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INFLUENCE OF CHOKE USE ON FUEL VAPORIZATION INSIDE THE INTAKE MANIFOLD OF ETHANOL AND ETHANOL-GASOLINE BLEND FUELED ENGINES DURING COLD START

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Abstract. *Cold start tests were accomplished in an Otto type carburetor engine using ethanol and ethanol-gasoline blends and the fraction of fuel vaporized in the intake manifold during the period was determined. Engine block, air and fuel supply were cooled down and the tests were accomplished for temperatures between 9° and 23°C. The tests indicated that for temperatures under 13°C, the engine cold start process gets very difficult using only ethanol due to its high latent heat of vaporization and, in this cases, the use of ethanol-gasoline blends is necessary. It was verified that the fraction of vaporized fuel and the cold start success or failure are directly related to ambient temperature and the characteristics of the used fuel. It was concluded that AFV values higher than 150:1 in the intake manifold always implied in engine cold start failure.*

Key Words: *Cold Start, Ethanol, Ethanol-Gasoline Blends, Internal Combustion Engines, Vaporization.*

NOMENCLATURE

A - area
$AF = m_a / m_f$
$AFV = m_a / m_{fv}$
c - specific heat
EN - entrance
EX - exit
h - enthalpy
L - latent heat of vap
m - mass
P - pressure

Q - heat
t - time
T- temperature
u - specific internal energy
U - internal energy
V - volume
V_n- velocity
W - work
$\dot{q} = \dot{Q} / m$
ρ - density
$\dot{Q} = Q / t$

$\dot{W} = W / t$
X - fraction of fuel vapor

subscrits
a - air
f - fuel
fv -fuel vapor
if - initial (fuel)
l - liquid
lv - liquid-vapor
sat - saturation
v - vapor

1. INTRODUCTION

Ethanol has being seen lately as the most promising substitute of fuels derived from petroleum because its source is renewable, produces less air pollutants, has a high octanage facilitating the use of higher compression rates, it is a pure substance, has a simple molecule implying in higher combustion efficiency, has an oxygen atom in its molecule implying in less carbon monoxide (CO) production and better preserves the integrity of the cylinder because ethanol does not dissolve the lubricating oil film.

In spite of those advantages in relation to the fuels derived from petroleum, cold start problems and rough running during the engine heating up period is a problem in ethanol fueled engines. This happens, as verified by FEITOSA (1998), due to the characteristics of the fuel:

· Ethanol is a pure substance, thus it does not have components with different volatilities and ebullition points as does gasoline;

· Ethanol has a high vaporization latent heat (about 2.3 times higher than that of gasoline);

· Ethanol has a high ebullition point in comparison to the lightest gasoline components (78°C for ethanol against 30°C for the lightest gasoline components).

These characteristics of ethanol imply in cold start difficulties in temperatures below 16°C and the impossibility of cold starts at temperatures under 13°C, as have been verified during experiments. This happens because under temperatures of that order, there is not enough available energy to heat up and to vaporize a minimum amount of ethanol.

Using gasoline or ethanol-gasoline blends, the problem is alleviated or even eliminated for the temperatures studied. This occurs because the lightest components of the fuel, that vaporize under lower temperatures, are responsible for the formation of the appropriated amount of vaporized fuel or, at least, complete the amount of vapor produced by the alcohol, providing an ideal fraction of vaporized fuel, implying in the success of the cold start. However, the convenience of an easier engine cold start using ethanol-gasoline blends is opposed by the inconvenience of a higher pollutant emission, mainly during the engine heating up period when the fuel combustion is not efficient due to the low temperatures of the gases, the liquid fuel and the engine metallic parts.

2. THE VAPORIZATION PROCESS

The fuel vaporization process, during the cold start, is divided into two phases: the first occurs in the intake manifold for engines with carburetors or indirect injection and the second during the compression process of the mixture. The second phase does not suffer a significant influence of the ambient temperature because at the end of the compression stage the final temperature is practically the same, independent of the ambient temperature, however the first phase is highly influenced by it. The vaporization in the intake manifold should complete the amount that will be vaporized in the second stage in order to obtain an adequate amount of vaporized fuel for ignition mixture, but for low temperatures, the *AFV* rate produced in the intake manifold is just a fraction of that produced inside the cylinder (see Table 3).

During the admission process, the vaporization is facilitated, in spite of the low temperatures, by the depression caused by the carburetor and the intake manifold. This implies in a decrease of the fuel saturation temperature.

The use of the choke, in engines with carburetor, besides causing an increase of the amount of fuel in the mixture (decrease of the air-fuel rate, *AF*), causes a decrease of the pressure in the intake manifold . As was verified by SANTOS (1985), for a pressure of 68.7kPa in the intake manifold, the ethanol vapor pressure drops to 2.3kPa, which represents a liquid ethanol saturation temperature of about 69°C, or in other words, about 10°C inferior to the saturation temperature at ambient pressure.

During the compression process, the pressure varies from approximately 85.9kPa to about 2000kPa (in the tested motor - ignition absence), which represents a liquid ethanol saturation temperature varying from 74°C at the lower dead point up to 182°C at the upper dead point.

The depressure in the intake manifold, caused due to the use of the choke, clearly causes an increase in the amount of fuel vapor (the tests of cold start success or failure validate that statement) (Table 4), proving that the pressure fall in the manifold causes a decrease of the fuel saturation temperature.

Table 4 represents the tests of cold start success or failure for several ethanol-gasoline blends in relation to the engine, intake air and fuel temperature. A time below 20s for cold starting to get a self-maintained tick-over was defined as success, however time values up to 60s were exhibited (the acronyms *S* and *F* represent, respectively, success and failure of the cold starting process and the acronyms *OC* and *CC* represent opened and closed choke, respectively).

3. THEORICAL DEVELOPMENT

Starting from what is described above in relation to the importance of the process of fuel vaporization in the intake manifold and from the studies accomplished by PAGLIUSO (1999) in relation to fuel vaporization in the manifold and by FEITOSA et al. (1998a) and FEITOSA et al. (1998b) in relation to fuel vaporization in the intake manifold and inside the cylinder, the fraction of vaporized fuel in the intake manifold was determined (Eq. (9)) by the use of the gases temperature difference in the intake manifold for two different situations:

a) Cold start with dry carburetor - cylinder just admitting air;

b) Cold start with wet carburetor - cylinder admitting air and fuel (with ignition absence in order to avoid a change of the *AF* supply due to the fast increase of engine rotation in the case of starting the combustion process).

Considering that the intake manifold does not change heat to the environment and does not receive or do work, the mixture air-fuel added to the intake manifold will suffer an adiabatic saturation process. However as the intake manifold is not enough extensive, there is not vaporization of all the liquid fuel, just as represented in Fig 1.

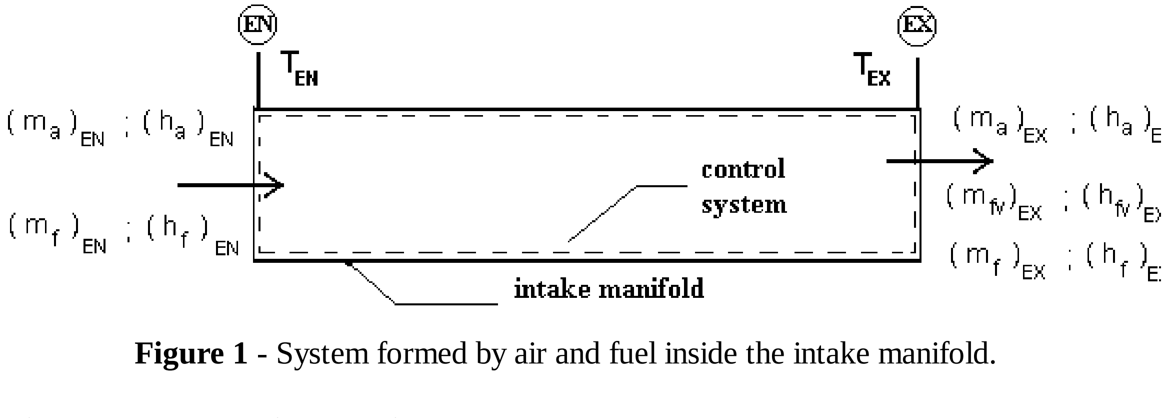

Figure 1 - System formed by air and fuel inside the intake manifold.

Using mass conservation equation, we get:

$$(m_a)_{EN} = (m_a)_{EX} = m_a \qquad (1)$$

$$m_f = m_{fv} + (m_f)_{EX} = X \cdot m_f + (1 - X) \cdot m_f \qquad (2)$$

And *X* is the fraction of vaporized fuel that, by definition, is the ratio between the mass of fuel vapor produced and the mass of admitted fuel:

$$X = \frac{m_{fv}}{m_c} \qquad (3)$$

So, analyzing the system formed by air and fuel drops inside the intake manifold in Fig. 1 and applying the equation of energy conservation, we can write :

$$\dot{Q} - \dot{W} + \iint_{EN} h \cdot \rho \cdot \vec{V} \cdot \partial A - \iint_{EX} h \cdot \rho \cdot \vec{V} \cdot \partial A = \frac{\partial}{\partial t} \iiint_{V} u \cdot \rho \cdot \partial V \qquad (4)$$

However

$$\dot{Q} = 0 \quad ; \quad \dot{W} = 0 \quad ; \quad \frac{\partial U}{\partial t} = 0 \qquad (5)$$

Then

$$m_{EN} \cdot h_{EN} = m_{EX} \cdot h_{EX} \qquad (6)$$

Being know that

$$h_{lv} = h_v - h_l = h_{fv} - h_f \qquad (7)$$

We get :

$$X = \frac{AF \cdot c_a \cdot (T_{EN} - T_{EX}) + c_f \cdot (T_{EN} - T_{EX})}{h_{lv}} \qquad (8)$$

Replacing T_{EN} - T_{EX} by ΔT and considering that h_{lv} is constant in the band of studied temperatures (0° a 30°C- between these values, h_{lv} varies between 943 and 912kJ/kg - to calculate *X* were used a mean value of h_{lv} because this do not imply in large errors - about 1,6%) and equal *L*:

$$X = \frac{\Delta T \cdot (AF \cdot c_a + c_f)}{L} \qquad (9)$$

4. EXPERIMENTAL DEVELOPMENT

The tests were accomplished originally in a Volkswagen Diesel engine, modified to an Otto cycle by HILDEBRAND Jr. (1998), who analyzed the performance of this engine with direct injection of pre-heated ethanol. This engine has a compression rate of 13,5:1, connecting rod length of 135 mm, course of 86,4 mm and cylinder diameter of 77mm. A WECARBRAS carburetor with double body and descending flow was used, which supplied an air-fuel rate between 4,3 and 7,8:1 in an opened choke condition and between 2 and 3,8:1 for a closed choke condition and the butterfly throttle in tick-over condition (Table 1).

Table 1 - Temperature difference observed in the intake manifold for the two conditions of mixture supplied by the carburetor and the air-fuel ratio, AF, supplied by the same.

T		***E100*** (100% ethanol)		***E61*** (61% ethanol + 39% gasoline)		***E50*** (50% ethanol + 50% gasoline)		***E22*** (22% ethanol + 78% gasoline)	
		ΔT (°C)	*AF*	ΔT (°C)	*AF*	ΔT (°C)	*AF*	ΔT (°C)	*AF*
9°C	*OC*	1,2	7,2	2	5,5	2,8	5,2	3,2	5,9
9°C	*CC*	2,5	3,4	4,5	2,6	5,8	3,7	5,5	3,8
13°C	*OC*	2	4,3	3,0	4,2	3,5	4,5	4,5	6,3
13°C	*CC*	3	2,5	6,0	2,6	6,5	2,5	6,0	3,3
16°C	*OC*	3	5,7	4,5	5,8	4,0	5,9	5,8	7,8
16°C	*CC*	6	2	5	3,4	7,5	2,6	6,8	3,0
23°C	*OC*	4,7	4,6	5	4,7	4,5	4,9	5,4	4,7
23°C	*CC*	8	2,5	9	2,0	8	2,9	7,2	3,0

(*OC*- opened choke; *CC*- closed choke).

Thermocouples were set at the carburetor entrance and in the proximities of the admission valve, and the measurements were made for the engine with the ignition system turned off in order to avoid the occurrence of combustion of the mixture in the cylinder. For this condition, engine rotation was 300rpm, supplied by the starter. In the case of the cold start success or failure tests, the ignition system was turned on and the necessary time for the engine to reach a self-maintained tick-over was measured.

The air-flow rate in the intake manifold and the fuel supplied by the carburetor for both opened and closed choke conditions were measured. In the case of the air, a flow nozzle was used into a pulse damping drum that was connected by a flexible hose to the engine carburetor. All the air which enters the engine must be drawn in through the nozzle. By measuring the pressure difference across the flow nozzle, the air flow rate was calculated to a high degree of accuracy. In the case of the fuel, it was used a graduated tube of about 1,5m high and diameter equal 0,01m. The variation of the fuel column height was measured in each test during about 20s, obtaining the fuel flow rate. Using those values, the respective supply ratio AF was calculated for each tested situation, as is shown in Table 1.

The tests were accomplished for temperatures varying between 9° and 23°C and an ambient pressure of 96kPa and were used ethanol and 3 ethanol-gasoline blends. The different test temperatures were obtained by cooling down the engine block by forced circulation of cold water cooled down using ice. The fuel and air were cooled down until they reach the temperature of the engine block, the test then took place. After each section of tests, cold water was circulated inside the engine block in order to maintain its temperature within the desired zone. Thermocouples in the engine block and oil were used to know the correct test temperature.

For the conditions described above, the air temperature was measured in the intake manifold for the dry carburetor (only air passing through the manifold) and wet carburetor (air and fuel passing through the manifold). The difference between the measured values represents the term ΔT, fundamental to calculate the amount of vaporized fuel (Eq. (9)).

Each combination of fuel type, test temperature and choke position was measured 3 times during about 30s and the values of ΔT after temperature stabilization of the intake manifold (after about 5s of the beginning of the test) were taken. The average of ΔT value during the 3 tests was used. The air and fuel flow rate mensuration process followed the same process.

5. RESULTS

Table 2 presents the values of the respective latent heats of vaporization (*L*) and specific heats (*c*), that were determined from the percentages of ethanol and gasoline in the mixture and from the values of *L* and *c* of the pure fuels. The *L* and *c* values were determined from the average values between 0° and 30°C.

Table 2 - Characteristics of tested fuels.

FUEL TYPE	***L*** [kJ/kg] 0° < T< 30°C	***c*** [kJ/kg °C]
E100 Pure Ethanol	928	2,64
Pure Gasoline (lightest components)	300	2,35
E61 61% ethanol 39% gasoline	683	2,53
E50 50% ethanol 50% gasoline	614	2,5
E22 22% ethanol 78% gasoline (Brazilian Gasoline)	438	2,41

(*OC*- opened choke; *CC*- closed choke)

Gasoline latent heat of vaporization was adopted by using the characteristics of its lighter components because, during a cold start, the temperature in the intake manifold is always low (equal or inferior to ambient), thus only the gasoline lightest components will change phase. These generally compose 19% of the gasoline, as verified by SHAYLER et al. (1992). Besides, the above studies, that consisted of the analyses of gas samples from the cylinder interior during admission and compression and that were accomplished for environment temperatures of 16°C, indicated that 46% of the whole sample were formed by light components (n-pentane and lighter), in the beginning of the compression stroke, during a cold start.

The analysis of the fraction of vaporized fuel inside the intake manifold considering just the gasoline lightest components is coherent. In fact gasoline possesses a latent heat of vaporization of 400kJ/kg, and a saturation temperature that varies between 30 and 210°C.

The results of the calculation of the fuel vapor fraction of vapor produced in the intake manifold and of the air-fuel vapor ratio, using Eq. (9) and the values supplied in Tables 1 and 2, are presented in Table 3.

The analysis of Table 3 indicates that the mixture of gasoline in the ethanol increases the rate of mixture vaporization, which explains the necessity of its addition during the cold start in ethanol fueled engines. This increase of the vaporization rate occurs due to the presence of more volatile components than ethanol. It must be noted that, for the analysis of Tables 3 and 4, for temperatures of 16°C, ethanol has difficulty in starting the combustion process, and at temperatures below 13°C, the process becomes impossible.

Table 3 - Calculated values of the vaporized fuel fraction and of the air-vapor ratio of the fuel.

T		***E100*** (100% ethanol)		***E61*** (61% ethanol + 39% gasoline)		***E50*** (50% ethanol + 50% gasoline)		***E22*** (22% ethanol + 78% gasoline)	
°C		*X*	*AVC*	*X*	*AVC*	*X*	*AVC*	*X*	*AVC*
9	*OC*	1,3 %	565	2,4 %	234	3,5 %	148	6,0 %	97
9	*CC*	1,6 %	209	3,4 %	78	5,8 %	63	7,8 %	49
13	*OC*	1,5 %	288	2,9%	142	4,0%	113	8,9%	60
13	*CC*	1,7 %	150	4,5%	58	5,3%	47	7,8%	42
16	*OC*	2,7 %	211	5,5 %	106	5,5 %	108	13,5 %	58
16	*CC*	3,0 %	67	4,3 %	78	6,2 %	42	8,4 %	36
23	*OC*	3,7 %	125	5,3 %	89	5,4 %	90	8,8 %	54
23	*CC*	4,4 %	56	6,0 %	34	7,0 %	41	8,9 %	34
(*OC*- opened choke; *CC*- closed choke)									

In some of the tests, the fraction of fuel vapor decreases with the closing of the choke, however the *AFV* ratio always decreases (richer mixture). This happens because *X*, by definition, is the ratio between m_{fv} and m_f . During the closing of the choke, the depressure in the intake manifold gets higher, so the fuel supply increases, also increasing the entire amount of fuel vapor due to the fall of fuel saturation pressure, even so, in some cases, the increase of fuel-flow rate caused by the closing of the choke is higher than the increase of fuel vapor mass, as can be seen in Table 3.

Notice that, in Table 1, the closing of the choke implies in a increase of ΔT value, what results in a decrease of *AFV* ratio, however this does not mean that there was a increase of *X* value.

Table 4 - Tests of cold start success and failure for different temperatures and different ethanol-gasoline blends.

T		***E100*** (100% ethanol)	***E61*** (61% ethanol + 39% gasoline)	***E50*** (50% ethanol + 50% gasoline)	***E22*** (22% ethanol + 78% gasoline)
9°C	*OC*	F	F 21s	S < 1s	S < 1s
9°C	*CC*	F	S 14s	S < 1s	S < 1s
13°C	*OC*	F	S 15s	S 3s	S < 1s
13°C	*CC*	F 60s	S 5s	S < 1s	S < 1s
16°C	*OC*	F	S 9s	S < 1s	S < 1s
16°C	*CC*	S 17s	S < 1s	S < 1s	S < 1s
23°C	*OC*	S < 1s	S < 1s	S < 1s	S < 1s
23°C	*CC*	S < 1s	S < 1s	S < 1s	S < 1s

It can be concluded that the reasonable minimum *AFV* ratio for cold start (produced in the manifold) should always be inferior for 100:1 to give a cold start success. As the minimum *AFV* ratio in the surroundings of the spark plug, in the moment of the spark liberation, should be approximately the double of the estequiometric air-fuel ratio (18:1 for the alcohol and 30:1 for pure gasoline), it is concluded that a great part of the fuel vaporization happens inside the cylinder during the compression of the mixture, even so the fraction vaporized within the intake manifold is of vital importance to the cold start success.

6. CONCLUSIONS

Ethanol possesses excellent characteristics as a fuel of internal combustion engines, despite the fact that its high latent heat of vaporization hinders, during a cold start, the formation of an adapted mixture of air and fuel vapor for its ignition and satisfactory combustion. This problem got worse for environments with temperatures under 13°C because the available energy in the air and in the liquid fuel gets insufficient to vaporize the surface of the ethanol drops due to the high latent heat of vaporization of this fuel (CHIN et al., 1984). In the case of the gasoline, that possesses more volatile components, even the little available energy in the intake manifold at the tested temperatures is enough to vaporize an adequate amount of fuel.

Gasoline addition to ethanol has the advantage of increasing the amount of more volatile components at low temperatures, facilitating the production of vapors and facilitating the ignition of the mixture. For temperatures of 9°C, the use of *E61* increases by about 2,7 times the amount of vapor in the intake manifold (in comparison to *E100*), while the use of *E50* and *E22* increases, respectively, by 3,3 times and 4,3 times that amount (a situation of closed choke having been analyzed - Table 3).

In all the tests, the closing of the choke implied in an increase of ΔT and an increase of the amount of fuel vapor mass (smaller *AFV*). This happens due to the depressure in the intake manifold caused by the choke, what implies in a fall of the fuel saturation pressure, facilitating its vaporization. In spite of the largest production of fuel vapor in that condition, in some cases a fall of the fraction of vaporized fuel, X, was noticed. This happens because the closing of the choke also implies in increase of the fuel flow rate.

Cold start success or failure under low temperatures is influenced by the *AFV* ratio produced in the intake manifold, in spite of this amount being very small compared with the amount produced inside the cylinder (for temperatures under 16°C). This can be verified, for a temperature of 16°C, where use of choke reduced the *AFV* ratio of *E100*, giving an engine start up. Something similar may be observed for *E61*, where the use of the choke decreased the engine start up time from 9 to less than 1s.

Despite the tests were accomplished using a quite simple test apparatus, the engine block cooling down process by forced circulation of water that was cooled down using ice, was shown quite efficient for the cold start tests. Despite the tests were accomplished in minimum temperatures of 9°C, the method allows tests in temperatures under 0°C, using anti-ice substances in the water.

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