Similarity Criterions for Liquid Propellants

Vasko Fotev
Assistant Professor
University of Belgrade
Faculty of Mechanical Engineering

In this very moment great effort in the field of air breathing propulsion and stationary gas turbine plants is doing on the combustion chamber improvement. The improvements are connected with, in one side, decreasing combustion chamber dimensions (micro propulsion), in second side with pollution decreasing and on the third side multi fuel capabilities. This paper presents the results of theoretical work on establishing relatively simple and inexpensive criterions for fuel similarity. The similarity means that original fuel can be replaced with other one in the scope of combustion chamber.
Presented results have great practical value and they are new in literature.

Keywords: *combustion, liquid, fuel, propellant, evaporation, pollution, propulsion, gas turbine.*

1. INTRODUCTION

Those days in the world of techniques there are lot of fields in which liquid is atomized in droplets with strongly controlled dimensions. Special field of technique in which this process is practically irreplaceable is liquid fuel combustion.

In this work we will comprise the aerospace engines, but the results are much wider.

From the energetic point of view propellant combustion is the core of aerospace engines.

Various types of permanently increasing demands [1] (economical, environment, health...) are articulated in technical requirements and standards. Procedures of meeting those standards may be divided in to the two main streams. First stream includes getting new technical solutions, which results in new products. Second, is using the existing technical solutions (devices) and implementing different or slightly different fuel types.

Let us use, for raff representation, the influence of increased fuel density for the air breathing engine. If increasing of density is made by 1%, it enlarges the flight vehicle range for 6%.

The benefit is very clear and attractive, but the question is: Is the engine (combustion chamber) capable to correctly work with this kind of fuel?

The main propose of this work is directly connected with this question and has as a target to gave the answer on it, or at leastways, valued values on which bases the engineers will be able to judge if they are on the right way or not.

Received: February 2004, accepted: April 2004.

Correspondence to: Vasko Fotev,
Faculty of Mechanical Engineering,
27. marta 80, 11120 Belgrade, Serbia and Montenegro
E-mail: vfotev@mas.bg.ac.yu

2. CONTEMPORARY STATE

Contemporary analyzing and solution methods in the field of combustion are mainly based on:

a) *Using the complex CFD software's combined with combustion models.* On the very first step [2] (impute values) we meet the problems, concerned with getting real droplet sizes, their distribution, complex physical constitutions, etc. Up to now the solvers and their methods are in the domain of proving the solutions. In one case results may be very useful and in other cases misleading.

b) *Using the experimental methods*. The experiments and test equipment are very expensive [3], so we have to take them in the cases for which we have real indicators that the planed solution will lead to the expected results.

c) *Simplified (integral) calculation methods*, which are acceptable as a first solution approach. In these methods there is one very efficient and meaningful – the *method of characteristic times* [4] and [5].

As we may see, all those methods need some cornerstone values, which authorized the planed ideas. This mentioned similarity criterions pretend to serve as ones, for introducing the new liquid propellant (fuel) type in to the existing CC. The criterion values have to be obtained by simple and inexpensive methods.

3. DEFINITION OF THE PROBLEM

As, it follows from preceding paragraph, the simplest way for reaching the required criterions have to be based on the simplest CC models. In other cases it will lead to expensive try and error physical or CFD experiments. The method which we adopt is the method of characteristic times.

The method of characteristic times lies on the next basic times:

1) droplet burning t_b,
2) droplet evaporation t_e,
3) mixing t_m and
4) chemical reacting t_c.

Droplet burning time depends of other three mentioned times, CC geometry and CC flow field. Droplet burning time is not just the simple sum of other three characteristic times [6], [7], [8] and [9], but rather function of them. This is the consequence of partially parallelism of those processes. Taking into account that we are dealing with introduction of new liquid fuel in the existing CC leads to following reasons:

a) Droplet evaporation for new fuel type will occur in same ambient conditions if droplet evaporation characteristics of new fuel are same as for old one.
b) Mixing times for both fuel types are same if the vapor production rates from the both droplets are same. This is the consequence that we use the same CC.
c) Chemical reaction times depend of the fuel chemical composition. In most cases main burning components are hydrogen and carbon. If the new fuel type has significant different chemical components, those influences have to be analyzed by a chemical kinetic method – which is out of our scope.

Following of these reasons leads to the next problem definition and strategy for finding the solution:

a) We have to study the droplet evaporation, and find the simple appropriate values which may serve as similarity criterions.
b) We have to define the "standard" evaporation conditions, for which the values of newly defined similarity criterions will be calculated.

4. DEFINING THE STANDARD EVAPORATION CONDITIONS

Taking into the account that temperatures in the CC's starts from ~500 K and rises up to ~2300 K, where the combustion is practically finished it is reasonable to accept temperature which is closer to the fuels boiling temperatures. From the other hand, using the legacy of characteristic times we adopt the following evaporation conditions – which are concern to the surrounding atmosphere in which liquid drops evaporates:

atmosphere – air
air is quiescent
air temperature T=1000 K
absolute air pressure p= 101325 Pa
droplet velocity U = 0 m/s
fuel vapor mass concentration far from droplet =0

5. SOME RESULTS FROM SIMPLIFIED NUMERICAL SIMULATION OF DROPLET EVAPORATION

For better understanding of evaporating process and getting the most important elements (values) which have dominant influence on the liquid fuel (propellant) vapor generation, we use the "DROPSE_01" computer program [10] and [11]. Important simplifications which are integrated into the DROPSE_01 are:

a) Droplet form is purely spherical.
b) Liquid is physically homogeneous (there is only one component with strictly defined physical characteristics).
c) Temperature inside droplet is uniform.
d) The main driving force is diffusion based on different mass concentrations.
e) There is no heat radiation.

For making the numerical experiment we take three different cases, which gave possibility to analyze the influence of three different parameters, which are in accordance with analyzed problem.

a) Influence of different liquids, when the *SMD*'s are same.
b) Influence of two different *SMD*'s for same type liquids.
c) Influence of two different liquids, and two different *SMD*'s.

For all three cases droplets evaporates in same standardized conditions, so the results are comparable. Analyzed fuels are kerosene JP_4 and diesel DF_2.

5.1. Stationary evaporation

DROPSE_01 is capable to calculate the stationary evaporation constant β_{st} upon imputed physical liquid and liquid vapor properties:

Table 1. Relevant results from DROPSE_01 calculations. Standard conditions and parameters defined on Figs. 1-3.

Fuel	D_{32} [μm]	β_{st} [m^2/s]	Vapor mass generation [kg/s]
DF_2	100	6.401e-7	2.197e-8
JP_4	100	6.089e-7	2.480e-8
JP_4	50	6.079e-7	1.238e-8

From the table 1 we may conclude that differences between presented values are relatively small and that DF_2 and JP_4 are almost same. The significant difference in vapor mass generation between JP_4, for two different *SMD*'s are the pure consequence of geometry. Nevertheless it indicates the point where similarities have to be search.

On the Fig. 1 are presented fuel mass vapor concentrations. They are important for combustion because of mixture ratio. A calculation shows that there is negligible difference between DF_2 and JP_4 for same *SMD*. The difference between same fuel droplets, JP_4 and different *SMD*'s is apparently. If we translate the curve for difference in droplet radius they will coincides.

From the Fig. 2 we can see fuel mass vapor flux distribution according distance from droplet evaporation surface. The curves show significant influence of droplet size.

Only the initial droplet size is purely function of atomizer. After entering the CC the droplet size (*SMD*) is function of evaporation rate. Fuel mass vapor flux may not be absolutely take as combustion driving value, rather it's influence have to be account through droplet dimensions, conditionally it leads back to vapor mass generation (table 1).

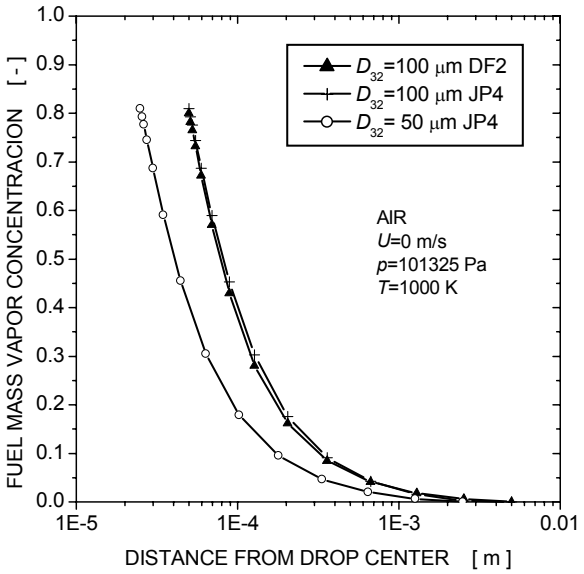

Figure 1. Distribution of fuel mass vapor concentration.

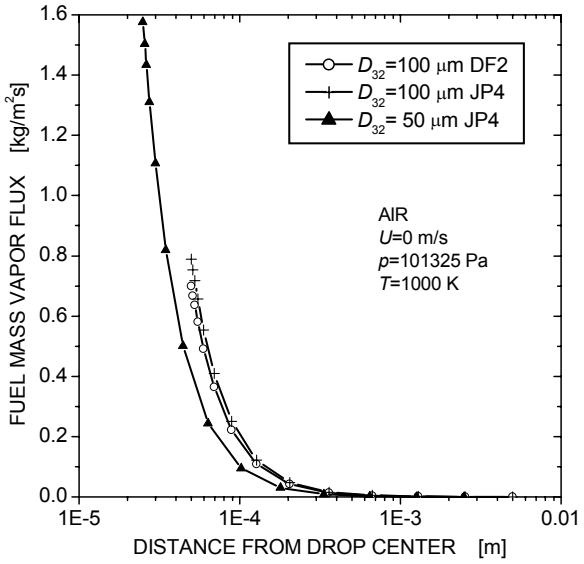

Figure 2. Distribution of fuel mass vapor flux.

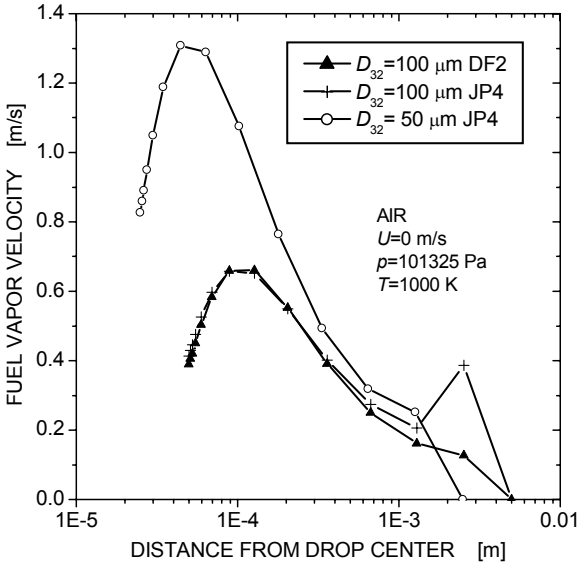

Figure 3. Fuel vapor velocity calculated in regard droplet evaporating surface.

From the Fig. 3 we can see the distribution of fuel vapor velocity along distance from droplet surface. This velocity is the sum of diffusion and convection type of vapor motion. Those velocities are directly responsible for vapor resident time in the droplet vicinity, and for this reason the flame position. The influence (as may be seen from Fig. 3) has absolutely local character and may not be connected with changing in CC overall process.

5.2. Transient evaporation

From previous analyzes it is clear that similarity parameters have to be searched in the direction of fuel vapor mass generation and time. The fig 4 presents mentioned process flow versus time.

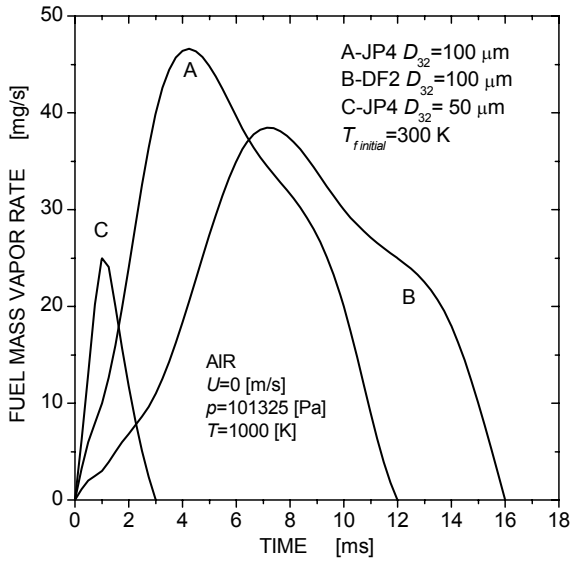

Figure 4. Dependence of fuel mass vapor rate versus fuel type, droplet initial *SMD* and time.

Those curves (A, B and C) present fuel mass vapor rate production versus time. They present transient part of evaporation (heating of the droplet until all liquid mass reach temperature slightly below boiling). During that period fuel *MVR* for all fuel types and droplet *SMD* increases. After that, the droplets reach stationary evaporation. Termination of the evaporation process defines evaporation time.

The key importance of this diagram, and presented values lies in several facts:

a) Time (from the Fig. 4) is directly connected with position in CC. Connection is retrieve by CC velocity flow field. It means that to the each time from Fig. 4 corresponds unique position in CC.

b) Fuel *MVR* from Fig. 4 is directly connected with mixture ratio in CC. Another time, connection is retrieved by CC velocity flow field. To the each fuel *MVR* from Fig. 4 correspond unique mixture ratio in CC.

c) If in the same position of CC we have same mixture ratio, it is no mater if mixture is produced with different fuels or droplets *SMD*'s.

d) The previous is valid if basic fuel compositions are same (hydrogen and carbon).

The last premise is necessary because of chemical kinetics, which is different for different chemical reactions, produced by different reactants.

6. FUEL SIMILARITY CRITERIONS

Now it is easy to define the fuel similarity criterions, under the previously mentioned requirements.

First of all, it is evident that if two droplets, each from different fuel type, produce congruence fuel *MVR* diagrams (curves) the processes in to the CC will be same. Not at all energetic difference may be notice on the gas flow and temperature field on the exit of CC. Of course, this is true if the both fuel types have same heating values.

Because we started with finding the similarity parameters which are easy to compare, we have to simplify method. Instead of comparing the whole curves (A, B and C) we suggest to compare some characteristic points from them. The characteristic points are:

t_e droplet evaporation time
MVR_{max} maximal value of *MVR*
t_{MVRmax} time when *MVR* is maximal

After adopting these characteristical points as curve representatives, we are able to define similarity criterions as follow.

6.1. First similarity criterion

It is ratio of droplet evaporation times in the standardized evaporation environment. The importance of this criterion lays in direct connection with flame length:

$$\tau_e = \frac{t_{eA}}{t_{eB}} . \quad (1)$$

The case τ_e=1 means that combustion will be ended for the fuel B in the same place of CC where it is for the fuel A.

The case τ_e<1 means that combustion will be ended for the fuel B in the further, from atomizer, place of CC then it is for the fuel A. It may have many consequences, which are function of CC dimensions and air distribution. In worst case the combustion is incomplete, with lot of unburned hydrogen and carbon, and with carbonmonooxide in growth.

The case τ_e>1 means that combustion will be ended for the fuel B in the near, from atomizer, place of CC then it is for the fuel A. But, this is true only if there is enough oxidizer in that region. Other vice it is a complex function of CC air distribution, and has to be analyzed including rest two similarity criterions.

6.2. Second similarity criterion

It is ratio of maximal fuel (propellant, liquid) mass vapor rate in the standardized evaporation environment:

$$\Omega = \frac{MVR_{\max A}}{MVR_{\max B}} . \quad (2)$$

The case Ω=1 means that same maximum amount of fuel vapor is generated. Criterion for itself is not enough, because it thus not means that the process will be identical until third similarity criterion is not satisfied (τ_Ω=1).

6.3. Third similarity criterion

It is ratio of times where maximal fuels (propellant, liquid) mass vapor rates are reached in the standardized evaporation environment:

$$\tau_\Omega = \frac{t_{MVR\max A}}{t_{MVR\max B}} . \quad (3)$$

The value of this similarity criterion is, as we see, necessary for properly interpretation of second.

We analyze the possible cases only up to the point which ensures that all three criterions are necessary.

7. CONCLUSION

The developed similarity criterions are based on theoretical work, which is used to highlight and separate values of greatest importance. The three similarity parameters values can be easy obtained by following procedure:

a) Calculation of *SMD* for new (B) fuel, for the existing atomizer.
b) Calculation of evaporation process for both, old (A) and new (B) fuel, for standardized environment.
c) Calculation the values of similarity parameters.
d) If the values of similarity parameters are close to 1, the implementation of new fuel type has justification.
e) Perform CFD and physical experiments with new fuel type.

The defined criterions are of high practical applicability. They are new into the literature, and for that reason have to be experimentally improved in the direction of more precise definition how much close to 1 they have to be.

NOMENCLATURE

Acronym:

CC - combustion chamber
CFD - computer fluid dynamics (software)
JP - kerosene, fuel
DF - diesel, fuel

Value:

MVR - mass vapor rate
p - pressure
SMD - drop Sauter main diameter (D_{32})
t - time
T - absolute temperature
U - relative velocity between air and droplet
β - evaporation constant
τ - time ratio
Ω - mass vapor rate ratio

Index:

b - burning
c - chemical
e - evaporation
f - fuel
initial initial conditions before evaporation start

m - mixing
st - stationary

REFERENCES

[1] Gupta A. K. and Lillay D. G. , Combustion and Environmental Challenges for Gas Turbine in the 1990s, J. of Propulsion and Power, No. 2, March-April, pp. 137-147, 1994.
[2] Rizk N. K. and Mongia H. C., Three-Dimensional Combustor Performance Validation with High-Density Fuels, J. Propusion Vol. 6, No. 5, pp. 660-667, 1989.
[3] Megaridis C. M., Comparison Between Experimental Measurements and Numerical Predictions of Internal Temperature Distributions of a Droplet Vaporizing under High – Temperature Convective Conditions, Combustion and Flame, 93, pp. 287-302, 1993.
[4] Plee S. L. and Mellor A. M., Characteristics Time Correlation for Lean Blowoff of Bluff-Body – Stabilized Flames, Combustion and Flame 35, pp. 61-80, 1979.
[5] Mellor A. M., Characteristics Time Emissions Correlations and Sample Optimization: GT-309 Gas Turbine Combustor, J. Energy Vol. 1, No. 4, pp. 244-249,1977.
[6] Hallet W. L. H. , A simple Model For the Vaporization of Droplets with Large Numbers of Components, Combustion and Flame, 121, pp. 334-344, 2000.
[7] Jarymowycz T. A. and Mellor A. M., Effects of Alternative Fuels on Ignition Limits of the J85 Annular Combustor, J. Propulsion Vol. 3, No. 3, pp. 283-287, 1987.
[8] Lefebvre A. H., *Atomization and Sprays*, Hemisphere Publishing Corporation, 1989.
[9] Qmaghy S., *Gorenye*, Moscow, izdatelstvo, Chemya, 1979.
[10] Fotev V., PhD Thesis, *Research of the parameters and criterions which are necessary for annular combustion chamber segment model*, Faculty of Mechanical Engineering, Belgrade, 1997.
[11] Fotev V., DROPSE_01 (*computer program for droplet evaporation*), Faculty of Mechanical Engineering, Belgrade, 2001.

КРИТЕРИЈУМИ СЛИЧНОСТИ ТЕЧНИХ ПОГОНСКИХ МАТЕРИЈА

Васко Фотев

Под критеријумима сличности течних погонских материја подразумевају се параметри на бази чије вредности се оцењује могућност примене друге врсте течног горива у постојећој комори сагоревања. У раду су изведена три критеријума сличности на бази физичких карактеристика горива за које је комора сагоревања пројектована и горива које може да га замени.

Изведени критеријуми сличности су нови у литератури и имају велики практични значај. За њихово израчунавање неопходно је познавање основних физичких својстава горива у течној и гасовитој фази. Поред тога је потребно израчунати ток процеса испаравања. У раду је то урађено ауторовим рачунарским програмом «ДРОПСЕ_01».