A PHENOMENOLOGICAL MODEL OF TWO-PHASE (AIR/FUEL) DROPLET OF CUMMINS SPRAY

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INTRODUCTION

In order to fulfill regulations for the emission of the exhausting products, Euro V and VI, as same as in order to reduce fuel consumption, manufacturers of diesel engines are using more often technologies with high-pressured fuel injection. Since 1980's a procedure, which atomizes liquid fuel (diesel), filled with the gas (air), under the pressure was known, this procedure is known in the newest editions [1] as the effervescent atomization – the atomization of the gas/liquid mixture. In the aerator, by means of special supplying system, gas is slowly injected in a liquid current, and on the exit of the atomizer a two-phase mixture – a liquid current mixed with air bubbles (air fractions) is created. The atomization process is stimulated with the gas expansion at very high speed on the atomizer exit, and this disintegrates fuel current on ligaments, lamellas and droplets [1]. Cummins's pump-injector under the high pressure injects two-phase of the diesel fuel mixture, air and the combustion products – and this is very interesting characteristic in the aspect of injection.

The aim of the present paper is to describe the recent research in the area of two-phase mixture air/diesel fuels atomization and to present our own a phenomenological model of two-phase (air/fuel) droplet developing and breakup on the Cummins's pump-injector example.

This paper is resumption and extending at a [9].

PREVIOUS RESEARCH

Roesler and Lefebvre [1, 2, 3] were investigated fluctuation of gas/liquid two-phase mixture. Through the atomizer's outlet, flowing can be in a form of bubbles, in a form of cylindrical gas tampons or in a form of the annular flow. On the outlet of the atomizer, gas fractions are getting into the phase of the relaxed pressure, they spreading very fast and disintegrate liquid into the droplets.

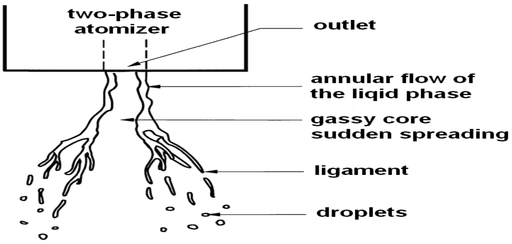

Figure 1: *Scheme of disintegration of two-phase annular flow after the atomizer's outlet [1]*

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The experiments that Sojke and coauthor has performed [1, 4] have shown the similar mechanism, as the air-filled fluid is getting out of the atomizer, the gas bubbles are spreading very quickly and thus they disintegrates fuel current on a thin ligaments. Under the aerodynamic influence of the gas, which is inside the space where the mixture is injected, they are rupturing, in such a way they are forming a droplets, figure 1.

In the paper [5] the results of performed examinations over the EDI injector - the atomizer of the air-filled gas are shown. The effects of injection pressure, gas/liquid mass ratio, atomizer outlet also, the influence of aerator parameters on atomization quality (the size of the droplet, and the spray conical angle) were examined.

MODEL OF TWO-PHASE DROPLET DEVELOPING AND DEFAULT ASSUMPTIONS

Introduction notes

In the chamber under the top of the needle of the Cummins's pump-injector, a liquid phase, fuel, is being mixed with the gas phase (air and the combustion products) and thus a two-phase mixture is created. A separate system for injector air supplying is not needed. A gas phase that is used for two-phase production, and which is consisting of air and the combustion products, comes into the Cummins's pump-injector out of the cylinders of the diesel engine, it is actually, being aspirated by the needle of the pump-injector, during its lifting of the seat in the atomizer.

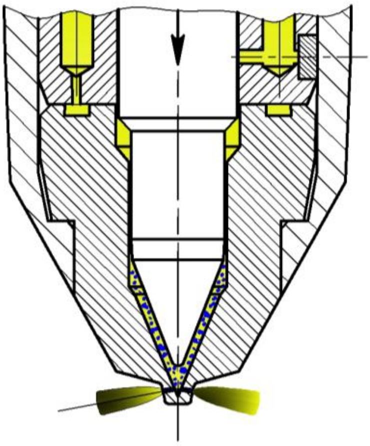

***Figure 2:** A mixture of gas phase and diesel fuel under the needle of Cummins's pump-injector*

A liquid phase, fuel, comes into the chamber, under the injector needle; it comes under the fuel pressure in the inlet channel which is approximately same as the fuel pressure inside the fuel supply pump p_{gnp}. The fuel pressure in the supplying pump is significantly lower comparing to injection pressure, i.e. the pressure in the chamber under the top of the needle of the pump-injector p_b that can reach the values higher then 1500 bar [6]. A two-phase mixture produced in this way is a characteristic feature of Cummins's PT injection system. A needle of Cummins's pump-injector is pushing out, through the openings of the atomizer, a two-phase mixture, figure 2. A gas phase of the mixture (air), affects to liquid (diesel fuel) to flow through the openings of the atomizer in a form of a small fragments**.** Sudden spreading of the gas fragments, just after it came out of the atomizer outlet, stimulates liquid disintegration into the droplets.

The observation of the fluctuation process that occurs through the Cummins's atomizer outlet and the influence of the compressed air onto disintegration of the liquid flow can be significantly simplified in the first approximation, by means of the following assumption. The air-filled liquid fragments (a chain of primary droplets) of diesel fuel in the shape of the sphere, and inside the sphere's core is a bubble of compressed air, figure 3, are being injected.

The size of the primary spherical droplet of diesel fuel, a droplet with the gassy core, in a great deal depends on pressures. Pressure variations along the Cummins's pump-injector outlet, during the two-phase fluctuation, are significantly lower comparing to the values in the injectors with the one-phase fluctuation [1]. At the exit of the atomizer's outlet a two-phase pressure has a significant drop of the pressure. Two-phase fluctuation has a drastically dropping of the pressure at the exit of the atomization outlet. Diameter of the primary spherical droplet D_{kapl} $f(p)$, depending on the pressure, varies in the range of D_{kaplp_b} - a primary droplet diameter under the injection pressure p_b, up to the "rupturing" droplet diameter itself D_{kaplp_z} - a primary droplet diameter under the pressure in the engine cylinder p_z. The gas (air) is in a form of the bubble, which is compressed in the core of the spherical liquid droplet (diesel fuel), under the pressure over which a liquid is exposed. D_{vp} is a diameter of the air bubble in the spherical droplet under the pressure p.

According to this model, an initial calculation diameter of the primary spherical droplet $D_{kaplpoc}$ at the maximum pressure that can be achieved at the atomizer's outlet, and this value is approximate to the injection pressure - p_b, is equal to the diameter of the injector outlet - d_o (figure 3 a).

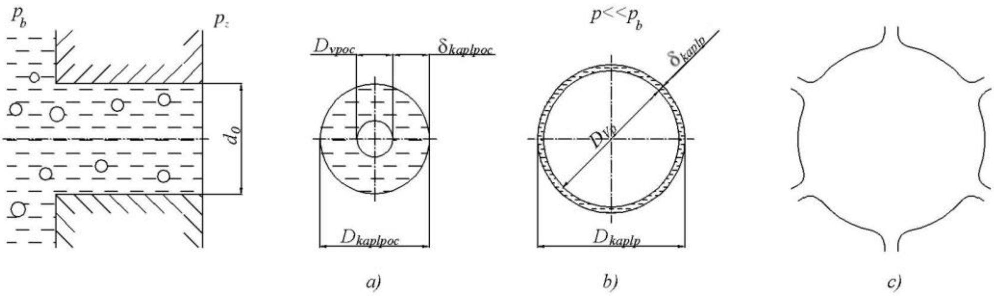

Figure 3: *Injecting scheme of air-filled liquid fragment of diesel fuel (a primary droplet), with the spherical shape and the air-compressed core*

$$D_{kaplpoc} = D_{kaplp_b} = d_o \tag{1}$$

Under the pressure of the engine cylinder - p_z, which is considerably lower then the injection pressure p_b, a droplet is spreading very fast**,** until the moment when it breakup (figure 3 b and c). Since a diesel fuel is the incompressible fluid**,** its volume is slightly increased, but due to that, the air volume inside the droplet is considerably increased. The volume of the air – that is compressible fluid is depending on the pressure in a great deal. While the droplet is spreading, a thickness of the liquid phase has been reduced more and more until the moment when a critical thickness of the liquid phase δ_{kaplkr} is reached, and then a droplet has been breakup- it decomposes. In that moment a droplet diameter is D_{kaplkr}. In order to perform a droplet volume calculation it is necessary to know air and diesel fuel specific density depending on the pressure, as same as the volume variations of the air and diesel fuel depending on the pressure.

Diesel fuel density ρ_g and elastic modulus e_g depending on the pressure p

Values of diesel fuel density and elastic modulus, depending on the pressure, which are experimentally determined, are given analytically in a form of the second-degree polynomial [6]. A diesel fuel density and elastic modulus at 20 °C:

$$\rho_{g20C}\, f(p) = 835{,}88 + 5{,}017x10^{-7}\, p - 6{,}974x10^{-16}\, p^2 \tag{2}$$

$$e_{g20C}\, f(p) = 1{,}4609x10^{9} + 11{,}598p - 1{,}125x10^{-8}\, p^2 \tag{3}$$

at 80 °C:

$$\rho_{g80C}\, f(p) = 791{,}43 + 6{,}520x10^{-7}\, p - 1{,}036x10^{-15}\, p^2 \tag{4}$$

$$e_{g80C}\, f(p) = 9{,}906x10^{8} + 11{,}497p - 1{,}0492x10^{-8}\, p^2 \tag{5}$$

In a above equations pressure is given in the units of Pa. Calculation results, which are presented, are performed under following assumption:

$$\rho_g\, f(p) = \rho_{g20C}\, f(p) \tag{6}$$

Air density ρ_v and elastic modulus e_v depending on the pressure p

In this model, a gassy part of the primary droplet – the air – is observed as the real gas, which is being very fast compressed at the pressure *p*. In a case of adiabatic air compression – (without heat exchanging with the environment) the air density at the pressure *p* is:

$$\rho_v f(p) = \rho_{vp} = \frac{p}{z(p,T) R_v T_{vo} \left(\frac{p}{p_o} \right)^{\frac{\chi-1}{\chi}}} \tag{7}$$

where:

z(p,T) - function that shows deviations of the real gases in regard to the ideal gas at specific pressure and temperature, in analytical form [6]:

$$z(p,T) = 1 + \frac{9}{128} \frac{p_r}{T_r} (1 - 6T_r^{-2}) \tag{8}$$

where:

$p_r = \frac{p}{p_c}$ - reduced pressure, $T_r = \frac{T}{T_c}$ - reduced temperature,

p_c = 37,7 bar - critical pressure and T_c =132,2 K - critical temperature, at those values the air has been transformed into the liquid phase.

The air temperature T_v at the pressure p in a case of adiabatic change of the state:

$$T_v f(p) = T_{vp} = T_{vo} \left(\frac{p}{p_o} \right)^{\frac{\chi-1}{\chi}} \tag{9}$$

where:

T_{vp} - the absolute air temperature at the pressure p,

T_{vo} - the absolute air temperature at the pressure p_o = 1 bar, T_{vo} = 20 oC ,

R_v - air gas constant R_v = 287 J·kg-1·K-1,

χ - adiabatic exponent, for air χ = 1,4.

Air compression is being performed very quickly, therefore there is no time for heat exchanging with the environment. The process of the air compression is considered as adiabatic change of the state, and that is the cause of the high temperatures of compressed air.

In a case of adiabatic air compression, while the system's entropy remains constant, a corresponding elastic modulus is called the adiabatic elastic modulus E_s.

$$E_s = -V\left(\frac{\partial p}{\partial V}\right)_{s=cons} \tag{10}$$

For the ideal gas:

$$E_s = \chi p \tag{11}$$

Air/ fuel mass and volume ratio in a two-phase droplet

It is difficult to evaluate the precise quantity of air presence in a two-phase fuel droplet. In this model is made an assumption that the same mass quotum is in every primary droplet and then the calculation is performed. During the droplet expansion, a mass quotum in a droplet remains the same. Ratio in between the air mass M_v and the fuel mass M_g inside the droplet is called air/fuel mass ratio glr.

$$glr = \frac{M_v}{M_g} \tag{12}$$

Ratio of air volume V_v and fuel volume V_g is called air/fuel volume ratio $vglr$:

$$vglr = \frac{V_v}{V_g} \tag{13}$$

There is an correlation In between air/fuel mass ratio glr and air/fuel volume ratio $vglr$:

$$vglrf(p) = vglr_p = \frac{V_v f(p)}{V_g f(p)} = \frac{V_{vp}}{V_{gp}} = glr\frac{\rho_{gp}}{\rho_{vp}} \tag{14}$$

where:

$vglr_p$ - gassy and liquid volume ratio at the pressure p,

V_{vp} - gassy phase volume (air) at the pressure p,

V_{gp} - liquid phase volume (diesel fuel) at the pressure p ,

ρ_{gp} - fuel density at the pressure p ,

ρ_{vp} - air density at the pressure p .

According to this - a volume ratio of gassy and liquid phase in the mixture (droplet) is depending on phase’s densities, which are depending on the pressure, i.e. it has changing depending on the pressure that the droplet is exposed.

The air bubble diameter in a two-phase droplet at the injection pressure

A volume of the two-phase droplet mixture of fuel and air, at the injection pressure p_b is:

$$V_{kaplpoc} = V_{kaplp_b} = \frac{d_o^3 \pi}{6} \tag{15}$$

where: $V_{kaplpoc}$ - a starting calculation volume of the two-phase droplet.

Since the droplet is consisting of the fuel and the air then follows:

$$V_{kaplpoc} = V_{gpoc} + V_{vpoc} \tag{16}$$

or:

$$V_{kaplp_b} = V_{gp_b} + V_{vp_b} \tag{16’}$$

‘

where:

V_{gpoc} - initial calculation volume of the liquid phase (fuel) of two-phase droplet.

V_{vpoc}- initial calculation volume of the gassy phase (air) of two-phase droplet.

According to equations 14, 16 and 16’ it follows:

$$V_{kaplp_b} = V_{gp_b} + vglr_{p_b}, \Rightarrow V_{gpoc} = V_{gp_b} = \frac{V_{kaplp_b}}{1 + vglr_{p_b}} = \frac{V_{kaplp_b}}{1 + glr \dfrac{\rho_{gp_b}}{\rho_{vp_b}}} \tag{17}$$

Initial calculation volume of the droplet liquid phase is determined according to the following equation:

$$V_{vpoc} = V_{kaplpoc} - V_{gpoc} \tag{18}$$

Initial calculation diameter of the air bubble D_{vpoc} can be obtained according to the following equation:

$$D_{vpoc} = D_{vp_b} = \sqrt[3]{\frac{6V_{vpoc}}{\pi}} \tag{19}$$

Thickness of the liquid "film" of two-phase droplet at the injection pressure p_b:

$$\delta_{kaplp_b} = \frac{1}{2}\left(D_{kaplp_b} - D_{vp_b}\right) \tag{20}$$

Expansion of a two-phase droplet

When a droplet of compressed fuel and air, at the injection pressure p_b, get into the space of pressure $p \langle\langle p_b$, i.e. in the cylinder of diesel engine, an air-filled bubble inside of the core starts spreading very fast. Pressure alteration is very quick. If an assumption is made that air is actually an ideal gas, for the adiabatic change of the state, a volume of the two-phase bubble V_v at the pressure p is:

$$V_v\, f(p) = V_{vp} = \left(\frac{p_b}{p}\right)^{\frac{1}{\chi}} V_{vp_b} \tag{21}$$

for $p = p_z \Rightarrow V_{vp_z} = \left(\frac{p_b}{p_z}\right)^{\frac{1}{\chi}} V_{vp_b}$ (22)

In a case of pressure change from $p_b = 1000$ bar to $p_z = 1$ bar, a volume of the air-filled bubble has considerably changed:

$$V_{vp=1} = \left(\frac{1000}{1}\right)^{\frac{1}{\chi}} V_{vp=1000} = 138 V_{vp=1000} \tag{23}$$

Diameter of an air-filled bubble at the pressure p :

$$D_v\, f(p) = D_{vp} = \sqrt[3]{\frac{6V_{vp}}{\pi}} \tag{24}$$

for $p = p_z \Rightarrow D_{vp_z} = \sqrt[3]{\frac{6V_{vp_z}}{\pi}}$ (25)

Diesel fuel is a hardly compressed liquid. Fuel volume depending on the pressure has changed according to following definition:

$$\Delta V_{gp} = V_{gp} - V_{gp_b} = -V_{gp_b}\left(\frac{\Delta p}{e_g}\right) = -V_{gp_b}\,\frac{p - p_b}{e_g} \tag{26}$$

namely:

$$V_{gp} = V_{gp_b}\left(1 + \frac{p_b - p_z}{e_g}\right) \tag{27}$$

where: ΔV_{gp} - diesel fuel volume alteration due to pressure alteration. In the equation 26 there is minus sign because a volume alteration has an opposite sign comparing to the pressure alteration, $V_{gp} = V_g\, f(p)$ - fuel volume inside the droplet depending on the pressure.

At the pressure p a volume of the mixture consisting of diesel fuel and air is:

$$V_{gp} = \frac{1}{6}\pi\left[\left(D_{kaplp}\right)^3 - \left(D_{vp}\right)^3\right] \tag{28}$$

According to above equation a droplet diameter at the pressure p is:

$$D_{kaplp} = \sqrt[3]{\frac{6}{\pi}V_{gp} + \left(D_{vp}\right)^3} \tag{29}$$

for $p = p_z \Rightarrow D_{kaplp_z} = \sqrt[3]{\frac{6}{\pi}V_{gp_z} + \left(D_{vp_z}\right)^3}$ (30)

Thickness of the liquid “film” in a droplet at the pressure *p:*

$$\delta_{kaplp} = \frac{1}{2}(D_{kaplp} - D_{vp}) \tag{31}$$

for $p = p_z \Rightarrow \delta_{kaplp_z} = \frac{1}{2}(D_{kaplp_z} - D_{vp_z})$ (32)

Perhaps this will never be reached – if the droplet breakup before. That will happen whenever is $\delta_{kaplkr} \rangle \delta_{kaplp_z}$.

In order to analyze the model such as this one here presented, the following estimation is accepted; when due to air bubble expansion within the two-phase droplet, the thickness of the liquid “film” has been reduced up to its critical value δ_{kaplkr}, a two-phase droplet will disintegrate. In the moment when a two-phase droplet is being disintegrated, its diameter D_{kaplkr} - is critical diameter, diameter of two-phase droplet “disintegration”. The pressure inside the air bubble, during two-phase droplet disintegration, is a critical pressure p_{kr} .
If disintegration pressure – i.e. critical pressure of two-phase droplet is:

$$p_{kr} \rangle p_z \tag{33}$$

Then critical thickness of the liquid “film” is:

$$\delta_{kaplkr} \rangle \delta_{kaplp_z} \tag{34}$$

A two-phase droplet will disintegrate before the thickness of the liquid “film” reduce to critical value δ_{kaplp_z} , i.e. before its expansion process, defined by the pressure inside of the engine cylinder, is finished.

If the assumed value of liquid “film” thickness of two-phase droplet during its disintegration is:

$$\delta_{kaplp} = \delta_{kaplp} f(p_b, d_o, glr, p) = \delta_{kaplkr} \tag{35}$$

Then critical pressure, depending of gas phase and liquid phase mass ratio is determined as glr :

$$p_{kr} = pf(glr) = p/.FindRoot\lfloor \delta_{kaplp} f(p_b, d_o, glr, p) = \delta_{kaplkr} \rfloor \tag{36}$$

For the assumed value of liquid “film” critical thickness δ_{kaplkr}, a minimal and real value of gas phase and liquid phase mass ratio has been calculated glr_{p_z}, when under certain pressure value inside engine’s cylinder p_z a two phase droplet has been disintegrated:

$$glr_{p_z} \to FindRoot\left[pf\left(glr\right)\right] = p_z \tag{37}$$

Critical pressure which is depending on gas/liquid phase mass ratio, is determined by equation 36 and has been graphically presented within the interval glr_{p_z} to $glr = 0{,}1$. Within the same interval a critical diameter of two-phase droplet D_{kaplkr} has been shown, which has been calculated for the state of critical pressure.

ANALYSIS OF OBTAINED RESULTS FROM TWP-PHASE DROPLET MODEL

Volume and diameter of the air-filled bubble inside the two-phase droplet

In figure 4 is shown a calculated volume alternation of the air-filled bubble V_{vp} inside the two-phase droplet of the diesel fuel (a liquid phase) and air (a gassy phase) mixture, depending on droplet gassy/fuel phase mass ratio *glr*, and depending on the pressure in a area close to the droplet *p*. It can be noticed that volume of the air-filled bubble considerably depends on the pressure in the area close to the droplet *p*.

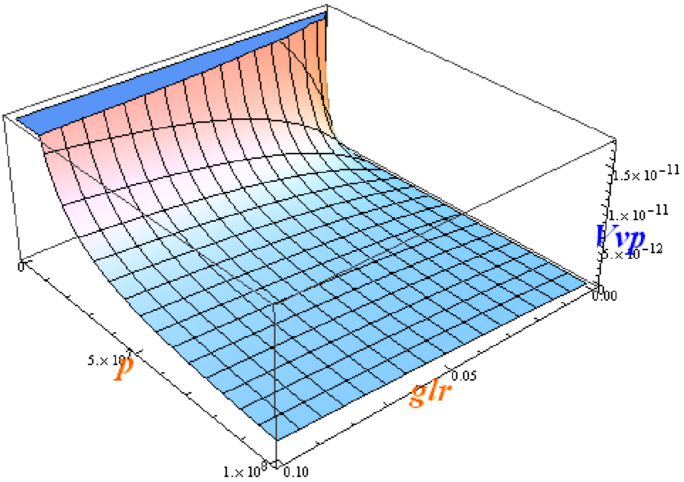

Figure 4: *Air-filled bubble volume alteration* V_{vp} *(* m^3*), inside the two-phase droplet of diesel fuel and air mixture, depending on droplet gassy/fuel phase mass ratio glr (–) and the pressure in the area close to the droplet p (Pa).*
Atomizer’s outlet diameter d_o*= 0,215 mm*

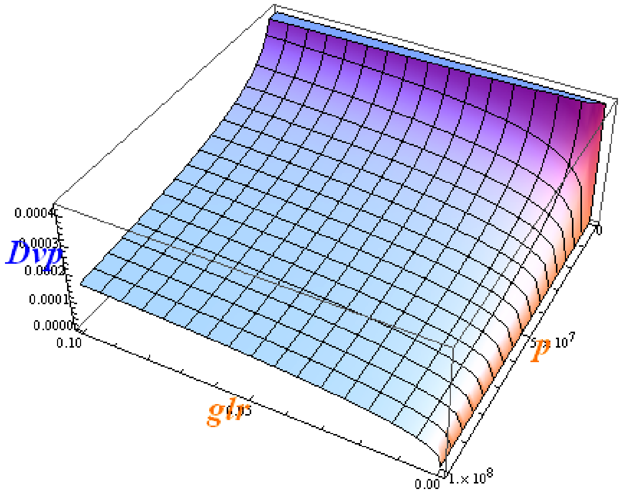

***Figure 5:** Diameter alteration of the air-filled bubble D_{vp} (m) inside the two-phase droplet a mixture of diesel fuel and air, depending on the droplet gassy/fuel phase mass ratio glr (–) and the pressure in the area close to the droplet p (Pa). Atomizer's outlet diameter d_o= 0,215 mm*

Volume alteration intensity of the air-filled bubble increases as the pressure that reacts on the droplet decreases, and the same occurs even for the lower *glr* ratio values. Presence of small air quantity inside the diesel fuel droplet that is spreading very fast after injection has a devastating effect onto droplet.

Character of the air-filled bubble diameter alteration $D_{vp} = D_v\, f(p, glr)$ is very same to air-filled bubble volume alteration inside the droplet, and that can be noticed according to figures 4 and 5.

A diesel fuel volume inside the two-phase droplet depending on the environmental pressure

In figure 6, a diesel volume alteration V_{gp} is presented, inside the droplet mixture of diesel fuel (a liquid phase) and air (a gassy phase) depending on the droplet gassy/fuel phase mass ratio *glr*, and the pressure in the area close to the droplet *p* Pa. Those values are calculated with the following assumption:

$$e_g = e_{g20C} \tag{38}$$

It can be noticed that diesel fuel volume – i.e. liquid "film" of air-filled bubble inside the droplet – very little, insignificantly depends on the pressure *p* that effects to the droplet. Influence that is more important has a droplet gassy/fuel phase mass ratio *glr*. There is a significant difference in the character of the gassy and the liquid phase volume alteration, depending on the pressure.

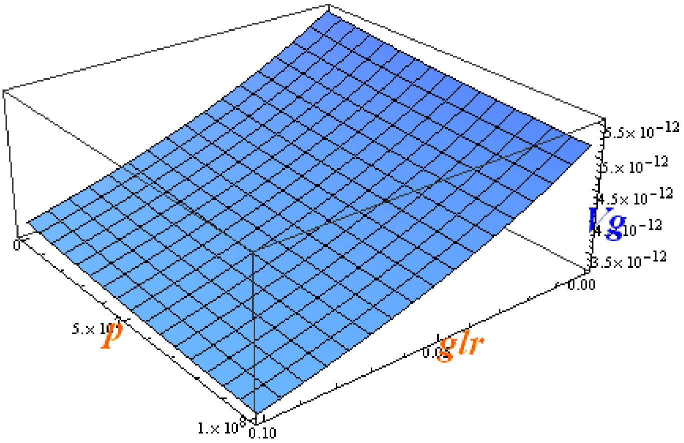

Figure 6: *Diesel fuel volume* V_{gp} *(*m^3*) in a two-phase droplet – mixture of diesel fuel and air, depending on the droplet gassy/fuel phase mass ratio glr (–) and the pressure in the area close to the droplet p (Pa)*

Outer diameter of the two-phase droplet depending on the environmental pressure

At the figure 7, a calculated correlation in between the outer diameter of the two-phase droplet of diesel fuel and air, depending on the environmental pressure and the droplet gassy/fuel phase mass ratio, is presented. Outer diameter of the two-phase droplet **considerably** depends on pressure *p* that effects to the droplet, and **not considerably** of gassy/fuel phase mass ratio. On the other hand, a presence of even small air quantities inside the mixture, at the low environmental pressure, increases very fast the outer diameter of the droplet – until it breakup, in that moment a droplet diameter is D_{kaplkr}.

Thickness of the liquid "film" of two-phase droplet depending on the environmental pressure

In figure 8 a calculated correlation in between the thickness of the liquid "film" of two-phase droplet is shown, depending on the droplet gassy/fuel phase mass ratio and the pressure in the area close to the droplet. Thickness of the liquid "film" of two-phase droplet is depending on the pressure in the area close to the droplet, it decreases as the pressure decreases. With the increase of the droplet gassy/fuel phase mass ratio, *glr,* the thickness of liquid "film" is reduced, a droplet become thinner. At lower pressures in the droplet environment, the thickness alternation intensity of droplet "film" becomes higher.

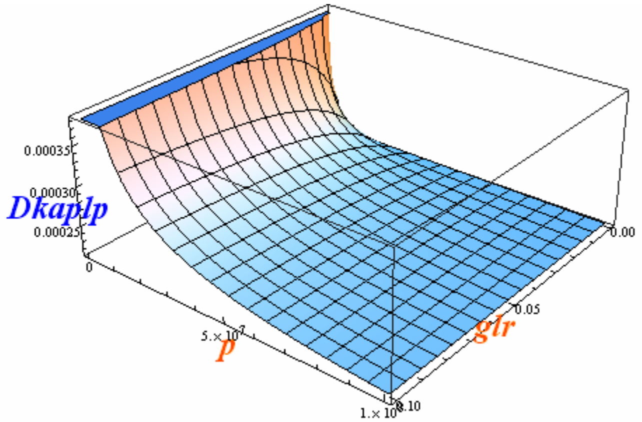

Figure 7: *Outer diameter* D_{kaplp} *(m) of the two-phase droplet of diesel fuel and air, depending on the droplet gassy/fuel phase mass ratio glr (–) and the pressure in the area close to the droplet p (Pa). Atomizer's outlet diameter* d_o*= 0,215 mm*

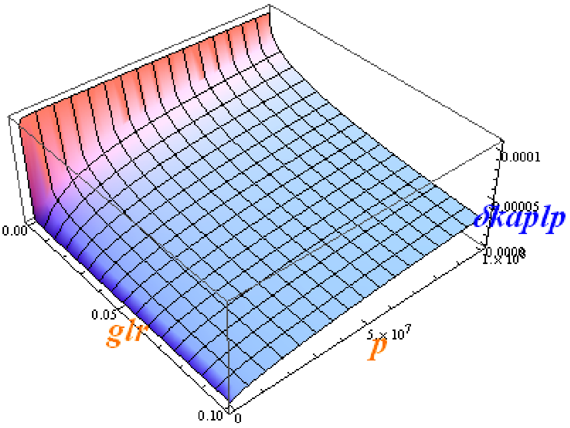

Figure 8: *Thickness of the liquid "film" of two-phase droplet – mixture of diesel fuel and air* δ_{kaplp}*(m) depending on the droplet gassy/fuel phase mass ratio glr (–) and the pressure in the area close to the droplet p (Pa). Atomizer's outlet diameter* d_o*= 0,215 mm*

It is very hard to distinguish criteria when the droplet is actually breakup. Inside the droplet, a spreading air is effecting, and from the outside an aerodynamic force, which is formed due to high values of relatives speed in between the droplets and the nearby air in a combustion area. In a reference [7] are given Mayer's criteria for the one-phase droplet breakup (one-phase droplet is consisting from the liquid phase – only) and those criteria are experimentally defined.

When the thickness of liquid "film" is reduced to it's critical value δ_{kaplkr}, a two-phase droplet is breakup. A critical thickness value of the liquid "film" can be experimentally determined. In figures 9 and 12 a values of environmental pressure and gassy/fuel phase mass ratio, in the moment of the two-phase droplet breakup are shown. A thickness of liquid “film” in the moment of two-phase droplet breakup is assumed to be δ_{kaplkr} = 0,00001 m (fig. 9) and δ_{kaplkr} = 0,000015 m (fig. 12). According to previously shown calculated values, it can be concluded following: if the two-phase droplet (air/fuel) has plenty of air (a gassy phase), then it will breakup at higher pressures. In that moment a droplet diameter is D_{kaplkr}.

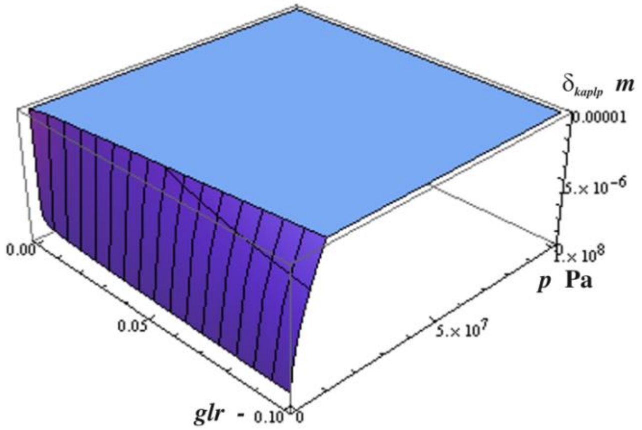

Figure 9: *The pressure in the area close to the droplet p (Pa) gassy/fuel phase mass ratio glr (–) in the moment of two-phase droplet breakup, with the liquid “film” thickness* δ_{kaplp} = *0,00001 m (0,01 mm),* d_o*=0,215 mm*

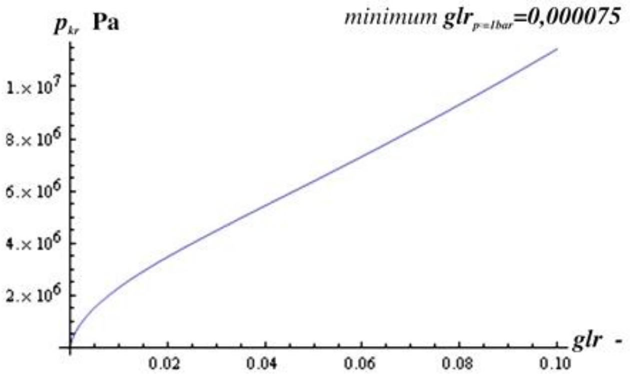

Figure 10: *Dependency of critical pressure* p_{kr} *(Pa) on gas/liquid mass ratio glr (–) during the two-phase droplet disintegration, liquid “film” critical thickens is* δ_{kaplkr} *= 0,00001 m,* d_o*= 0,215 mm. Injection pressure* $p_b = 1x10^8$ *Pa. The environmental pressure, where the two-phase droplet has been injected is* p_z *= 1bar =* $1x10^5$ *Pa. Minimal value of gas/liquid phase mass ratio* $glr_{p=1bar}$ *= 0,000075 which will cause disintegration of the droplet under the pressure* p_z *= 1bar*

In figures 10 and 11 is shown dependency, among the pressure and diameter during the disintegration of two-phase droplet, dependency of critical pressure p_{kr} and critical diameter D_{kaplkr} on gas/liquid phase mass ratio *glr*,, which is calculated based on here presented model under the assumed value of liquid "film" critical thickness δ_{kaplkr} = 0,00001 m (0,01 mm). In figures 13 and 14 dependency of the values of critical pressure and critical diameter on gas/liquid phase mass ratio are shown, calculated based on assumed value of liquid "film" critical thickness of two-phase droplet δ_{kaplkr} = 0,000015 m (0,015 mm).

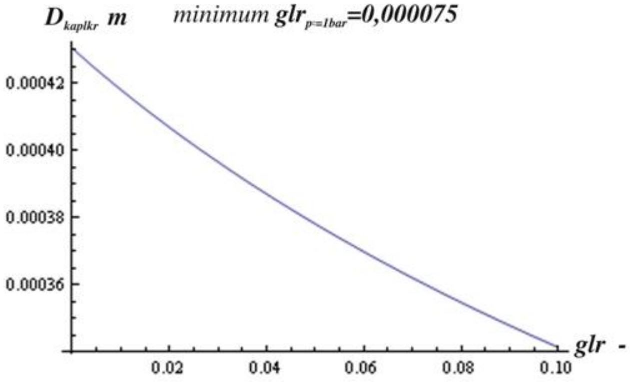

Figure 11: *Dependency of critical diameter D_{kaplkr} (m) on air/fuel mass ratio glr(–) during the two-phase droplet disintegration, critical thickness of liquid "film" is δ_{kaplkr} = 0,00001 m. Diameter of nozzle's outlet is d_o= 0,215 mm. Injection diameter p_b = $1x10^8$ Pa. The environmental pressure, where the two-phase droplet has been injected is p_z = 1bar = $1x10^5$ Pa. Minimal value of gas/liquid phase mass ratio $glr_{p=1bar}$ = 0,000075 which will cause disintegration of the droplet under the pressure p_z = 1bar*

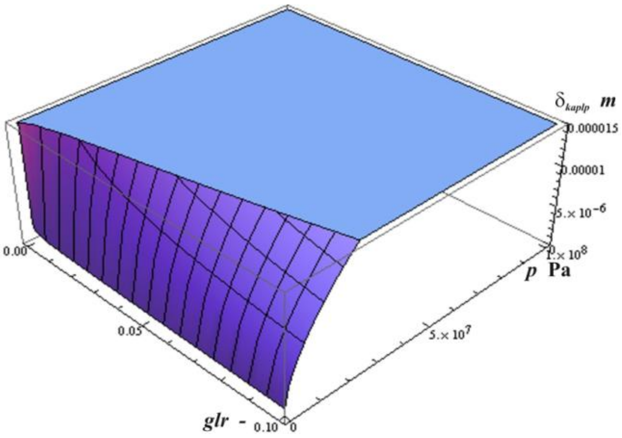

Figure 12: *The pressure in the area close to the droplet p (Pa), gassy/fuel phase mass ratio glr (–) in the moment of two-phase droplet breakup, with the liquid "film" thickness δ_{kaplp} = 0,000015 m, d_o=0,215 mm*

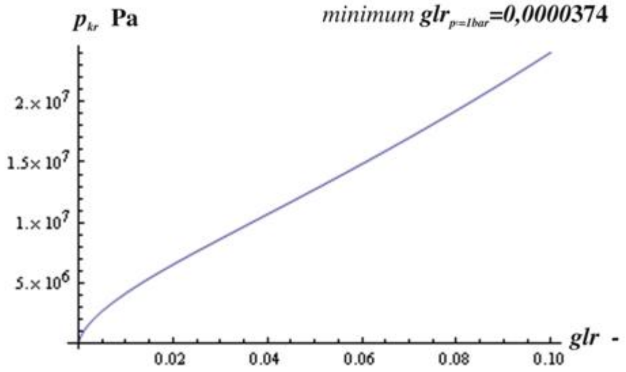

Figure 13: *Critical pressure dependency p_{kr} (Pa) on gas/liquid phase mass ratio glr (–) during two-phase droplet breakup, critical thickness of liquid "film" is δ_{kaplkr} = 0,000015m. Diameter of nozzle's outlet is d_o= 0,215 mm. Injection pressure $p_b = 1x10^8$ Pa. The environmental pressure, where the two-phase droplet has been injected is p_z = 1bar = $1x10^5$ Pa. Minimal value of gas/liquid phase mass ratio $glr_{p=1bar}$ = 0,0000374 which will cause disintegration of the droplet under the pressure p_z = 1bar*

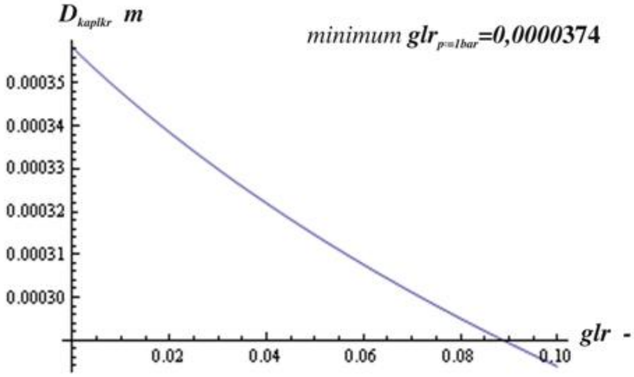

Figure 14: *Dependency of critical diameter D_{kaplkr} (m) on gas/liquid phase mass ratio glr (–) during two-phase droplet breakup, critical thickness of liquid "film" is δ_{kaplkr} = 0,000015 m. Diameter of nozzle's outlet is d_o= 0,215 mm. Injection pressure $p_b = 1x10^8$ Pa. The environmental pressure, where the two-phase droplet has been injected is p_z = 1bar = $1x10^5$ Pa. Minimal value of gas/liquid phase mass ratio $glr_{p=1bar}$ =0,0000374 which will cause disintegration of the droplet under the pressure p_z = 1bar*

Under specified calculation conditions a minimal value of gas/fluid phase mass ratio has been calculated, under which a two-phase droplet will breakup (disintegrate) by the pressure p_z = 1bar and assumed critical thickness of liquid "film" minimum $glr_{p_z=1bar}$= 0,000075 for the thickness δ_{kaplkr} = 0,00001 m (0,01 mm), i.e. minimum $glr_{p_z=1bar}$= 0,0000374 for the thickness δ_{kaplkr} = 0,000015 m (0,015 mm). Two-phased droplet, according to the presented model and specified calculation assumptions, should contain a considerable small amount of air in order to breakup – i.e. to disintegrate, under the pressure p_z = 1bar. Considerable small amount of air, specified by glr = 0,000075, which is compressed inside the droplet under the injection pressure $p_b = 1x10^8$ Pa, is spreading and make the liquid “film” thinner up to δ_{kaplkr} = 0,00001 m (0,01 mm), and then a two–phase droplet will breakup.

For the constant value of the environmental pressure p_z under which a two-phase droplet has been injected, if the assumed value of liquid “film” thickness δ_{kaplkr} is being increased then a minimal value of droplet’s gas and liquid phase (minimum glr_{p_z}), which will cause the breakup of a droplet under the pressure p_z, will be reduced, same as the diameter of two-phase droplet during the disintegration.

$$\begin{aligned} &\delta_{kaplkr} \Uparrow \Rightarrow minimum\, \delta_{p_z} \Downarrow za\ p_z = constans \\ &\delta_{kaplkr} \Uparrow \Rightarrow D_{kaplkr} \Downarrow\ za\ p_z = constans \end{aligned} \tag{39}$$

Based on here presented model it might be concluded, if inside the droplet the air is not present, glr = 0, then the droplet will not breakup – it will not disintegrate at all. In that case liquid “film” thickness is equal to droplet’s diameter and practically it’s not depending on pressure.

It’s not so easy to determinate the thickness of a two-phase droplet during its disintegration. In the literature, for the time being, such a data do not exist. So in that sense, in order to make the comparison, the experimental results of some other researchers might be used, “dispersion gas which is injected, inserts much more energy than it is really needed for the droplets forming. Even under low injection pressures 10 MPa and at 1% air/fuel mass ratio, Sovani [5, 8] estimates that the energy consisted inside dispersion gas is almost 30 times higher than it is necessary to disperse the mixture.”

In figure 15. by coordinate axes p, glr a critical thickness of two-phase droplet liquid “film’ has been shown δ_{kaplkr} calculated under the injection pressure p_b =10 MPa, all other calculation terms and conditions are shown in the figure. Based on here presented results, under specified calculation terms, it can be concluded following: inside the nozzle’s outlet if glr>0,065 =6,5%, where the pressure is $p = p_b$, a two-phase droplet, consisted of air and diesel fuel mixture, with the thickness of the liquid “film” δ_{kapl} = 0,000015 m, cannot be formed. In that case, through the nozzle’s outlet gas and liquid phase "spills” has been frequently injected.

Based on presented results of mathematical two-phase droplet disintegration, it can be concluded that during the injection under high pressure $p_b = 1x10^8$ Pa, compared to injection under considerable lower pressure $p_b = 1x10^7$ Pa = 10 MPa inside the nozzle’s droplet will occur bubbled flow regime, in that case a gas phase will flow in the form of small bubbles. This conclusion is in the compliance with the results of the experimental researches performed for two-phase flow. By the experimental researches it is estimated that if the injection pressure is been increased then glr values, which will preserve bubbled flow regime, will be increased as well [1]. It should be emphasized that here mentioned experimental researches of two-phase flow are presented in literature [1], performed under injection pressures within the scope 0,1 MPa to 1,1 MPa.

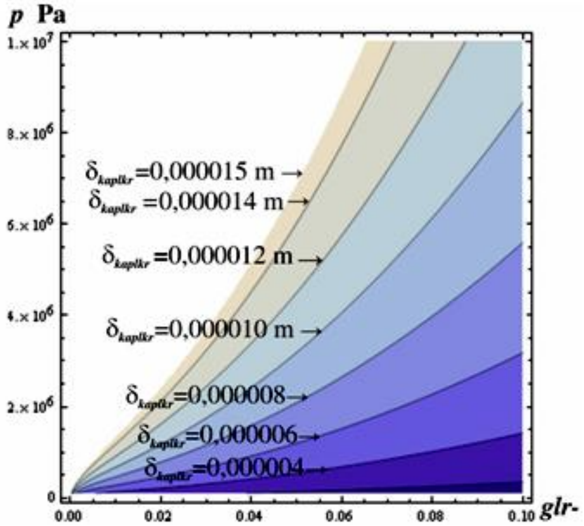

Figure 15: *Dependency of critical thickness of two-phase droplet liquid "film"* δ_{kaplkr} *(m) on gas/liquid phase mass ratio glr (-). Diameter of nozzle's outlet is* d_o*= 0,215 mm. Injection pressure* $p_b = 1x10^7$ *Pa = 10 MPa. The environmental pressure, where the two-phase droplet has been injected is* p_z *= 1bar =* $1x10^5$ *Pa*

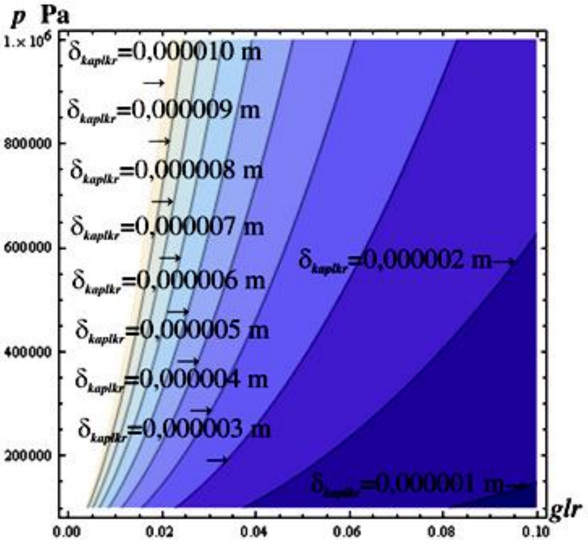

Figure 16: *Dependency of critical thickness of two-phase droplet liquid "film"* δ_{kaplkr} *(m) on gas/liquid phase mass ratio glr (-). Diameter of nozzle's outlet is* d_o*= 0,215 mm. Injection pressure* $p_b = 1x10^6$ *Pa = 1 MPa. The environmental pressure, where the two-phase droplet has been injected is* p_z *= 1bar =* $1x10^5$ *Pa*

In figure 16 is shown a segment of two-phase droplet breakup calculation, injected under the injection pressure p_b = 1 MPa. Based on the presented results of two-phase droplet breakup, when the injection pressure is p_b = 1 MPa, if the gas/liquid phase mass ratio is *glr* > 0,021 inside the nozzle's outlet, then two-phase droplet made of air and diesel fuel mixture, with the thickness δ_{kapl} = 0,00001 m of the liquid "film" cannot be formed. So, in that case, under the assumption that the thickness of the liquid "film" is δ_{kaplkr} = 0,00001 m a two-phase droplet will disintegrate – breakup, inside the nozzle's outlet and through the outlet a "spills" of gas and liquid phase will be injected. Obtained result is in the compliance with the experimental researches. In the experiment described in work-paper [1], researchers Santangelo and Sojka made the examination based on the injection pressures of two-phase air/water mixture in the scope 0,1 MPa do 1,1 MPa and *glr*<0,02 – and they have noticed that some gas bubbles fluently flow through the nozzle's outlet, i.e. the bubbled flow boundary is *glr*<0,02 - .

CONCLUSIONS

Here presented computer model shows the influence of the gassy phase (i.e. air) onto the development of the two-phase droplet – a mixture of diesel fuel (i.e. a liquid phase) and the air, depending on the gassy/fuel phase mass ratio *glr*, and the pressure in the area close to the droplet *p*. Initial calculation droplet diameter $D_{kaplpoc}$ is equal to the atomizer's outlet diameter d_o. A process of air compression is considered as adiabatic change of the state, and that's the reason of high temperatures of compressed air. A relative speed in between the droplet and a nearby air is not taken into consideration. A volume of the liquid phase (a fuel) practically is not depending on the environmental pressure. Intensity of volume alteration of the gassy phase (i.e. the air) and the alteration of the outer two-phase droplet diameter are higher at lower environmental pressures. Compressed air inside the two-phase droplet has a devastated effect on it. If there is more air inside the droplet, then it will disintegrate at higher environmental pressures, actually it will disintegrate faster. Based on the calculation it was established that increased injection pressure will also increase *glr* up to the value which will preserve bubbled flow regime inside of the nozzle's outlet, what is in the compliance with the experimental researches. Though this model is made with the variety of assumptions, it is indeed "rough", the obtained results are giving the essential basic information regarding a two-phase flow inside the engine cylinder behavior.

Any form of the liquid phase, with a certain gas quantity, can be identified to "equivalent" spherical liquid-phase droplet with the spherical gassy volume inside it. It is necessary to upgrade this calculation model and by means of experimental testing to determinate the criteria of droplet decomposing.

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