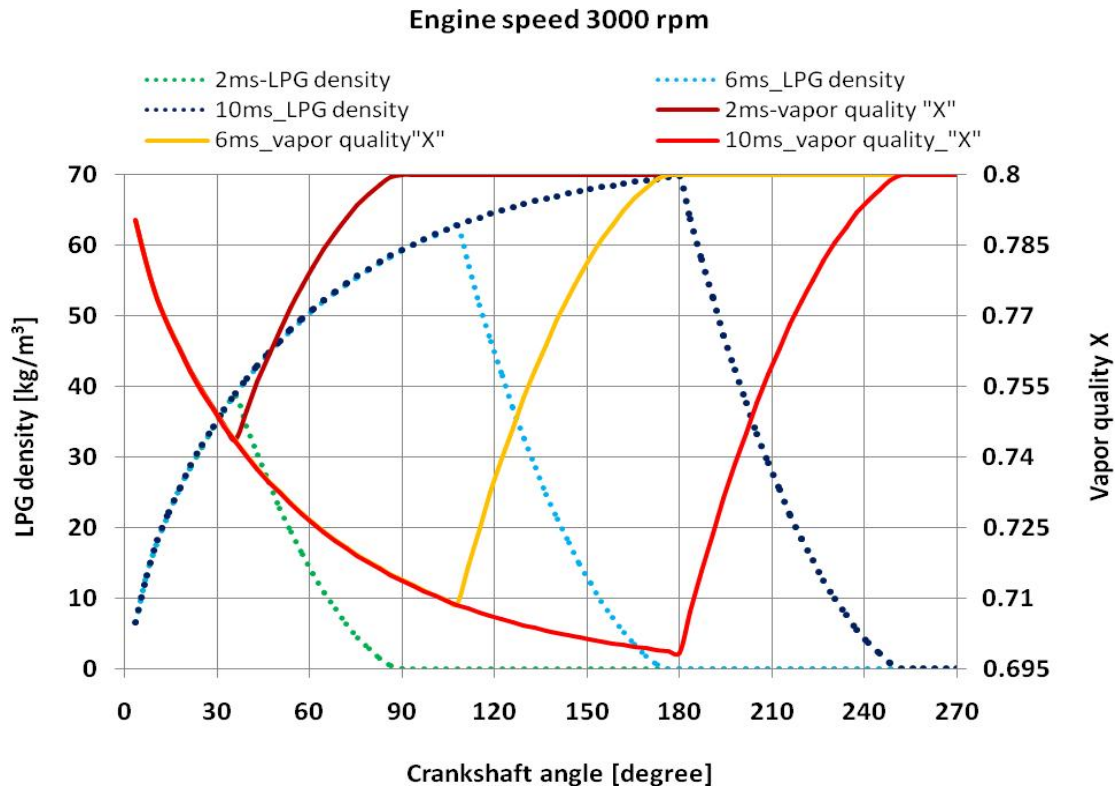


Figure 8.8: Density of LPG in the channel and vapor quality x depend on variations of injection durations (amount of LPG injected) at the engine speed 3000 rpm.

Vapor quality x gives the minimum value of the highest of pressure or density. It will go up in value of 1 bar. However, in the theoretical analysis values of vapor quality depends on evaporation coefficient " k_{evap} " and this is a value, which cannot give exactly hence x increase nearly of value 1 bar that is approved in the computerized program. To achieve a good compliance of the calculated and measured during the pressure in the channel of the end part of the injector of " k_{evap} " range in values are from 0.75 to 0.85. Calculation is based on certain simplifications. The model assumes that the entire LPG flow into the intake manifold is in the damp steam phase ($x < 1$) [6].

8.5. Temperature of cylinder charge mixture and estimate of engine performance.

As analyses at sections above, during injection of liquid LPG into intake manifold there is a rapid evaporation of LPG and thus to reduce intake air temperature and increasing of the LPG amount in the cylinder. This has the consequence that when running on LPG has the same or higher engine performance such as when running on petrol. In the scope of the dissertation, this comparison is realized the same as below:

The performance of the engine running on LPG was calculated from values of LPG mass injected of cycles in the computational model and compared to the performance of the engine running on petrol for condition of wide open throttle (WOT): volumetric efficiency and overall efficiency were the same as the engine running on petrol, the excess air ratio was calculated as stoichiometric ($\lambda=1$).

When conversion to LPG fuel is based on the assumption that the output parameters from a purely the petrol operation will be the same. For this reason, both the calculations based on the basic performance and dimensional parameters specified in Tables 8.1 and 8.2.

Table 8.1: Basic parameters of an engine.

Engine	Value	Unit
Bore	76.5	mm
Stroke	86.9	mm
Compression ratio λ	10.3	-
Number of cylinders i	3	-
Displacement volume V_d	0.0004	m ³

Table 8.2: Ambient condition of engine operation.

Ambient conditions	Value	Unit
Air pressure p_{amb}	99000	Pa
Air temperature T_{air} (for petrol running)	300	K
Mixture temperature T_{FM} (for LPG running)	293	K

In Table 8.2, mixture temperature T_{FM} had a value of 293K, that is determined by the calculation program as the final temperature after injection of liquid LPG amount (or LPG damp steam at the outlet nozzle) into the intake manifold, where has a temperature of 300K

The basic prerequisite for the operation of the engine to LPG fuel is that it will achieve the same (or higher) performance while maintaining the coefficient of excess-air ratio. Volumetric efficiency is the same as pure petrol engine mode.

In the intake process of the engine, fresh mixture is determined by equation

$$V_{d/1} \cdot \eta_v = \frac{M_{air/1}}{\rho_{air}} + \frac{M_{air/1}}{\rho_{fuel}} \cdot \frac{1}{\lambda \cdot A_{theor}} = M_{air/1} \cdot \frac{T_{air}}{p_{amb}} \cdot \left(r_{air} + \frac{r_{fuel}}{\lambda \cdot A_{theor}} \right) \quad (8.1)$$

Where: $V_{d/1}$: Displacement volume of each working cycle [m³]
 η_v : Volumetric efficient.
 $M_{air/1}$: Mass of fresh air in a working cycle [kg/cycle].
 ρ_{air}, ρ_{fuel} : Density of air and density of fuel [kg/m³].
 r_{air} : Specific gas constant of air [J/kg.K]
 r_{fuel} : Specific gas constant of fuel [J/kg.K].
 p_{amb} : Pressure in ambient condition [bar].
 A_{theor} : Theoretical consumption of air for fuel [kg/kg].
 T_{air} : Temperature of fresh air, it is mixture temperature T_{FM} when engine running on LPG [K]

The mode of engine speed and load (100% load) can be calculated mass of air $M_{air/1}$ by the excess air fuel ratio λ and mass of fuel in the cycle $M_{fuel/1}$ in mixture as follows:

$$M_{fuel/1} = \frac{M_{air/1}}{\lambda \cdot A_{theor}} \quad (8.2)$$

From equations 8.1 and 8.2, we will have an equation

$$M_{air/1} = V_{d/1} \cdot \eta_v \cdot \frac{p_{amb}}{T_{air}} \cdot \frac{1}{\left(r_{air} + \frac{r_{fuel}}{\lambda \cdot A_{theor}} \right)} \quad (8.3)$$

Heat power of the fuel which is supplied to the engine by equation

$$P_{input} = M_{fuel/1} \cdot i \cdot \frac{n}{2 \cdot 60} \cdot H_u \cdot \frac{1}{1000} \quad (8.4)$$

Where

i : number of cylinders
 n : Engine speed [rpm]
 H_u : Heating value of fuel [J/kg].

So the effective power of the engine will be

$$P_e = P_{input} \cdot \eta_{tot} \text{ with } \eta_{tot} \text{ is overall efficient} \quad (8.5)$$

Mean effective pressure is determined by an equation

$$p_e = \frac{120 \cdot P_e}{i \cdot V_d \cdot n}$$

Some values of fuel properties of the equation above are shown in the table 8.3

Table 8.3: Petrol and LPG properties for calculation.

Properties	Unit	Petrol	LPG
Heating value H_u	MJ/kg	42,5	46,1
Theoretical consumption of air for fuel A_{theor}	kg/kg	14,6	15,6
Specific gas constant of fuel $r_{fuel-gas}$	J/kgK	73	168

Thanks to equations above and values range of parameters when engine running on petrol Data from measurements of the engine running on petrol at the Skoda Auto manufacturer. Those are shown on the left of Table 8.3 (blue color numbers). The computational model is applied to find values correspond when engine running on LPG. In this case, values need to determine in computational model are masses of air, mass of fuel and temperature of the LPG - air mixture. Parameters of LPG by calculation are displayed on the right of Table 8.3 (red color numbers). The result of calculation and comparison represent by Figure 8.9.

Table 8.3: Performance of an engine operating on petrol and LPG

Speed	$M_{t/e}$ (petrol)	P_e (petrol)	P_e (petrol)	η_v	η_{tot}	$M_{air/1}$ (LPG)	$M_{LPG/1}$	P_e (LPG)	P_e (LPG)
rpm	Nm	kW	bar	-	-	g/cycle	g/cycle	kW	bar
1500	91	14.3	9.5	0.907	0.314	0.413	0.026	14.4	9.6
2000	95	19.9	9.9	0.926	0.322	0.422	0.027	20.1	10.0
2500	99	25.9	10.4	0.967	0.321	0.440	0.028	26.1	10.4
3000	107	33.6	11.2	1.037	0.323	0.472	0.030	33.8	11.3
3500	100	36.7	10.5	0.972	0.322	0.443	0.028	36.9	10.5
4000	92	38.5	9.6	0.923	0.312	0.420	0.027	38.8	9.7
4500	84	39.6	8.8	0.853	0.308	0.388	0.025	39.8	8.8
5000	77	40.3	8.1	0.814	0.297	0.371	0.024	40.7	8.1
5500	68	39.2	7.1	0.766	0.278	0.349	0.022	39.4	7.2

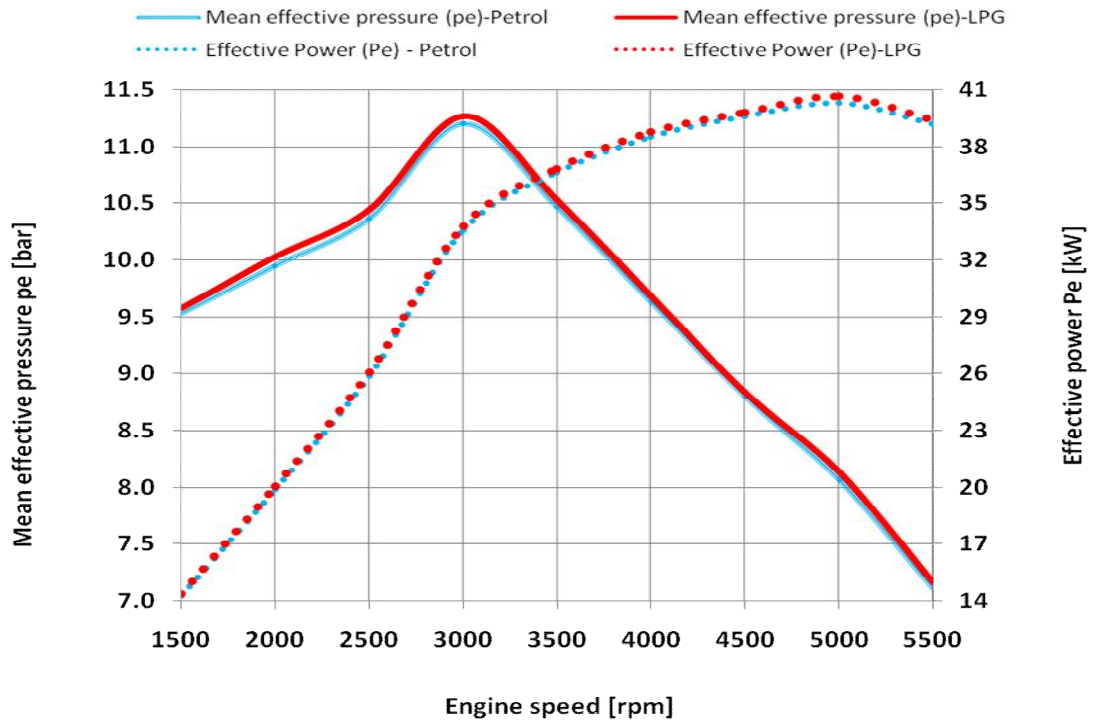


Figure 8.9: Comparison of mean effective pressure, effective power of the engine running on petrol and LPG.

The result of the calculation and the comparison of effective power and mean effective pressure (in Table 8.3 and Figure 8.9) were indicated an equal value of power or pressure (rather slight higher) when engine running on LPG compared to the engine running on petrol.

9. CONCLUSION

Theoretical analysis of the processes in the channel of the end part of the LPG injector, conducted experimental research on problems and model calculation explain and demonstrate important relationships between the state (pressure, temperature and density) of damp steam LPG in the channel of the injector end part and its discharge into the intake manifold.

Model of calculation program is established, which based on certain simplifications of describing problems. It allows us to study how are effects of main parameters input (such as orifice area of electromagnetic valve, outlet nozzle of the EP, dimensions of channel etc.) to the process in the channel of injector end parts, the discharge of LPG damp steam through an outlet nozzle into the intake manifold and the temperature of the fresh mixture (air and LPG) in the intake manifold.

The results of the calculations and experiments reflect that the damp steam LPG in the channel and the outlet nozzle has an extremely low temperature (240K-245K). An effective measure against the risk of icing around the outlet nozzle and the body surface of the injector is necessary to intensify temperature by heating elements near the position of outlet nozzle. The measurements performed with a variant of the electric heater at the EP of the injector, that increasing temperature of heating element was significantly increased of LPG pressure in the channel. The LPG pressure increasing in the channel in this case leads to prolonged damp steam LPG mass flow to the intake manifold. Extension of mass flow duration of damp steam LPG is as a saturation increasing of damp steam LPG in the channel. It is explained in the theoretical analysis of the damp steam mass flow through an outlet nozzle in the section 6.

To eliminate the risk of icing on the discharge nozzle, heating elements insert to near outlet nozzle will be necessary. The structure of the end part will be changed to heating power is concentrated in parts of the outlet nozzle. To optimize the construction of the end part of the injector appropriate modeling of the temperature field in the end part of the injector, using data from the calculation program (section 8) at a temperature of damp steam LPG in the channel and the heat transfer from the body end part of the injector to the LPG in the channel.

The experimental part of the dissertation is in terms of "icing" significant experience even for routing LPG stream flowing from the outlet nozzle. Installation of the injector in the intake manifold must be designed so that an LPG spray from the outlet nozzle will not direct injection to the wall of the plastic manifold. When the LPG spray wall plastic intake manifold arises at the impact of significant icing - optimal spray is directed from the outlet nozzle into the intake port to the cylinder head.

Dissertation brought out new knowledge in both parts of the theoretical and experiments, that can be used in the further technical development and design of the LPG injector for injection of liquid LPG into the intake manifold.

REFERENCES

- [1]. Norazlan Bin Hashim.: The study of combustion characteristics for different compositions of LPG, A thesis submitted in fulfillment of the requirements for the award of the degree of Bachelor of Chemical Engineering. Malaysia, May 2008.
- [2]. Kazimierz Lejda, Artur Jaworski.: Influence of liquid LPG injection change pressure on the injection control. TEKA Kom. Mot. Energy. Roln. – OL PAN, 2008, 8, 141–148.
- [3]. Yorkshire Autogas. http://www.lpgc.co.uk/index_files/TypesofLPGsystems.htm
- [4]. The trade association for the LPG industry in the UK. <http://www.go.lpg.co.uk>
- [5]. LPG induction system.: <http://www.zavoli.com/prodotti.php>.
- [6]. Martin hošek.: Conversion of the internal combustion engine to LPG operation. Master work. Liberec 2010.
- [7]. Rohan BRC Gas Equipment Pvt. <http://www.tradeindia.com/fp1009641/LPG-Sequential-Injection-System.html>
- [8]. Stanislav Beroun. Alternative fuels and the conditions of their employment in the low-emission piston engines. KVM, none publication.
- [9]. European LPG Association.: Autogas in Europe, The Sustainable Alternative, An LPG Industry Roadmap. 2009.
- [10]. M. Ihsan Karamangil.: Development of the auto gas and LPG-powered vehicle sector in Turkey: A statistical case study of the sector for Bursa. Energy Policy 35 (2007) 640–649
- [11]. Eva LIU, S.Y. YUE, Joseph LEE. A study on LPG as a fuel for vehicles. Research and Library Services Division Legislative Council Secretariat. 1997.
- [12]. Hansub Sim, Kangyoon Lee, Namhoon Chung, and Myoungho Sunwoo. A study on the injection characteristics of a liquid-phase liquefied petroleum gas injector for air–fuel ratio control. Proc. ImechE Vol.219 Part D: J.Automobile Engineering, 2005.
- [13]. Amplifier system MGCplus with display and control panel AB22A/AB32. www.hbm.com.pl/pdf/b0534.pdf

- [14]. Beroun Stanislav, Brabec Pavel, Dittrich Ales, Drab Ondrej, Nguyen Thanh Tuan.: Coputational modeling of the liquid LPG injection into the suction manifold of an SI vehicle engine. Journal Applied Mechanics and Materials Vol. 390 (2013) pp 355-359.
- [15]. Automobile part supplies.: <http://automotivepartsuppliers.com>
- [16]. LPG properties. <http://www.gailonline.com>
- [17]. Nguyen Thanh Tuan, Stanislav Beroun, 2011.: Performance of a spark ignition engine with different LPG injection systems. 4th international mechanical engineering conference, Prague – Czech Republic 1st Feb. 2011.
- [18]. Josef Blažek.: The combustion process analysis by means of in-cylinder pressure measurement. International Scientific Meeting Motor Vehicles & Engines Kragujevac, 10.2004.
- [19]. Daeyup Lee, Seunghwan Cho, Beomho Lee, Seil Ko and Jiho Choi: Intake flow observation with gaseous lpg injection in a si engine. ILASS–Asia 2005, Oct. 13-14, 2005, Seoul, Korea.
- [20]. Daeyup Lee, Seunghwan Cho, Beomho Lee, Seil Ko, Jongyoung Park, Jiho Choi.: Enhancement of volumetric efficiency in a gaseous LPG injection engine. The 13th International Pacific Conference on Automotive Engineering.
- [21]. Albela H.Pundkar, S.M. Lawankar, S.M.Lawankar, Dr. S.Deshmukh.:Performance and emission of LPG fueled internal combustion engine: A review. International journal of scientific and engineering research, Volume 3, Issue 3, March 2012. ISSN 2229-5518.
- [22]. Josef Blažek, Jan Mareš.: Problem analysis for a vehicle's engine with a liquid LPG injection into suction manifold. International scientific conference KOKA 2009. Nitra 7. - 8. 9. 2009, Slovak Republic.
- [23]. Beroun, S., Blažek, J., Mareš, J.: Vývojové práce na motoru EA 111 03D-LPG. Výzkumná zpráva SM 611/2009, KVM FS TU v Liberci, 2009.
- [24]. Taib Iskandar Mohamad.: Combustion characteristics of methane in a direct injection engine using spark plug fuel injector. Journal Kejuruteraan 22 (2010): 43-52.

- [25]. Taib Iskandar Mohamad, Mark Jermy, Anni Kaisa, Matthew Harrison.: The effects of propane and gasoline sprays structure from automotive fuel injector under various fuel and ambient pressure on engine performance. World applied sciences journal 18 (3): 396-403,2012.
- [26]. Bruner, G., Chmela, F., Pachta-Reyhofen: Flüssiggasbetrieb bei Omnibussen. Gräf and Stift, Wien, 1988.
- [27] Critical point.: [http://en.wikipedia.org/wiki/Critical_point_\(thermodynamics\)](http://en.wikipedia.org/wiki/Critical_point_(thermodynamics)).
- [28] Suzukituning Vialle LPi Technical Manual.:
<http://www.suzukituning.com/General/VialleLPi/Vialle%20LPi%20Technical%20Manual.htm>
- [29] Jesus Moreno Quiben.: Experimental and analytical study of two-phase pressure drops during evaporation in horizontal tubes. Thèse Pour l'obtention du grade de docteur ès sciences. Dea - dynamique des fluides et des transferts, université pierre et marie curie, Paris, France et de nationalité espagnole 2005.
- [30] Guide to thermodynamics, heat & mass transfer, and fluids engineering.:
<http://www.thermopedia.com/content/267/>.
- [31] Šesták, J., Rieger, F.: Přenos hybnosti, tepla a hmoty. Skripta ČVUT v Praze, 2005. ISBN 80-01-02933-6.
- [32] Šesták, J., Bukovský, J., Houška, M.: Tepelné pochody. Transportní a termodynamická data. Skripta ČVUT v Praze, 2004. ISBN 80-01-02934-4.
- [33] Propane – butane mixture.: http://www.engineeringtoolbox.com/propane-butane-mix-d_1043.html.
- [34] Šebor G., Pospíšil M., Žákovec J.: Technicko – ekonomická analýza vhodných paliv v dopravě, Praha, 2006.
- [35] Nguyen Thanh Tuan, 2010.: Applicability and development LPG vehicles in Vietnam. XLI. international scientific conference of czech and slovak university departments and institutions dealing with the research of combustion engines, Czech republic. 2010. ISBN 978-80-7372-632-4.
- [36] Willard W. Pulkrabek.: Engineering Fundamentals of the Internal Combustion Engine. USA,1997.
- [37] Alternative Fuels Data Center.: <http://www.afdc.energy.gov/data/>

- [38] Zuhdi Salhab, Mohammad G. Quawasmi, Hussein Amro, Mosa Zalloum, Mohammad S. Quawasmi and Nafez and Nafez Sharawi.: Comparative performance and emission properties of spark ignition outboard engine powered by gasoline and LPG. Jordan Journal of Mechanical and Industrial engineering. Volume 5, number 1. 2011. ISSN 1995-6665. pp 47-52.
- [39] Manoj Kumar Mittal.: The performance analysis of a si engine using gasoline, LPG and blend of gasoline and LPG. Master work. University of Delhi. 2004.
- [40] Beroun, S., Brabec, J., Dráb, O., Dittrich, A., Nguyen Thanh Tuan: Pracovní materiály Centre for Nanomaterials, Advanced Technologies and Innovation. KVM FS TU v Liberci, 2013.
- [41] Directorate for standard, metrology and quality.:
<http://en.tcvn.vn/default.asp?action=article&ID=2730>

LIST OF AUTHOR'S PUBLICATION

1. Nguyen Thanh Tuan.: *Using liquefied petroleum gas – LPG as an alternative fuel to spark ignition engine by LPG injection into the intake manifold method*. Journal of Science and Technology of Fishery , Vietnam. No 2, 2009. ISSN 1859-2252
2. Nguyen Thanh Tuan.: *Calculation the movement and vaporization of the single liquefied petroleum gas droplet after injection into the intake manifold*. Journal of Science and Technology of Fishery , Vietnam. No. 2 , 2009. ISSN 1859-2252
3. Nguyen Thanh Tuan.: *Compressed natural gas (CNG) as an alternative fuel for internal combustion engine, problems and propose technical solutions for growth CNG vehiles in Vietnam*, XLI. An international scientific conference of Czech and Slovak university departments and institutions dealing with the research of combustion engines, Czech republic. 2010. ISBN 978-80-7372-632-4
4. Nguyen Thanh Tuan.: *Applicability and development LPG vehicles in Vietnam*. XLI. An international scientific conference of Czech and Slovak university departments and institutions dealing with the research of combustion engines, Czech republic. 2010. ISBN 978-80-7372-632-4
5. Nguyen Thanh Tuan, Stanislav Beroun.: *Performance of a spark ignition engine with difference LPG injection systems*. 4th international mechanical engineering conference, Prague – Czech Republic 1st Feb. 2011. ISBN 978-80-213-2156-4
6. Nguyen Thanh Tuan.: *Calculation the movement and vaporization of the single liquefied petroleum gas droplet after injection into the intake manifold*. 5th Annual International Travelling Conference, Tatranská Kotlina – High Tatras – Slovakia 13th – 16th April 2011. ISBN 978-80-89347-04-9
7. Nguyen Thanh Tuan.: *Emission concentration of spark ignition engine using liquefied petroleum gas, before and after three way catalyst converter*. 5th Annual International Travelling Conference, Tatranská Kotlina – High Tatras – Slovakia 13th – 16th April 2011. ISBN 978-80-89347-04-9 and The 7th International Conference on Automotive Engineering ICAE-7, Challenger, Impact, Muang Thong Thani, Bangkok, Thailand. March 28 – April 1, 2011.

8. Nguyen Thanh Tuan, Ho Duc Tuan, Nguyen Van Thuan.: *Exhaust emission of motorcycle engines running on ethanol blended gasoline*. KOKA 2011 xlii. An international scientific conference of Czech and Slovak university departments and institutions dealing with the research of combustion engines, September 8 - 9, 2011 – Zilina, Slovakia. ISSN 1337-8996
9. Bui Tuan Viet, Nguyen Thanh Tuan, Chi-na Benyajati.: *FEM simulation of impact testing for aluminum alloy wheel*. KOKA 2011 xlii. An international scientific conference of Czech and Slovak university departments and institutions dealing with the research of combustion engines, September 8 - 9, 2011 – Zilina, Slovakia. ISSN 1337-8996
10. Nguyen Thanh Tuan, Tran Viet Tien.: *Performance and emission of a motorcycle engine with bi-fuel petrol or ethanol*. Workshop Světlanka 2011. 19-22.9 Rokytnice nad Jizerou. Czech Republic 2011. ISBN 978-80-7372-765-9
11. Nguyen Thanh Tuan, Stanislav Beroun.: *A design the end of the LPG injector nosed to minimizing the icing around outlet injector nozzle with liquid phase LPG injection system*. Conference on structural mechanics and materials science 7th April 2012, Nha Trang, Vietnam.
12. Nguyen Thanh Tuan.: *Biogas as a fuel for internal combustion engine in the Vietnam*”, an interdisciplinary scientific conference for PhD students and assistants, 14-18th May 2012, Praha, Czech republic. ISBN: 978-80-905243-0-9. (Journal Of Interdisciplinary Research, ISSN 1804-7890.)
13. Nguyen Thanh Tuan, Tran Viet Tien.: *Performance experiment of an automobile engine running on E85*. Workshop Světlanka 2012. 17. - 20. září Rokytnice nad Jizerou. Czech Republic 2012. ISSN: 978-80-7372-891-5
14. Nguyen Thanh Tuan, Ondřej Dráb, Dittrich Aleš.: *Multi-point injection system of liquid LPG fuel: problem and solution to minimize icing around the injector nozzle tip*. The International Conference Technologia Europe 2012. Praha, Czech Republic, December 11 - 14, 2012. ISSN: 978-80-905243-4-7
15. Nguyen Thanh Tuan, Tran Viet Tien.: *Biodiesel fuel for engines – effect of exhaust emission on the engine wear performance of lubricant*. Interdisciplinary Scientific

Conference for PhD students and assistants. 20-24.5.2013. The Czech Republic. ISBN: 987-80-905243-7-8.

16. Beroun Stanislav, Brabec Pavel, Dittrich Aleš, Dráb Ondřej, Nguyen Thanh Tuan.: *Computational modeling of the liquid LPG injection into the suction manifold of an SI vehicle engine*. Journal Applied Mechanics and Materials Vol. 390 (2013) pp 355-359. ISBN 978-3-03785-833-2.

M 2:1



Appendix 2: Window image of computational model in the Excel sheet

Model of calculation (30.9.2013)_T= 291K_298K [Compatibility Model] - Microsoft Excel

HomeInsertPage LayoutFormulasDataReviewViewFoxit Reader PDF

CutCopyFormat PainterClipboard

Font

Align

Number

General

Wrap Text

Merge & Center

Conditional Formatting

Format as Table

Styles

Insert

Delete

Format

Cells

AutoSum

Fill

Sort & Find & Filter

Select

Editing

Model of calculation during the injection of liquid LPG into the intake manifold (2013)

Calculation parameters and boundary conditions

air

LPG

injection

pressure

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

injection

temp

Appendix 3: Temperature of LPG at ON and velocity of damp steam LPG at ON in the case: $n = 3000$ rpm and variants of channel volume and diameter of ON.

